# Università degli Studi di Ferrara

DOTTORATO DI RICERCA IN
SCIENZE DELL'INGEGNERIA

CICLO XXVII

COORDINATORE Prof. Stefano Trillo

# Strategic planning of biomass and bioenergy technologies

Settore Scientifico Disciplinare ING-IND/09

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Anni 2012/2016

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## Abstract

The design of sustainable, environmentally friendly energy systems which have adequate capacity is a critical challenge faced by nations across the globe. This challenge is compounded in developing countries, which contain with remote areas yet to be connected to the grid, an over-dependence on conventional sources of energy, a shortage of financial resources, and, limited supporting policies and legislation.

The objective of this thesis is to develop methods for strategic planning of biomass and bioenergy technologies in developing countries. The approach followed is to start from the general and move to the specific. After a general formulation of methods, an exemplary case study of Colombia is presented.

The formulated methods cover four main areas. Firstly, a method to estimate the current biomass energy potential and its uncertainty at a country level is formulated when availability and quality of data are limited. For this purpose, a bottom-up resource-focused approach with statistical analysis using a Monte Carlo algorithm is proposed. Secondly, a method to estimate the future biomass energy potential and land use change is formulated for countries with domestic markets unable to influence international markets. The proposed method is a combination of resource-focused and demand driven approaches, in which the biomass energy potential is influenced by the internal demand, land use, economics, macroeconomics and global biofuel use. Thirdly, a method for energy technology roadmapping adapted to the conditions of developing countries and a new strategy to build consensus based on the Delphi method are formulated. These tools are employed for defining a plan to deploy sustainable bioenergy technologies in Colombia until 2030. The plan consists of a set of long-term goals, milestones, barriers and action items identified by over 30 experts for different bioenergy technology areas. Fourthly, a modeling framework to evaluate the impacts that long-term deployment of bioenergy technologies might cause on the energy supply and demand, emissions and land use at a country level is proposed. The method combines a quantitative and a qualitative element. The qualitative element integrates outcomes of technology roadmapping with scenario analysis to investigate various storylines with different underlying assumptions on policy measures. The quantitative element comprises four integrated tools, namely the energy system model (ESM), the land use and trade model (LUTM), an economic model, and an external climate model. These tools quantify in an integrated manner the impacts of implementing different scenarios on the energy system, emissions and land-use at a country level as well as the linkages with the economy and climate.

Results of the study case of Colombia suggest that the deployment of technologies for biomethane production, power generation & CHP should be prioritized. These technology routes avoid methane release, substitute fossil fuels, reduce $CO_2$ emissions and maximize the GHG reductions per incremental land of bioenergy.

# Strategic planning of biomass and bioenergy technologies

## Sommario

Il dimensionamento di sistemi energetici sostenibili e rispettosi dell'ambiente è una sfida fondamentale che deve essere affrontata dalle nazioni di tutto il mondo. Questa sfida è particolarmente rilevante nei paesi in via di sviluppo, in quanto vi sono aree remote ancora non elettrificate, vi è una eccessiva dipendenza da fonti convenzionali di energia, si registra una carenza di risorse finanziarie e non sono sviluppate ed implementate adeguate politiche e regolamentazioni.

L'obiettivo di questa tesi è lo sviluppo di una metodologia per la pianificazione strategica delle tecnologie basate su biomasse e bioenergie in genere, nei paesi in via di sviluppo. L'approccio seguito è quello di iniziare da un approccio generale e poi passare ad uno specifico contesto di applicazione, che nel caso in esame è la Colombia.

Le metodologie sviluppate ed applicate nella tesi sono relative a quattro aree principali.

In primo luogo, viene sviluppato un metodo per stimare l'attuale potenziale energetico della biomassa e la sua incertezza a livello nazionale, per tenere conto del fatto che la disponibilità e la qualità dei dati possono essere limitati. A questo scopo, si propone un approccio focalizzato sul tipo di risorsa e bottom-up, con analisi statistica che utilizza un algoritmo Monte Carlo. In secondo luogo, viene sviluppato un metodo per stimare il futuro potenziale energetico della biomassa e il cambiamento di uso del suolo, per paesi il cui mercato nazionale non influenza i mercati internazionali. Il metodo proposto è una combinazione di approcci focalizzati sul tipo di risorsa e guidati dalla domanda, in cui l'energia potenziale della biomassa è influenzato dalla domanda interna, dall'uso del suolo, dall'economia, dalla macroeconomia e dall'uso di biocarburanti globale. In terzo luogo, la tesi propone un metodo per tracciare la roadmap per l'utilizzo di tecnologie energetiche, adattato alle condizioni dei paesi in via di sviluppo, e una nuova strategia per costruire il consenso sulla base del metodo Delphi. Questi strumenti sono impiegati per la definizione di un piano per implementare tecnologie bioenergetiche sostenibili in Colombia fino al 2030. Il piano è costituito da una serie di obiettivi a lungo termine, di tappe, di barriere e di "azioni" individuate da più di 30 esperti per le diverse aree tecnologiche. In quarto luogo, viene sviluppato un modello generale di simulazione per valutare gli impatti che l'implementazione a lungo termine delle tecnologie bioenergetiche potrebbe causare su domanda e richiesta di energia, emissioni e uso del territorio a livello nazionale. Il metodo combina elementi sia quantitativi sia qualitativi. L'elemento qualitativo integra i risultati della tecnologia di sviluppo della roadmap con analisi di scenari per indagare varie storie con diverse ipotesi circa le azioni di politica energetica da attuare. L'elemento quantitativo comprende quattro strumenti integrati, vale a dire il modello di sistema energetico (ESM), l'uso del suolo e un modello di mercato (LUTM), un modello economico e un modello che tiene conto del clima. Questi strumenti servono per quantificare in modo integrato gli impatti conseguenti all'attuazione di diversi scenari sul sistema energetico, le emissioni e l'uso del suolo a livello nazionale, così come i legami con l'economia e il clima.

I risultati dello studio per il caso della Colombia indicano che la diffusione di tecnologie per la produzione di biometano, la generazione di energia e la cogenerazione dovrebbero essere le tecnologie sulle quali investire per il futuro, in quanto permettono di ridurre le emissioni di metano, la sostituzione dei combustibili fossili, la riduzione delle emissioni di $CO_2$ e la massimizzazione della riduzione di gas serra per suolo incrementale utilizzato per la produzione di bioenergia.

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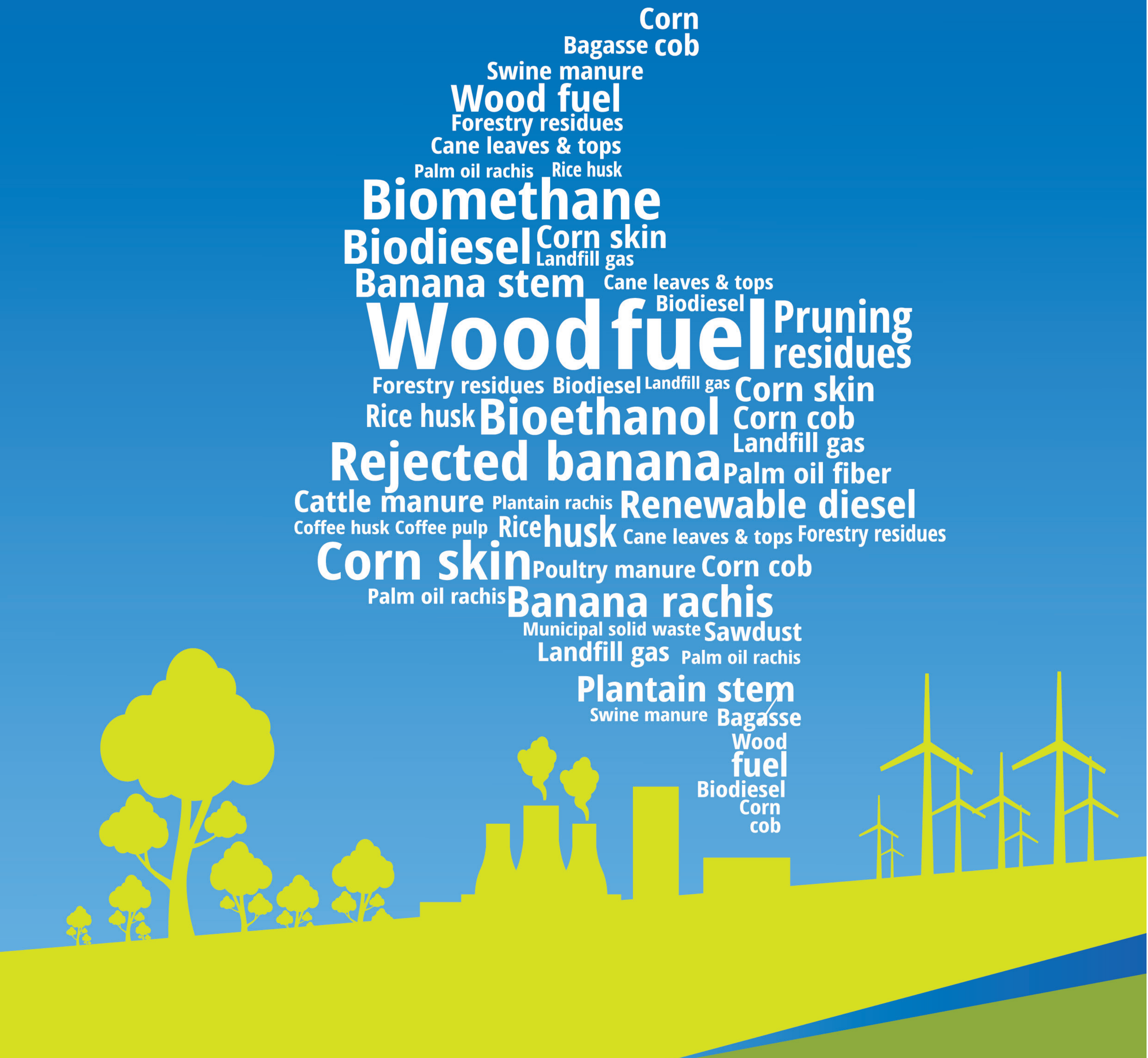

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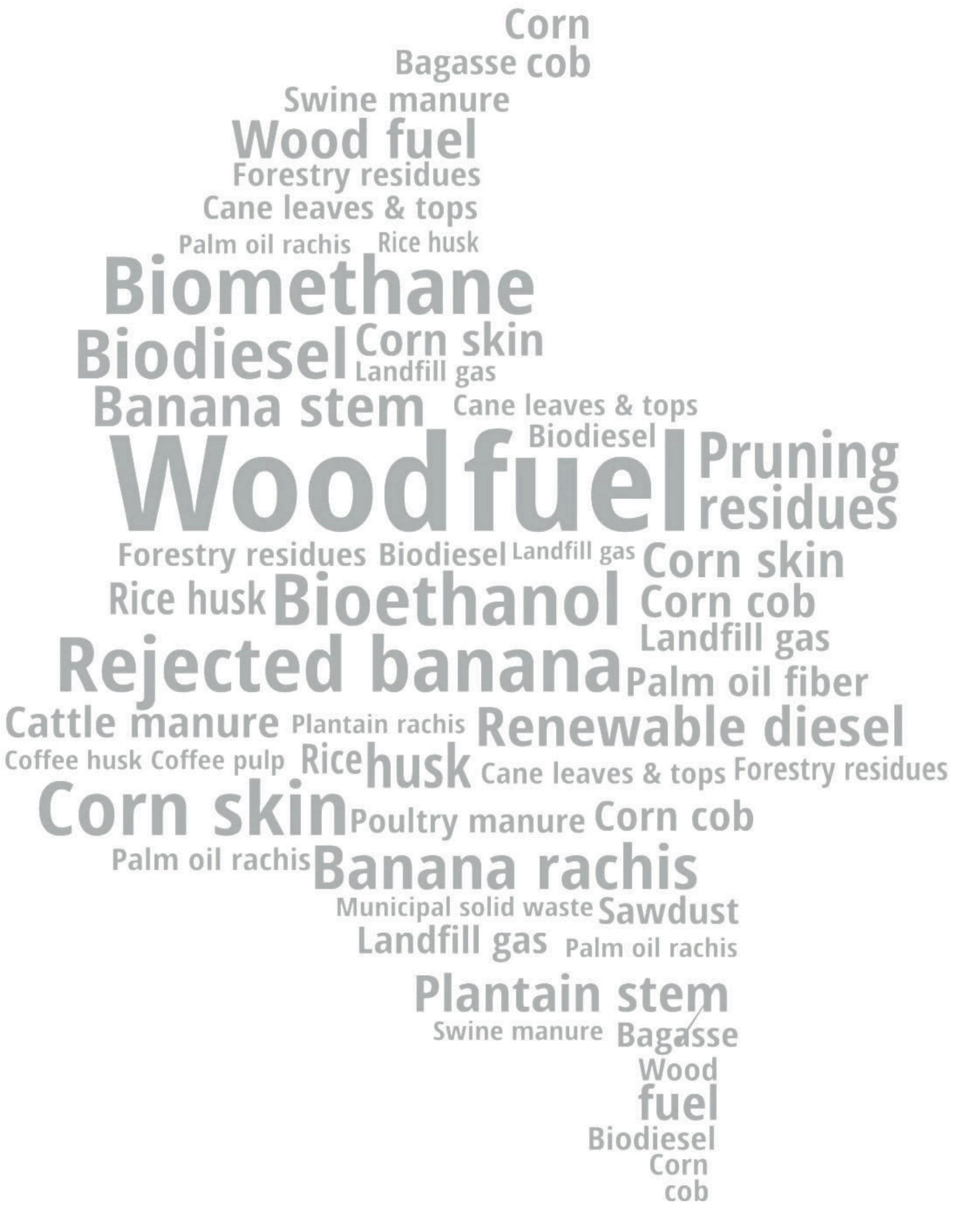

# Strategic planning of biomass and bioenergy technologies

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# Abstract

The design of sustainable, environmentally friendly energy systems which have adequate capacity is a critical challenge faced by nations across the globe. This challenge is compounded in developing countries, which contain with remote areas yet to be connected to the grid, an over-dependence on conventional sources of energy, a shortage of financial resources, and, limited supporting policies and legislation.

The objective of this thesis is to develop methods for strategic planning of biomass and bioenergy technologies in developing countries. The approach followed is to start from the general and move to the specific. After a general formulation of methods, an exemplary case study of Colombia is presented.

The formulated methods cover four main areas. Firstly, a method to estimate the current biomass energy potential and its uncertainty at a country level is formulated when availability and quality of data are limited. For this purpose, a bottom-up resource-focused approach with statistical analysis using a Monte Carlo algorithm is proposed. Secondly, a method to estimate the future biomass energy potential and land use change is formulated for countries with domestic markets unable to influence international markets. The proposed method is a combination of resource-focused and demand-driven approaches, in which the biomass energy potential is influenced by the internal demand, land use, economics, macroeconomics and global biofuel use. Thirdly, a method for energy technology roadmapping adapted to the conditions of developing countries and a new strategy to build consensus based on the Delphi method are formulated. These tools are employed for defining a plan to deploy sustainable bioenergy technologies in Colombia until 2030. The plan consists of a set of long-term goals, milestones, barriers and action items identified by over 30 experts for different bioenergy technology areas. Fourthly, a modeling framework to evaluate the impacts that long-term deployment of bioenergy technologies might cause on the energy supply and demand, emissions and land use at a country level is proposed. The method combines a quantitative and a qualitative element. The qualitative element integrates outcomes of technology roadmapping with scenario analysis to investigate various storylines with different underlying assumptions on policy measures. The quantitative element comprises four integrated tools, namely the energy system model (ESM), the land use and trade model (LUTM), an economic model, and an external climate model. These tools quantify in an integrated manner the impacts of implementing different scenarios on the energy system, emissions and land-use at a country level as well as the linkages with the economy and climate.

Results of the study case of Colombia suggest that the deployment of technologies for biomethane production, power generation & CHP should be prioritized. These technology routes avoid methane release, substitute fossil fuels, reduce $CO_2$ emissions and maximize the GHG reductions per incremental land of bioenergy.

**Keywords:** strategic planning, policy analysis, bioenergy, energy systems, land use, biomass potential.

# Preface

This PhD thesis was developed at the Dipartimento di Ingegneria of the Università degli Studi di Ferrara (Italy), within the framework of a collaboration initiative with the Institute for Technology Assessment and System Analysis (ITAS) at the Karlsruhe Institute of Technology (Germany) and the Kempten University of Applied Sciences (Germany). It was supervised by Prof. Ing. Mauro Venturini at the Università degli Studi di Ferrara and co-supervised by Dr. Witold-Roger Poganietz at the Institute for Technology Assessment and System Analysis and by Prof. Dr. Matthias Finkenrath at the Kempten University of Applied Sciences. This thesis is based on various scientific manuscripts published or submitted to publication in peer-reviewed international journals, peer-reviewed conferences, peer-reviewed special reports and patent applications. These scientific publications are listed below. In all the scientific publications the author of this thesis was the leading author. Prof. Ing. Mauro Venturini, Dr. Witold-Roger Poganietz and Prof. Dr. Matthias Finkenrath jointly supervised the work.

**Peer-reviewed international journals**

1. Gonzalez-Salazar, M., Venturini, M., Poganietz, W., Finkenrath, M. (2015). Effects of long-term deployment of bioenergy in Colombia (submitted).
2. Gonzalez-Salazar, M., Venturini, M., Poganietz, W., Finkenrath, M., Kirsten, T., Acevedo, H., Spina, P. (2015). Development of a roadmap for bioenergy exploitation (submitted).
3. Gonzalez-Salazar, M., Venturini, M., Poganietz, W., Finkenrath, M., Kirsten, T., Acevedo, H., Spina, P. (2015). A framework to evaluate the energy, economy, emissions and land-use nexus for bioenergy exploitation (submitted).
4. Gonzalez-Salazar, M., Venturini, M., Poganietz, W., Finkenrath, M., Spina, P. (2015). Methodology for improving the reliability of biomass energy potential estimation (submitted).
5. Gonzalez-Salazar, M., Morini, M., Pinelli, M., Spina, P., Venturini, M., Finkenrath, M., Poganietz, W. (2014). Methodology for estimating biomass energy potential and its application to Colombia. Applied Energy, 136, 781-796.
6. Gonzalez-Salazar, M., Morini, M., Pinelli, M., Spina, P., Venturini, M., Finkenrath, M., Poganietz, W. (2014). Methodology for biomass energy potential estimation: projections of future potential in Colombia. Renewable Energy, 69, 488-505.

**Peer-reviewed international conferences**

1. Gonzalez-Salazar, M., Morini, M., Pinelli, M., Spina, P., Venturini, M., Finkenrath, M., Poganietz, W. (2013). Methodology for biomass energy potential estimation: projections of future potential in Colombia. International Conference on Applied Energy (ICAE).
2. Gonzalez-Salazar, M., Morini, M., Pinelli, M., Spina, P., Venturini, M., Finkenrath, M., Poganietz, W. (2013). Methodology for biomass energy potential estimation: assessment of current potential in Colombia. International Conference on Applied Energy (ICAE).

**Peer-reviewed special reports**

1. Gonzalez-Salazar, M., Venturini, M., Poganietz, W., Finkenrath, M., Kirsten, T., & Acevedo, H. (2014). Bioenergy technology roadmap for Colombia. Università degli Studi di Ferrara. DOI: http://dx.doi.org/10.15160/unife/eprintsunife/774

**Patent applications**

1. Gonzalez-Salazar, M., Becquin, G. (2015). Process of producing, transporting and combusting novel fuels consisting of gas hydrocarbons (including biomethane) dissolved in liquid fuels. Filed in the U.S. Patent Office on November 25th 2015, Application Number (Serial Number) 14/951,700.

# Acknowledgements

A smooth sea never made a skillful sailor. That's true. Four years ago I had the crazy idea of pursuing a PhD, to become, you know, "a skillful sailor". I didn't really know how to do it, but I wanted to do it anyway. So, I set out against the wind and tide, like in the Odyssey. By the middle of the project, my life had completely changed. I had got married, my father had passed away and I myself had become a father. I struggled to find the right balance between my new life and the PhD thesis. Many people inspired me and helped me in different ways to find answers to these challenges. Thanks to them this work has survived many storms and wild seas. This thesis is dedicated to all of them. On a different level, the thesis is devoted to my homeland, Colombia, as a reward for so many good things I experienced there.

First, I want to thank Maria, my wife, for travelling with me in this adventure, for supporting me all the time and for forgiving the difficult moments. You are the reason to start a thousand Odysseys. Amelia, my dear, thanks for being here and for showing us what is important in life, you are our most precious treasure. Many thanks to my mom and dad for teaching me all I know and for encouraging me to pursue my dreams ¡muchas gracias! I would not be here writing this without you. Thanks to my sisters Ana & Efa, for their love and unconditional backing. Many thanks to the Salazar family (Abuelita, María Claudia, Sofía, Claus, Iván, Mariana, Sami, Carlitos, Tere, Robledo and Felipe), for being my spiritual support back at home, for the crazy ideas, stubbornness, appetite and good moments. Thank you so much to my parents-in-law Kathrin and Jörg, for looking after us so many times.

Many people believed in me from the beginning and I am very grateful to all of them. To my supervisor Prof. Ing. Mauro Venturini, thanks a lot for your advice and guidance, for supporting my unconventional research setup and crazy initiatives, for encouraging me in difficult moments and for being my friend. To my co-advisor Dr. Witold-Roger Poganietz, thanks for bringing your thoroughness and experience to our team, for your valuable contributions and constructive feedback, which helped me to improve this work. To my co-advisor Prof. Dr. Matthias Finkenrath, thank you so much for supporting my work unconditionally, for sharing your technical depth, experience and enthusiasm with me, for teaching me how to enjoy life at work and for your friendship (and Fasching!). Many, many, many thanks to Trevor Kirsten - finishing this thesis would have not been possible without your help, continuous support, encouragement, and good humor.

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Finally, thanks from the bottom of my heart to my friends for helping me to return to Ithaca from the underworld and for being here when I needed help: Jorge Pérez, Andrés & Anni, Rodrigo & Ariana, Alvaro & Mayra, Renato & Fafa and Mani.

*"Never give in, never give in, never, never, never, never—in nothing, great or small, large or petty— never give in except to convictions of honour and good sense" – Churchill*

*"¡Quiero comprar el avión que está hundido en el río Vaupés!" – El Alcaraván, German Castro Caycedo*

Para mi Papá

y

para Amelia

# Nomenclature

## Chapter C

Symbols

| | |
|---|---|
| $a$ | availability factor |
| $b$ | biogas yield from manure |
| $c$ | by-product to product ratio in forestry |
| $d$ | dry basis |
| $f$ | manure production per head |
| $k$ | by-product to product ratio in agriculture |
| $H$ | heads, animal stocks |
| $LHV$ | lower heating value |
| $HHV$ | higher heating value |
| $M$ | moisture content |
| $P$ | production |
| $Q$ | theoretical energy potential |
| $Q^T$ | technical energy potential |
| $w$ | wet basis |
| $\overline{x}$ | mean of x |
| $\propto$ | constraint factor to calculate availability |
| $\sigma$ | standard deviation |
| $\eta$ | energy efficiency |
| $\rho$ | density |

Subscripts

| | |
|---|---|
| $AR$ | agricultural residue |
| $AW$ | animal waste |
| $current$ | state-of-the-art technology |
| $F$ | forest-based |
| $i$ | i-th agricultural crop |
| $j$ | j-th residue for each i-th agricultural crop |
| $m$ | m-th type of animal |
| $n$ | n-th sub-category of type of animal |
| $r$ | r-th forestry resource |
| $s$ | s-th biofuel |
| $x$ | x-th type of urban waste |
| $U$ | urban waste |

## Chapter D

Symbols

| | |
|---|---|
| $A$ | area |
| $c$ | production cost |
| $d$ | demand per capita of commodities |
| $D$ | domestic demand of commodities |
| $E$ | exchange rate |
| $FPI$ | fertilizers price index |
| $GDG$ | GDP deflator growth |
| $I$ | volume of imported commodities |
| $I1$ | volume of imported commodities subject to tariffs |
| $I2$ | volume of imported duty free commodities |
| $k$ | price sensitivity coefficient |
| $LPI$ | local price index |
| $M$ | profit |
| $N$ | population |
| $P$ | domestic production of commodities |
| $PI$ | price index |
| $PIC$ | price index for Colombia |
| $Y$ | yield |
| $W$ | local minimum wage |
| $\pi$ | price “Free On Board” (FOB), non-discounted |
| $\pi^*$ | price “Cost Insurance and Fright” (CIF), non-discounted |
| $\pi^{**}$ | price “Cost Insurance and Fright” plus margin for importer, non-discounted |

Subscripts

| | |
|---|---|
| $i$ | i-th time step, year |
| $j$ | j-th commodity |
| $T$ | theoretical |

Superscripts

| | |
|---|---|
| $D$ | domestic production |
| $E$ | exports |
| $I$ | imports |
| $I1$ | imports subject to tariffs |
| $I2$ | duty free imports |
| $Max$ | maximal |

## Chapter F

Symbols

| | |
|---|---|
| $A$ | dummy variable to estimate vehicle ownership |
| $AL$ | activity level |
| $b$ | coefficient of equation to estimate saturation of appliances |
| $BMV$ | blend mandate of biofuels by volume |
| $C$ | installed power generation capacity |
| $C1$ | coefficient to estimate the energy consumption of other appliances |
| $C2$ | coefficient to estimate the energy consumption of other appliances |
| $CAD$ | annual addition of power generation capacity |
| $CC$ | capacity credit |
| $CDD$ | cooling degree days |
| $CF$ | capacity factor |
| $CK1$ | coefficient to evaluate the annual energy demand for cooking per household |
| $CK2$ | coefficient to evaluate the annual energy demand for cooking per household |
| $CK3$ | coefficient to evaluate the annual energy demand for cooking per household |
| $CKE$ | annual energy demand for cooking |
| $CKEp$ | annual energy demand for cooking per person |
| $COP$ | coefficient of performance for air conditioners |
| $Cov$ | supply coverage |
| $D$ | population density |
| $d$ | parameter of Gompertz function to estimate the ownership of refrigerators |
| $DC$ | total discounted cost |
| $DE$ | decommissioning cost |
| $Deg$ | factor representing the change in a property (e.g. efficiency, emission) as a technology ages |

| | |
|---|---|
| $E$ | access to energy services (electricity and natural gas) |
| $e$ | parameter of Gompertz function to estimate the ownership of refrigerators |
| $ECA$ | energy consumption for appliances |
| $ECAp$ | energy consumption for appliances per capita |
| $ECC$ | energy consumption for cooking |
| $ECCH$ | energy consumption for cooking per household |
| $ECCI$ | energy consumption in the cane industry |
| $ECCp$ | energy consumption for cooking per capita |
| $ECF$ | energy consumption by fuel for various sectors |
| $ECL$ | energy consumption for lighting |
| $ECLH$ | energy consumption for lighting per household |
| $ECLp$ | energy consumption for lighting per capita |
| $ECP$ | consumption of energy resources for power generation |
| $ECPI$ | energy consumption in the palm oil industry |
| $ECV$ | energy consumption for a vehicle |
| $ECW$ | energy consumption for water heating |
| $ECWp$ | energy consumption for water heating per capita |
| $EF$ | emission factor |
| $EIC$ | energy intensity in the cane industry |
| $EIP$ | energy intensity in the palm industry |
| $F$ | fuel cost |
| $FE$ | fuel economy for a new vehicle |
| $FFB$ | fresh fruit bunches |
| $FS$ | floor space per person |
| $FSQ$ | floor space quintile factor |
| $FU$ | energy produced in a final use, e.g. power generation, heat production, etc. |
| $GDP$ | gross domestic product |
| $GDPp$ | gross domestic product per capita |
| $GHG$ | greenhouse gas emission |
| $H$ | number of households |
| $HDD$ | heating degree days |
| $HH$ | household expenditure |
| $HHp$ | household expenditure per person |
| $I$ | investment cost |
| $IS$ | income share for different regions or quintiles |
| $LE$ | lighting energy demand per household |
| $LEp$ | lighting energy demand per capita |
| $LHF$ | lighting hours factor coefficient |
| $LHV$ | lower heating value |
| $M$ | motorcycle ownership |
| $m$ | coefficient of equation to estimate saturation of appliances |
| $\dot{m}$ | mass flow |
| $MEF$ | multiplying emission factor for biofuels |
| $Mil$ | mileage for a vehicle |
| $OD$ | annual number of days demanding hot water |
| $OM$ | operation & maintenance cost |
| $OW$ | appliance ownership |
| $P$ | population, e.g. number of inhabitants |
| $PG$ | power generation |
| $PL$ | peak load |
| $Q$ | quintile number, i.e. 1, 2, 3, 4 and 5 |
| $R$ | dummy variable to estimate vehicle ownership |
| $r$ | discount rate |

| | |
|---|---|
| $RM$ | planning reserve margin |
| $S$ | household size |
| $Sales$ | number of vehicle sales |
| $SH$ | vehicle share |
| $Stock$ | number of vehicles |
| $Sur$ | survival rate of vehicles |
| $T$ | temperature |
| $t$ | year |
| $TEP$ | technical biomass energy potential |
| $U$ | urban fraction of population |
| $UEC$ | unit energy consumption by type of appliance |
| $V$ | vehicle ownership |
| $VE85$ | percentage of vehicles able to run with E85 |
| $VEFF$ | percentage of vehicles that are flex fuel |
| $W$ | unit energy consumption per light bulb |
| $x$ | mass content |
| $\alpha$ | parameter of Gompertz function |
| $\beta$ | parameter of Gompertz function |
| $\psi$ | saturation level of Gompertz function |
| $\lambda$ | negative constant of Gompertz function |
| $\varphi$ | negative constant of Gompertz function |
| $\theta$ | speed of adjustment |
| $\varepsilon$ | random error |
| $k$ | cost exponent in logit function |
| $\gamma$ | cost sensitivity coefficient in logit function |
| $\mu$ | fuel share |
| $\vartheta$ | coefficient that influence the unit energy consumption in appliances |
| $\zeta$ | coefficient that influence the unit energy consumption in appliances |
| $\xi$ | coefficient that influence the energy consumption by fuel for various sectors |
| $\nabla$ | gradient to model differences in access to energy services across quintiles |

Subscripts

| | |
|---|---|
| $a$ | a-th type of appliance |
| $AC$ | related to air conditioners |
| $b$ | b-th type of biomass resource |
| $ba$ | related to bagasse |
| $bg$ | related to biogas |
| $bio$ | related to biofuels |
| $biom$ | related to biomethane |
| $blend$ | related to blends of fossil fuels and blends |
| $c$ | c-th type of vehicle |
| $cj$ | related to cane juice |
| $cnl$ | related to cane without leaves |
| $cwl$ | related to cane with leaves |
| $d$ | d-th time step, day |
| $E$ | type of energy service, e.g. electricity, natural gas, heating, etc. |
| $E20$ | related to the fuel program E20 (ethanol 20%v) |
| $E85$ | related to the fuel program E85 (ethanol 85%v) |
| $El$ | related to electricity |
| $et$ | related to bioethanol |
| $F$ | period of falling |
| $f$ | f-th type of fuel |
| $fossil$ | related to fossil fuels |
| $g$ | g-th type of power generation technology |

| | |
|---|---|
| *ko* | related to kernel oil |
| *lg* | related to landfill gas |
| *MAX* | maximum |
| *nby* | related to non-usable by-products from palm oil |
| *O* | related to outputs |
| *OA* | related to other appliances |
| *Other* | related to other pollutants |
| *p* | p-th type of pollutant |
| *po* | related to palm oil |
| *pr* | related to palm residues |
| *Q* | q-th quintile |
| *R* | period of rising |
| *r* | region, i.e. rural and urban |
| *Re* | reference |
| *Ref* | related to refrigerators |
| *Ro* | related to the different routes to produce sugar and bioethanol, i.e. Route 1, Route 2 and Route 3 |
| *ru* | related to rural regions |
| *s* | related to sugar |
| *t* | t-th time step, year |
| *tl* | related to cane tops and leaves |
| *u* | related to urban regions |
| *v* | v-th year of production (vintage) of a certain type of vehicle or motorcycle |

## Acronyms in all chapters

| | |
|---|---|
| ARIMA | autoregressive integrated moving average model |
| Asocaña | Asociación de Cultivadores de Caña de Azúcar de Colombia (Association of Sugar Cane Growers of Colombia) |
| BID | Inter-American Development Bank |
| BOD | biochemical oxygen demand |
| BRICS | Brazil, Russia, India, China & South Africa |
| CHP | combined heat and power |
| CI | confidence interval |
| CIF | Cost, insurance and freight |
| CNG | compressed natural gas |
| COE | cost of electricity |
| COL | Colombian peso |
| COP | coefficient of performance |
| CREG | Comisión de Regulación de Energía y Gas, Colombia (Energy and Gas Regulatory Commission) |
| DANE | Departamento Administrativo Nacional de Estadística, Colombia (National Administrative Department of Statistics) |
| DNP | Dirección Nacional de Planeación, Colombia (National Planning Division) |
| DOE | U.S. Department of Energy |
| Ecopetrol | Empresa Colombiana de Petróleos (Colombian Petroleum Co.) |
| EIA | U.S. Energy Information Administration |
| ENSO | El Niño and La Niña southern oscillation |
| ESCO | energy service company |
| ESM | energy system model |
| EUD | extended uniform distribution |
| FAO | Food and Agriculture Organization of the United Nations |
| FAPRI | Food and Agriculture Policy Research Institute |
| FFB | fresh fruit bunches (palm oil) |
| FFV | flex-fuel vehicles |
| FTA | Free Trade Agreement |
| GBEP | Global Bioenergy Partnership |
| GDP | gross domestic product |
| GHG | greenhouse gas |
| GT | gas turbine |
| GWP | Global Warming Potential |
| HHD | Human Development Index |
| IDEAM | Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (Colombian Institute of Hydrology, Meteorology and Environmental Studies) |
| IEA | International Energy Agency |
| IIASA | International Institute for Applied Systems Analysis |
| ILUC | indirect land-use change |
| IPCC | Intergovernmental Panel on Climate Change |
| LCOE | levelized cost of electricity |
| LDPS2 | Livestock Development Planning System v2 |
| LEAP | Long-range Energy Alternatives Planning System |
| LHV | lower heating value |
| LPG | liquefied petroleum gas |
| LULUCF | land use, land-use change and forestry |
| LUTM | land use and trade model |
| MME | Ministry of Mines and Energy, Colombia |
| MSW | municipal solid waste |
| MUV | Manufactures Unit Value |
| NGO | non-governmental organization |
| NGCC | natural gas combined cycle |
| NIZ | non-interconnected zones |
| NMVOC | non-methane volatile organic compounds |
| NOx | nitrogen oxides |
| NREL | U.S. National Renewable Energy Laboratory |
| OECD | Organisation for Economic Co-operation and Development |
| OEM | original equipment manufacturer |
| PPP | purchasing power parity |
| R&D | research and development |
| SME | small and medium-sized enterprises |
| SOx | sulfur oxides |
| TED | technology and environmental database |
| TOE | ton of oil equivalent |
| TRQ | Tariff Rate Quota |
| UEC | unit energy consumption |
| UPME | Unidad de Planeación Minero Energética, Colombia (Mining and Energy Planning Unit) |
| WB | World Bank |
| WEO | World Energy Outlook |

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# Chapter A. Introduction

## A.1. Overview

Assuring the quality of life of citizens and increasing their economic prosperity are some of the most important responsibilities of a nation. One resource necessary to both quality of life, and economic development is energy. Access to energy contributes in several ways to the reduction of extreme poverty and to meeting the U.N. Millennium Development Goals: it is essential for the provision of clean water, sanitation, healthcare, reliable and efficient lighting, heating, cooking, mechanical power, transport and telecommunication services (IEA-UNDP-UNIDO, 2010).

Energy is also critical in order to sustain economic growth. Economic growth has, in fact, historically been accompanied by an increasing energy demand. In the 20th century, industrialization and population growth led to a rapid increase in energy consumption and economic growth in OECD countries. This trend has been followed in recent years by various emerging economies (e.g. Brazil, Russia, India, China and South Africa –BRICS–) and it is likely that many other developing countries will follow suit. However, the need to meet a growing energy demand to sustain economic growth has resulted in serious negative impacts. The demand for fossil fuel resources and the resulting deterioration of natural resources have dramatically increased. In a planet with finite resources, this has ultimately led to major international conflicts over resources and unsustainable environmental practices, such as deforestation, soil and water contamination, loss of biodiversity, higher greenhouse gas emissions and climate change.

Nations therefore face the critical challenge of designing energy systems able to ensure an adequate energy supply and a sustainable development, while protecting the environment and avoiding conflicts with other nations. Thus, it has become apparent that long-term and strategic planning of energy resources, as well as energy supply and demand, is urgently required. Long-term and strategic planning offers multiple benefits: a) it enables a nation to prepare for the future in an orderly and systematic way, b) it provides a basis for building consensus on needs and for measuring progress and impact and c) it turns consensus and analytical work into systematic actions. While long-term and strategic planning is highly advantageous, it is also demanding. It involves many uncertainties in a rapidly changing external environment that demands significantly more time and resources than short-term planning (McKay, 2001).

But what exactly is strategic planning?

Generally speaking, strategic planning is the process of defining future goals for an organization (i.e. a vision) and determining the priorities and measures (i.e. strategies) to achieve that vision. In other words, strategic planning identifies what should be attempted and how to achieve it. While there is not a single, definitive and unambiguous approach for it, there are common key elements across studies:

- The span of strategic planning places emphasis on the long-term rather than on the short-term.
- Long-term goals are measureable and achievable, but also challenging.
- Strategic planning identifies opportunities and barriers to achieve long-term goals.
- Strategic planning assumes that strategies can influence certain aspects of the future and design them to exploit opportunities and overcome barriers.

In the particular context of energy, strategic planning relates to various processes (IEA, 2010; DOE-VEIC-ORNL, 2013), including:

a) Assessing the current and future energy demand and supply, policies and programs.
b) Defining a long-term energy vision, goals and strategies.
c) Identifying barriers and gaps in knowledge to achieve long-term goals.
d) Identifying specific actions (e.g. policies, funding, programs, projects, etc.) and priorities to achieve the long-term goals.
e) Developing a plan for implementing concrete actions, measuring progress and monitoring impacts.

Strategic planning can be applied to any energy technology, but for many reasons, which will now be discussed, it is particularly useful for renewable energy technologies. While benefits of renewable energies are apparent (e.g. enhancing energy security, mitigating climate change and contributing to sustainable economic development), various barriers hinder their deployment in many regions of the world. Barriers to deployment include: techno-economic barriers, regulatory and policy barriers, institutional barriers, market barriers, financial barriers, environmental barriers and public acceptance barriers. Strategic planning has recently been employed in different countries to envisage a challenging, but beneficial long-term future where these barriers are overcome and the deployment of renewable energy technologies is accelerated (IEA, 2015).

The use of strategic planning to define programs to exploit biomass resources and to deploy bioenergy technologies is not new. It has been applied in numerous examples in industrialized countries and emerging economies. Examples include: global technology roadmaps on biofuels for transport (IEA, 2011b) and bioenergy for heat and power (IEA, 2012c), European Union roadmaps on biomass technology (RHC, 2014), biofuels for transport (E4tech, 2013) and biogas (AEBIOM, 2009), United States roadmaps on bioenergy and biobased products (Biomass Technical Advisory Committee, 2007) and algal biofuels technology (DOE, 2010a), a roadmap for sustainable aviation biofuels for Brazil (Boeing-Embraer-FAPESP-UNICAMP, 2014), China roadmaps on biomass energy technologies (ERI-NDRC, 2010) and rural biomass energy (Zhang, Watanabe, Lin, DeLaquil, Gehua, & Howell Alipalo, 2010), and a roadmap for biorefineries in Germany (Bundesregierung, 2012).

## A.2. Motivation

While most R&D activities regarding biomass and bioenergy technologies have so far been carried out in industrialized countries and in few large economies, the largest growth in biomass to power and biofuel production is expected in developing countries (Eisentraut, 2010; IEA, 2011b; IEA, 2012c). Despite the vast potential, developing countries face several challenges to using biomass resources sustainably. Hurdles include limited industrial experience, constrained investment in R&D and absence of support policies. In order to ensure sustainable exploitation of biomass resources in the future, governmental and industrial efforts are required in developing countries and emerging economies in Africa, Asia and Latin America. These efforts include diffusing best agricultural practices, modernizing agriculture and bioenergy technology and promoting national and regional policies (IEA, 2009). Strategic planning might substantially contribute to putting these efforts into practice in a well-structured and systematic manner.

## A.3. Objective and research questions

The objective of this thesis is to develop methods for strategic planning of biomass and bioenergy technologies in developing countries. While Colombia is selected as a case study, the approach is intended to be applicable to other countries. Colombia is selected as a case study for various reasons. Firstly, Colombia is one of the seven countries in the world where more than half of the potentially available global arable land is concentrated (FAO, 2003). Secondly, Colombia has an obvious interest in biomass as it is the second largest renewable energy resource after large hydro (UPME, 2011b). Thirdly, Colombia is currently negotiating peace agreements with guerrilla groups after a 50-year armed conflict; in a post-conflict context, Colombia faces the challenge of reinventing rural regions and planning a long-term energy system capable of supporting ambitious reforms.

In this framework, the thesis focuses on providing answers to the following research questions in the particular context of developing countries:

Q1. How to estimate the current and future biomass energy potential at a country level?
Q2. How to create a strategic plan to deploy bioenergy technologies at a country level?
Q3. What are the impacts of deploying bioenergy technologies on the future energy supply and demand, greenhouse gas emissions and land use of a country?

The three questions are approached in sequence. The first question relates to the challenge of developing well-structured approaches to quantifying the magnitude and significance of biomass in the energy mix of a country and to design structured approaches to exploit it, particularly in developing countries. The first question is addressed in Chapter C and Chapter D of this thesis. The second question addresses the challenge of identifying long-term goals regarding sustainable bioenergy deployment as well as identifying barriers and defining strategies, plans, and action items to accomplish the proposed goals. Assessing the future biomass energy potential is important in order to understand the strategic importance of biomass and to design sound policies that ensure sustainable operation and environmental benefits. The second question is addressed in Chapter E and Chapter F. Finally, the third question relates to the challenge of quantifying the impacts of deploying bioenergy technologies and of using findings to enable sound policy-making. The third question is analyzed in Chapter G.

## A.4. Challenges

Applying strategic planning for exploiting biomass resources and deploying bioenergy technologies in developing countries involve various challenges that can be divided into four main categories.

Category I: the unpredictability of future events challenges the heuristic process of defining long-term energy visions, goals, strategies and plans. Challenges do not only relate to the definition of a long-term vision for bioenergy deployment (see Chapter E), but also to the uncertainties associated with the unknown unfolding future path of technologies, energy resources, politics, markets, economics and macroeconomics, geopolitics, etc. (see Chapter D, Chapter E and Chapter F).

Category II: strategic planning partly involves the development of analytical and modeling tools with multiple types of associated uncertainties. In general, there are five levels of uncertainties linked to mathematical models (Spiegelhalter & Riesch, 2011): 1) uncertainty regarding the unavoidable unpredictability of future events, 2) uncertainty regarding the limited information of model parameters, 3) uncertainty regarding which model is best (limited knowledge about the model structure), 4) uncertainties regarding known limitations of the mathematical model due to gaps in knowledge, computational limitations or methodological disagreements and 5) uncertainty regarding unknown limitations of the mathematical model (i.e. ignorance). This type of challenge applies to all modeling tools presented in Chapter C, Chapter D, Chapter E and Chapter F.

Category III: biomass and bioenergy involve various complexities that add new levels of uncertainty. Recent studies conclude that: 1) not all uncertainties associated with bioenergy may be completely resolved using probabilistic methods, 2) some types of uncertainties cannot be tested empirically (e.g. indirect land use change), 3) many issues are addressed diversely by different stakeholders resulting in indeterminacy and ignorance and 4) the scale of uncertainty and ignorance with respect to many energy crops is very large (Upham, Riesch, Tomei, & Thornley, 2011; McDowall, Anandarajah, Dods, & Tomei, 2012). This type of challenge also applies to all modeling tools presented in Chapter C, Chapter D, Chapter E and Chapter F.

Category IV: there are additional complexities associated with developing countries. Firstly, the availability and quality of data and analyses are limited. Secondly, the characteristics of energy systems in developing countries are significantly different from industrialized countries, where strategic planning is a common practice. In industrialized countries, the energy system is characterized by a constant match of supply and demand, universal access to modern energy services, small regional differences, effective financing and adequate subsidies (Urban, Benders, & Moll, 2007). In contrast, in developing countries, energy is characterized by demand far in excess of energy supply, remote areas yet to be connected to the grid, continued over-dependence on conventional sources of energy, informal economies, large structural differences between urban and rural regions, modest contribution of renewable energy and shortage of resources for R&D as well as for building additional capacity and infrastructure (Urban, Benders, & Moll, 2007). This type of challenge has been an important factor to consider when developing various modeling tools presented in this thesis (e.g. Chapter D, Chapter E and Chapter F), which need to account for the limited availability and quality of data and to be inexpensive, and easily implemented and reproduced.

## A.5. Criteria to design methods

Recommendations from prior art are used as guidelines to define a set of criteria to design research methods that address the challenges described above.

Regarding modeling energy systems and their linkages with the economy and the environment, various recent studies recommend best practices to design research methods. For example, (DeCarolis, Hunter, & Sreepathi, 2012) recommend six best practices for energy economy optimization (EEO): 1) make source code publicly available, 2) make model data publicly available, 3) make transparency a design goal, 4) utilize free software tools, 5) develop test systems for verification exercises and 6) work toward interoperability among models. (Pfenninger, Hawkes, & Keirstead, 2014) recommend energy modelers to improve the understanding of uncertainty and to design methods and analyses that are more transparent and reproducible. Similarly, (AfDB-OECD-UN-World Bank, 2013) propose a toolkit to design inclusive green growth strategies, which recommend the following good practices: 1) be flexible, transparent and adaptable to context, 2) provide explicit justification for preferred options, 3) establish clear goals, 4) analyze potential effects, risks and alternatives against a framework of sustainability criteria, 5) involve key stakeholders and encourage public involvement.

With regard to addressing uncertainty, Roos & Rakos (2000) recommend a balance between simplicity and realism and avoidance of overly complex models that tend to lose credibility. In addition, Spiegelhalter & Riesch (2011) suggest firstly selecting a model structure, boundaries and assumptions based on a pragmatic compromise between the credibility of results and the effort to create and analyze the model. Secondly, they suggest acknowledging all known and unknown limitations of the selected approach.

Regarding biomass and bioenergy, (Batidzirai, Smeets, & Faaij, 2012) recommend various key elements that an ideal approach to estimate biomass energy potential should have. For the current potential, these key elements include: bottom-up techniques for assessing biomass production volumes, crop yields and reduction factors to avoid socio-economic and environmental impacts. For the future potential, these key elements include: demographic data, market data, land use, macro-economic effects and environmental impacts.

Regarding the additional complexities found in developing countries, (Urban, Benders, & Moll, 2007) discuss how research methods need to ensure an adequate representation of these complexities. While today various energy tools exist for analyzing the energy sector in developing countries, many of these models tend to be biased towards industrialized countries (Urban, Benders, & Moll, 2007). According to Urban et al., as much top-down as bottom-up approaches found in literature offer a sub-optimal characterization of energy systems in developing countries (Urban, Benders, & Moll, 2007). They suggest to develop new simulation or toolbox models featuring a better description of the power sector, access to modern energy services, investment decisions and subsidies, preferably following a bottom-up or hybrid approach (Urban, Benders, & Moll, 2007).

To be consistent with these guidelines, the following criteria to develop methods for strategic planning of bioenergy in developing countries are proposed:

1. Methods should be transparent, easy to implement, generic and replicable.
2. Methods should be inexpensive to adapt to constrained R&D budgets.
3. Methods should be built in well-known and generic platforms in order to increase the level of accessibility.
4. Methods should follow robust and state-of-the-art approaches (preferably bottom-up) in order to address the research questions formulated in Section A.3.

These criteria are followed throughout the thesis for designing or adapting methods for strategic planning of biomass and bioenergy technologies in the particular context of developing countries.

## A.6. Research approach

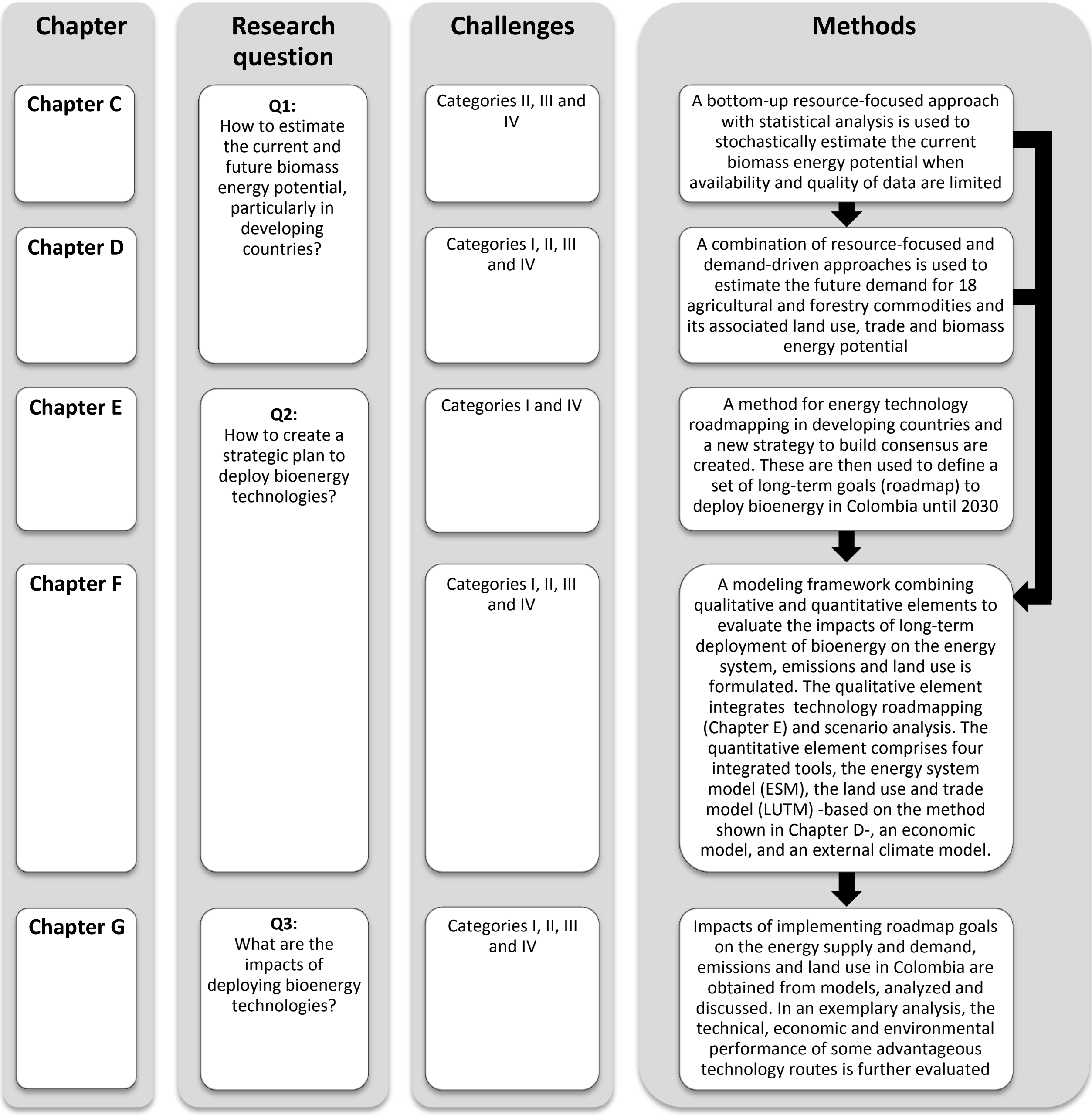
A research approach aimed at providing answers to the research questions defined above is proposed (see Figure 1). The approach also aims at fulfilling the design criteria defined in previous sections. The approach followed is to start from the general and move to the specific. After a general formulation of methods, an exemplary case study of Colombia is presented.

### A.6.1. Addressing research question Q1

Research question Q1 is addressed in Chapter C and Chapter D, respectively. Chapter C addresses the problem of estimating the current biomass energy potential and its associated uncertainty at a country level when availability and quality of data are limited. The problem involves the challenges of categories II, III and IV. The proposed method combines four steps to address Q1: 1) use a simple bottom-up, resource-focused accounting framework, 2) use a robust selection of probability density functions, 3) use a Monte Carlo simulation and a probabilistic propagation of uncertainty and 4) use sensitivity analysis to identify key variables contributing to uncertainty as well as a root cause analysis and a set of sub-models to improve estimation of key variables. The proposed method is built in well-known platforms, i.e. Microsoft Excel and Crystal Ball.

The novelty of this method is explained as follows. Step 1 is common practice in the bioenergy field. Step 2 has been proposed before, though not for bioenergy. Step 3 (uncertainty estimation) has been performed before, but it is not a common practice in biomass energy potential assessments. Instead, Step 4 and the combination of Steps 1-4 is novel in the context of bioenergy. The method is subsequently applied to the study case of Colombia. The method and its application are used as inputs in further chapters of the thesis. Examples include Chapter D, to estimate the future biomass energy potential associated with various commodities and Chapter F, to define the amount of biomass resources that can be targeted for long-term strategic exploitation.

Chapter D addresses the problem of estimating the future biomass energy potential and the land use change for countries with domestic markets unable to influence international markets. The problem involves challenges of all categories. The proposed method follows these steps to address Q1: 1) use a non-spatially explicit analysis which is simple and generic to facilitate replication, 2) use a well-known platform (e.g. Microsoft Excel) to perform calculations, which is relatively inexpensive and broadly accessible, 3) perform a sensitivity analysis to identify key parameters contributing to results, 4) employ a scenario analysis to address the unpredictability of future events and 5) acknowledge the limitations of the model structure. The novelty of the method is explained as follows. Firstly, an improvement over other bottom-up, resourced-focused approaches found in prior art is proposed.



| Chapter | Research question | Challenges | Methods |
|---|---|---|---|
| Chapter C | **Q1:** How to estimate the current and future biomass energy potential, particularly in developing countries? | Categories II, III and IV | A bottom-up resource-focused approach with statistical analysis is used to stochastically estimate the current biomass energy potential when availability and quality of data are limited |
| Chapter D | | Categories I, II, III and IV | A combination of resource-focused and demand-driven approaches is used to estimate the future demand for 18 agricultural and forestry commodities and its associated land use, trade and biomass energy potential |
| Chapter E | **Q2:** How to create a strategic plan to deploy bioenergy technologies? | Categories I and IV | A method for energy technology roadmapping in developing countries and a new strategy to build consensus are created. These are then used to define a set of long-term goals (roadmap) to deploy bioenergy in Colombia until 2030 |
| Chapter F | | Categories I, II, III and IV | A modeling framework combining qualitative and quantitative elements to evaluate the impacts of long-term deployment of bioenergy on the energy system, emissions and land use is formulated. The qualitative element integrates technology roadmapping (Chapter E) and scenario analysis. The quantitative element comprises four integrated tools, the energy system model (ESM), the land use and trade model (LUTM) -based on the method shown in Chapter D-, an economic model, and an external climate model. |
| Chapter G | **Q3:** What are the impacts of deploying bioenergy technologies? | Categories I, II, III and IV | Impacts of implementing roadmap goals on the energy supply and demand, emissions and land use in Colombia are obtained from models, analyzed and discussed. In an exemplary analysis, the technical, economic and environmental performance of some advantageous technology routes is further evaluated |

***Figure 1.*** *Research approach describing research question, challenges and methods by chapter*

This improvement relates to the inclusion of the impact of global biofuel use on agricultural prices, production and demand. Secondly, rather than evaluating the cost of supplying biomass for energy purposes, an evaluation of the cost competitiveness of biomass for different uses (food, wood, biofuels, others) through the use of a land use and trade model is proposed. The method is applied to the same study case of Colombia. This method is used in subsequent sections of this thesis. In particular, the method is employed with minor modifications in Chapter F to estimate the trade and land use requirements to accomplish the long-term goals to deploy bioenergy technologies at a country level.

### A.6.2. Addressing research question Q2

Research question Q2 is addressed in Chapter E and Chapter F. Chapter E addresses the problem of developing a technology roadmap for bioenergy exploitation in developing countries. This problem involves challenges of categories I and IV. The proposed method consists of three components to address question Q2: 1) a simplified version of the guide to develop and implement energy technology roadmaps by the International Energy Agency (IEA, 2010), 2) a new strategy to build consensus and 3) a strong focus on analytical modeling for supporting expert judgment.

The novelty of the proposed method is explained as follows. While the IEA's guide is a very detailed and robust method that can be applied to any country, its structure is best adapted to OECD countries. For developing countries, it can be challenging to implement the full method, which requires various detailed and lengthy processes and involve multiple working groups. Another improvement over prior art is the use of a new strategy to build consensus based on the Delphi method via two surveys and a workshop. In this strategy, the opinion of individual experts about long-term technology strategies is influenced by the opinion of the group of experts, which facilitates reaching consensus. The proposed method is applied to Colombia for creating a plan to deploy sustainable bioenergy technologies until 2030. This plan consists of a set of long-term goals, milestones, barriers and action items identified by over 30 experts for different bioenergy technology areas. The method and its application to Colombia are further used as inputs in Chapter F.

Chapter F addresses the problem of formulating a modeling framework to investigate the impacts of implementing a technology roadmap for bioenergy exploitation in developing countries. This problem involves challenges of all categories. A modeling framework to evaluate the impacts that long-term deployment of bioenergy technologies might cause on the energy supply and demand, emissions and land use at a country level is proposed. This method combines a quantitative and a qualitative element to address Q3. The qualitative element integrates two components: 1) technology roadmapping to identify long-term technology targets through expert judgment (Chapter E) and 2) scenario analysis to investigate different future storylines. The quantitative element comprises four integrated tools, namely the energy system model (ESM), the land use and trade model (LUTM), an economic model, and an external climate model.

The novelty of the method is explained as follows. Firstly, the proposed framework combines qualitative and quantitative methods to investigate long-term deployment of bioenergy and its associated impacts, whereas prior art concentrate in one or the other. Secondly, the proposed framework offers a comprehensive approach to investigate the energy sector and a relatively simple approach to investigate the economy, land use and climate linkages. This allows the possibility to provide preliminary assessments. In contrast, most prior art is characterized by having complex frameworks that do not allow preliminary estimations (Ferroukhi, et al., 2015). The proposed framework fulfills the design criteria by: 1) using various state-of-the-art modeling techniques that are robust and acknowledged in the scientific community, 2) using well-known platforms (i.e. LEAP and Microsoft Excel), which are relatively inexpensive and easy to replicate, 3) employing scenario analysis to consider possible alternative future storylines and to allow policy analysis and 4) being calibrated and fully supported by official data. This modeling method is applied to the study case of Colombia, whose boundary conditions and assumptions are described in detail. Outputs of this application are discussed and analyzed in Chapter G.

### A.6.3. Addressing research question Q3

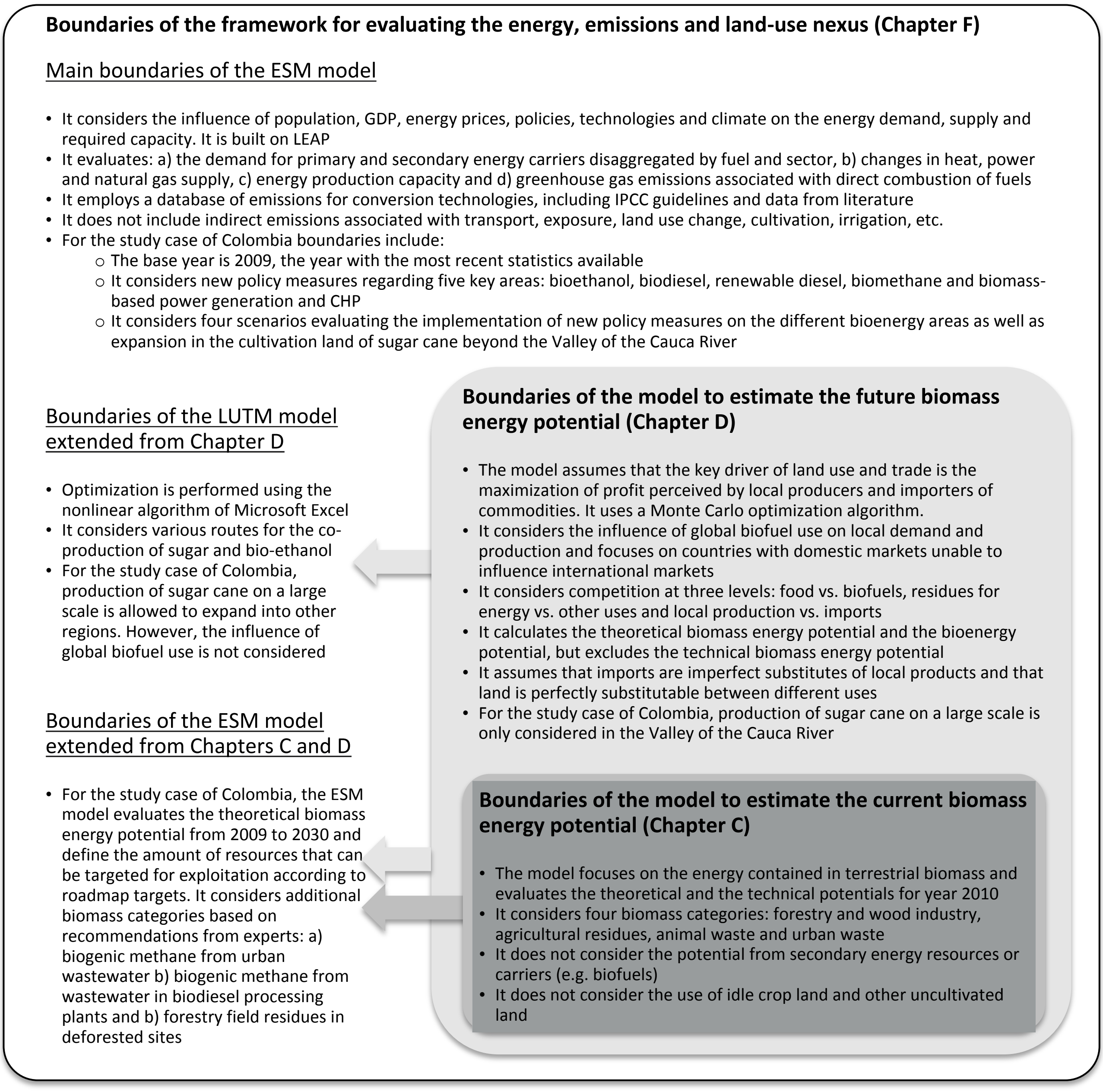
Research question Q3 is addressed in Chapter G. Chapter G describes the outcomes of applying the proposed modeling framework shown in Chapter F to the study case of Colombia. Assessed impacts include: 1) the variation in demand for primary and secondary energy carriers (e.g. oil, coal, biomass, etc.) by sector (residential, transport, industrial, etc.), 2) changes in heat, power and natural gas supply, 3) energy production capacity, 4) land use required to accomplish long-term goals and 5) greenhouse gas emission reduction caused by different technology routes and policy measures. The novelty of this analysis is explained as follows. Impacts of deploying some bioenergy technologies on the energy system and emissions in Colombia have been estimated in prior art. In contrast, the present study evaluates in an integrated manner the impacts of deploying multiple bioenergy technologies not only on the energy system and emissions, but also on the land use and with clear links to the economy and the climate. While prior art focused either on 1st gen biofuels or bagasse CHP, the present study covers these technologies and analyzes further the deployment of biomethane, renewable diesel, biomass co-firing, biogas- and landfill gas-fired power generation. The results and discussion presented can be helpful to policymakers and scientists evaluating the role of bioenergy in a post-conflict context and to other countries with significant bioenergy potential.

## A.7. Boundary conditions

Boundary conditions of models to estimate the current and future biomass energy potential as well as the LUTM and ESM models are nested, as illustrated in Figure 2. The boundary conditions of the model to estimate the future biomass energy potential (Chapter D) contain the boundary conditions of the model to estimate the current biomass energy potential (Chapter C). Likewise, the boundary conditions of these two models are contained within the boundary conditions of the ESM and LUTM models (Chapter F) and further extended, as explained below.

The model to estimate the current biomass energy potential focuses on the energy contained in terrestrial biomass and evaluates the theoretical and the technical potentials. It considers four biomass categories: forestry and wood industry, agricultural residues, animal waste and urban waste. However, it does not consider the potential from secondary energy resources or carriers (e.g. biofuels) as well as the use of idle crop land and other uncultivated land. The model to estimate the future biomass energy potential assumes that the key driver of land use and trade is the maximization of profit perceived by local producers and importers of commodities. The model focuses on countries with domestic markets unable to influence international markets. The model assumes that imports are imperfect substitutes of local products and that land is perfectly substitutable between different uses. Additionally, the model calculates the theoretical biomass energy potential and the bioenergy potential associated with biofuels, but excludes the technical biomass energy potential. Its boundary conditions thus contain the boundary conditions of the model to estimate the current biomass energy potential described above. When applied to Colombia, it only considers production on a large scale of sugar cane in the Valley of the Cauca River.

The land use and trade model (LUTM) contains and extends the boundary conditions of the model to estimate the future biomass energy potential. In addition to the characteristics described for the latter, the LUTM model offers extended features. It considers various routes for the co-production of sugar and bio-ethanol, which were previously not available. It performs the optimization using the nonlinear algorithm of a generic platform, i.e. Microsoft Excel, which was previously performed in Crystal Ball.



**Boundaries of the framework for evaluating the energy, emissions and land-use nexus (Chapter F)**

Main boundaries of the ESM model

- It considers the influence of population, GDP, energy prices, policies, technologies and climate on the energy demand, supply and required capacity. It is built on LEAP
- It evaluates: a) the demand for primary and secondary energy carriers disaggregated by fuel and sector, b) changes in heat, power and natural gas supply, c) energy production capacity and d) greenhouse gas emissions associated with direct combustion of fuels
- It employs a database of emissions for conversion technologies, including IPCC guidelines and data from literature
- It does not include indirect emissions associated with transport, exposure, land use change, cultivation, irrigation, etc.
- For the study case of Colombia boundaries include:
    - The base year is 2009, the year with the most recent statistics available
    - It considers new policy measures regarding five key areas: bioethanol, biodiesel, renewable diesel, biomethane and biomass-based power generation and CHP
    - It considers four scenarios evaluating the implementation of new policy measures on the different bioenergy areas as well as expansion in the cultivation land of sugar cane beyond the Valley of the Cauca River

Boundaries of the LUTM model extended from Chapter D

- Optimization is performed using the nonlinear algorithm of Microsoft Excel
- It considers various routes for the co-production of sugar and bio-ethanol
- For the study case of Colombia, production of sugar cane on a large scale is allowed to expand into other regions. However, the influence of global biofuel use is not considered

Boundaries of the ESM model extended from Chapters C and D

- For the study case of Colombia, the ESM model evaluates the theoretical biomass energy potential from 2009 to 2030 and define the amount of resources that can be targeted for exploitation according to roadmap targets. It considers additional biomass categories based on recommendations from experts: a) biogenic methane from urban wastewater b) biogenic methane from wastewater in biodiesel processing plants and b) forestry field residues in deforested sites

**Boundaries of the model to estimate the future biomass energy potential (Chapter D)**

- The model assumes that the key driver of land use and trade is the maximization of profit perceived by local producers and importers of commodities. It uses a Monte Carlo optimization algorithm.
- It considers the influence of global biofuel use on local demand and production and focuses on countries with domestic markets unable to influence international markets
- It considers competition at three levels: food vs. biofuels, residues for energy vs. other uses and local production vs. imports
- It calculates the theoretical biomass energy potential and the bioenergy potential, but excludes the technical biomass energy potential
- It assumes that imports are imperfect substitutes of local products and that land is perfectly substitutable between different uses
- For the study case of Colombia, production of sugar cane on a large scale is only considered in the Valley of the Cauca River

**Boundaries of the model to estimate the current biomass energy potential (Chapter C)**

- The model focuses on the energy contained in terrestrial biomass and evaluates the theoretical and the technical potentials for year 2010
- It considers four biomass categories: forestry and wood industry, agricultural residues, animal waste and urban waste
- It does not consider the potential from secondary energy resources or carriers (e.g. biofuels)
- It does not consider the use of idle crop land and other uncultivated land

***Figure 2.*** *Boundary conditions of the different models*

For the particular case of Colombia, it allows the large-scale cultivation of sugar cane beyond the Valley of the Cauca River, although it does not consider the influence of global biofuel use.

The energy system model (ESM) focuses on simulating the demand and the transformation sides of the energy system. The ESM model is able to evaluate: a) the demand for primary and secondary energy carriers disaggregated by sector, b) changes in heat, power and natural gas supply, c) energy production capacity and d) greenhouse gas emissions associated with direct combustion of fuels. It employs a database of emissions for conversion technologies, including Intergovernmental Panel on Climate Change (IPCC) guidelines and data from literature, but it does not include indirect emissions associated with transport, exposure, land use change, cultivation, irrigation, etc. When applied to Colombia, the ESM model considers new policy measures on five key areas (bioethanol, biodiesel, renewable diesel, biomethane and biomass-based power generation and CHP) and four scenarios evaluating different implementation of these policies. The base year is 2009, which is the year with the most recent statistics available, and the end year is 2030. The ESM model evaluates the theoretical biomass energy potential from 2009 to 2030 using the methods described in Chapter C and Chapter D and defines the amount of resources that can be targeted for exploitation according to the roadmap targets. In this framework, the boundary conditions of the ESM model contain and extend the boundary conditions of the models presented in Chapter C and Chapter D. Extensions are based on recommendations from roadmap experts and relate to the inclusion of new biomass resources not investigated in Chapter C. These resources include: a) biogenic methane from urban wastewater b) biogenic methane from wastewater in biodiesel processing plants and c) forestry field residues in deforested sites.

## A.8. Limitations

There are various aspects of bioenergy that are considered beyond the scope of study. Firstly, a comprehensive analysis of the environmental implications of deploying bioenergy technologies has not been covered and is considered beyond the scope of this thesis. Themes not covered include: soil quality, water use and efficiency, water quality, biodiversity, emissions of non-GHG pollutants, and lifecycle GHG emissions. While the emission of GHG pollutants by combusting fuels has been analyzed in Chapter F and Chapter G, the GHG emissions associated with fuel transport, exposure, dose/response effects, land-use change, cultivation, irrigation, etc. are not considered. Thus, emissions presented in this thesis cannot be considered lifetime emissions. Additionally, while an exploratory sustainability scheme is proposed for Colombia in Section E.4.5.1, a dedicated effort to select and define a thorough sustainability scheme and a set of bioenergy sustainability criteria is beyond the scope of this study.

Secondly, a dedicated investigation of the social impacts of deploying bioenergy is not considered within the scope of this study. Themes not explored include: impacts on rural development, living standards of rural communities, generation of employment, water demand and supply, expansion of access to modern energy services, expansion of access to health services, food vs. biofuels, change in income, deforestation, etc. Thirdly, effects of climate and climate change on the demand and supply of biomass, as well as on the deployment of bioenergy technologies have also been considered beyond the scope of this thesis. In particular, the effects of climate and climate change on the future demand, price and supply of commodities and on the operation of bioenergy technologies have not been analyzed. While the impact of El Niño–Southern Oscillation (ENSO) on the energy demand, supply and required capacity has been investigated in Chapter F and Chapter G, the models rely on historical data recorded for the last 15 years. Predictive models able to stochastically estimate how the production of biomass and the operation of bioenergy technologies might change under different ENSO scenarios have not been considered.

## A.9. Thesis structure

This thesis is divided into seven chapters, which address the three research questions. Firstly, a brief description of the current status of bioenergy in Colombia is presented in Chapter B. The method to estimate the current biomass energy potential at a country level is shown in Chapter C, while the method to estimate the future potential is shown in Chapter D. Chapter E presents a method for energy technology roadmapping adapted to the conditions of developing countries. It also presents a technology roadmap to deploy sustainable bioenergy technologies in Colombia until 2030, which follows the proposed method. Chapter F presents a modeling framework to evaluate the impacts of implementing a technology roadmap for bioenergy exploitation on the energy system, emissions and land use at a country level. It also presents the application of this method to the case study of Colombia. Chapter G presents the results from applying this modeling framework to Colombia, i.e. the impacts of implementing roadmap targets on energy supply and demand, emissions and land use. Finally, conclusions, recommendations and ideas for future work are addressed in Chapter H.

# Chapter B. Current status of bioenergy in Colombia

## B.1. Global status

Among the different renewable energy resources, one of particular interest, as much to industrialized countries as to emerging and developing countries, is biomass. Biomass is today the largest renewable resource, accounting for roughly 10% (50 EJ) of world total primary energy supply today (IEA, 2012c). Global interest regarding the sustainable use of biomass and its potential to reduce dependency on fossil fuels and decrease greenhouse gas emissions continues to grow (IEA, 2012c).

Biomass is primarily used in developing countries as an energy source for cooking and heating, using inefficient open fires or cookstoves with negative impacts on health and environment. To a lesser extent, biomass is employed in industrialized countries to supply heat, combined heat and power (CHP) and biofuels. In the buildings sector, modern bioenergy for providing heat accounted for 5 EJ in 2012 (IEA, 2012c). Bioenergy contributed to 8 EJ to provide low- and medium- temperature process heat in the industry (viz. pulp and paper and food processing) (IEA, 2012c). In power generation, bioenergy contributed to 370 TWh in 2012, which corresponds to 1.5% of world energy generation (IEA, 2012c). Regarding biofuels, global production has been growing from 16 billion liters in 2000 to 110 billion liters in 2013. Biofuels contribute today to a 3.5% of the global road transport fuel (Eisentraut, 2010; IEA, 2011b). Demand for biomass is expected to increase in the future, as populations grow and cost-effective technologies become available. Hence, various countries promote policy mechanisms for a sustainable use of biomass (Eisentraut, 2010; IEA, 2011b; IEA, 2012c). However, economic incentives are currently needed in many cases to compensate the cost differences between bioenergy and fossil fuels (IEA, 2012c). Moreover, a variety of different environmental, social and economic issues need to be addressed to justify this compensation and to ensure that the overall impact of bioenergy is positive compared to fossil fuels.

## B.2. Status in Colombia

In the last 30 years, Colombia has shifted from an agricultural economy to one based on minerals and energy resources. This shift has allowed the country to grow in the last decade from 4 to 5% annually, doubling public expenditure and increasing per capita income by 60% and foreign investment five-fold (Gaviria, 2010; Gaviria, 2012). However, widespread corruption, ineffective policies and weak institutions have hindered better wealth distribution. In addition to this, a 50-year armed conflict has resulted in one million casualties, six million civilians internally displaced and thousands of hectares of usurped land (RNI, 2014).

These socioeconomic and political transformations have also brought serious consequences to the energy sector and the environment. Primary and secondary energy demand doubled between 1975 and 2009 (UPME, 2011b), which required the energy conversion capacity to grow rapidly. New coal- and gas-fired power plants were built to reduce the over-dependence on hydro power, which has proven vulnerable to droughts caused by El Niño oscillation. In the transport sector, vehicle ownership grew exponentially while road infrastructure collapsed, deteriorating mobility in large cities. More people demanding more energy resulted in more pollution. GHG emissions increased 2.5 times between 1975 and 2009 (UPME, 2011b), while the percentage of the fresh water supply that is not drinkable has increased to 50% in recent years (UN Periódico, 2014). Deforestation ate up 6.2 million hectares of tropical forest between 1990 and 2010 (an area as large as Norway), which has mostly been replaced by extensive cattle farms (El Tiempo, 2013).

Yet, despite a turbulent and difficult past, Colombia is looking forward to the future. There is hope that peace talks with the main guerrilla groups and ambitious post-conflict reforms might turn around the history of violence and build foundations for a more equitable and prosperous country.

In this context, it is critical to address the challenge of planning a long-term energy system able to ensure: a) energy security, b) clean energy supply to the whole population, c) food and water security and d) enhancement of rural development. Various technological paths have been envisioned to supply energy while reducing GHG emissions: renewables, energy efficiency, fuel switching, distributed power generation & CHP, carbon capture and storage, nuclear, etc. (IEA, 2014a). While individual measures offer separate benefits, a portfolio of measures is needed at a national level to achieve significant GHG emissions reduction and to fulfill other requirements such as enhancing energy and water security.

### B.2.1. Biomass for energy purposes

The current use of biomass for energy purposes in Colombia can be divided into four main categories. Firstly, and most predominantly, it is used in the form of wood and charcoal as a traditional fuel for cooking and water heating (see national energy balances (UPME, 2011b)). Secondly, it is used in the form of cane bagasse and palm oil residues as a fuel in boilers and cogeneration power plants to provide heat and power. Thirdly, it is used after conversion in the form of bioethanol and biodiesel as road transport biofuels. Other forms of using biomass for energy purposes have been explored to a much lesser extent as demonstration or pilot projects with varying degrees of success. These forms include among others: a) use of landfill gas and biogas for in situ heat or power production, b) biomass gasification and combustion in reciprocating engines and c) methane collection from wastewater treatment plants for heating.

Biomass plays an important role in the energy mix of the country as today it is the second largest renewable energy resource after hydroelectricity. In 2009, biomass contributed 67% of renewably generated electricity excluding large hydro (69 kTOE), 4.6% of the energy supply in road transport (337 kTOE) and 10% of the overall primary energy demand (3.77 mio TOE) (UPME, 2011b). The historical demand for biomass in the form of wood, cane bagasse[1] and biomass residues[2] has remained relatively constant since 1975, ranging between 3.72 and 4.47 mio TOE (see Figure 3[3]). However, its contribution to the primary energy supply has significantly reduced from about 26% in 1975 to 10% in 2009. In contrast, the contribution of natural gas has grown from 10% to 22% in the same period. The reduced contribution of biomass relative to other fuels is the consequence of a combination of factors including increasing urbanization, greater access to electricity and natural gas services nationwide and an increased deployment of fossil fuel-based thermal power plants.

Colombia is also characterized by a vast biomass energy potential that remains untapped. Various studies have recently estimated theoretical biomass energy potential, ranging between 5 and 18 mio TOE, depending on the assumptions (see Chapter C and (Gonzalez-Salazar, et al., 2014a)). From this potential, a fraction ranging between 1 and 10 mio TOE might be technically available at current conditions and constraints for energy exploitation.

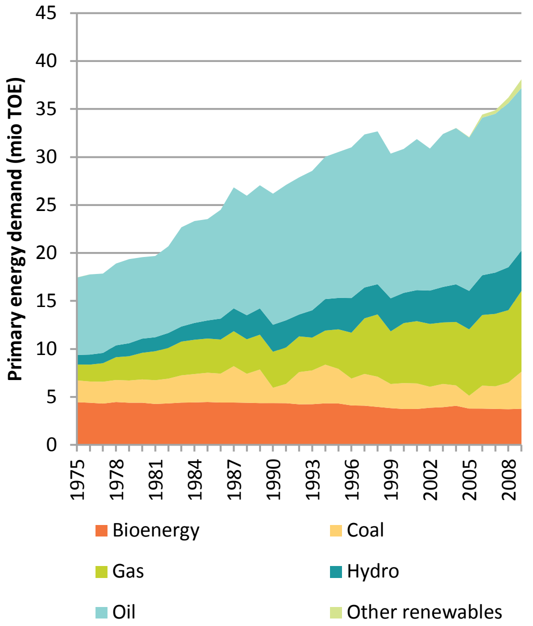


***Figure 3.*** *Primary energy demand and contribution*

### B.2.2. Regulations

The Ministry of Mines and Energy (MME) leads and coordinates policy making and regulations in the energy sector in Colombia and is supported by various governmental agencies such as the Mining and Energy Planning Unit (UPME), the Electricity and Gas Regulation Commission (CREG), the Institute of Planning and Promoting of Energy Solutions in Non-Interconnected Zones (IPSE). While UPME and IPSE are in charge of capacity planning and support of policy making, CREG regulates power and gas tariffs. Recognizing the importance of biomass, the MME and its affiliated agencies have adopted several policies and programs in the last decade aimed at encouraging the deployment of bioenergy technologies. Examples include obligatory blends for bioethanol and biodiesel (Laws 788 from 2002 and 939 from 2004 and Decree 4892 from 2011), policy guidelines for the promotion of biofuel production (Conpes 3510 from 2008) and programs on the promotion of the efficient and rational use of energy and alternative energies (Law 697 from 2001, Resolution 180919 from 2010, Law 1715 from 2014). This support to bioenergy has been driven by the government's rationale to generate rural employment, enhance rural development, diversify the energy portfolio, reduce carbon emissions in the transport sector and decrease dependence on oil (DNP, 2008).

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[1] Includes bagasse from sugarcane but excludes bagasse from jaggery cane

[2] Palm oil residues

[3] Data taken from (UPME, 2011a) and further adapted. Imports of oil-based secondary fuels are converted into primary energy.

### B.2.3. Wood

Similarly to other developing countries, wood and charcoal have traditionally been used in Colombia for cooking and water heating. In 2009 the demand for wood amounted to 2.48 mio TOE, of which 56.2% was used in the rural residential sector, 5.5% in the urban residential sector, 24.5% for the production of charcoal and the remaining 13.8% in the agricultural and industrial sectors (UPME, 2011b). Colombia's forest coverage is large (~ 69 mio ha), spanning more than 60% of the country's land surface (IDEAM, 2010). In 2009, 13.6 mio $m^3$ of roundwood were produced, mostly extracted from primary forests and to a lesser extent from plantations (FAO, 2012b). However, according to IDEAM's estimations, about two fifths of logging is illegal, which indicates that wood is not only extracted from permitted areas but also from protected forests and national parks (IDEAM, 2010). Using wood for cooking in traditional stoves is a very inefficient and unhealthy process. UPME estimates an average energy efficiency of 10% by using wood for cooking in urban residences and as low as 2.5% in rural residences, although there are acknowledged uncertainties in this estimation (UPME, 2011b; UPME, 2011c; UPME, 2011d). In addition, the use of woodfuel for cooking generates various health-damaging pollutants due to incomplete combustion, including methane, black carbon and other short-lived climate forcers (Bailis, Drigo, Ghilardi, & Masera, 2015). On the other hand, charcoal is produced by slow pyrolysis by heating wood in ovens in the absence of oxygen. Typical energy efficiencies of the charcoal conversion process are about 72% as described by UPME (UPME, 2011b; UPME, 2011c; UPME, 2011d). Illegal production of charcoal exists, but its dimension is unknown. It is a serious cause of deforestation, which has reportedly destroyed natural forests in various regions (IDEAM, 2010).

### B.2.4. Sugar cane and bioethanol

Driven by energy security concerns and the ambition to reduce emissions in the transport sector, in 2004 Colombia implemented a bioethanol blending mandate (Decree 4892, Laws 788 and 939). This mandate defines a blending of 10% bioethanol by volume (E10) that must be used in road transport gasoline fuel. The mandate is accompanied by tax incentives for selling bioethanol and importing process machinery. Biofuel blends, tax incentives, quality standards and biofuel prices are regulated by the government through the Ministry of Mines and Energy. Production of bioethanol reached 334 mio liters in 2009 (167 kTOE), which contributed 2.3% of the overall energy demand in road transport (UPME, 2011b). Demand for ethanol requires an installed production capacity of close to 2 mio liters per day. Bioethanol is currently produced using sugar cane as feedstock. In contrast to other countries, in Colombia the climatic and soil conditions allow the cultivation of sugar cane throughout the entire year and not in sessional harvests (e.g. zafra). Sugar cane is cultivated on a large scale only in the Valley of the Cauca River on the western side of the country, where yields as high as 120 tons/ha are commonly obtained. In 2009 sugar cane cultivation in this region amounted to 217 kha, of which 38% was exclusively allocated to sugar production and 62% to the co-production of sugar and bioethanol (BID-MME, Consorcio CUE, 2012).

Two thirds of the cane fields are manually harvested while only one third is mechanically harvested. For this reason, about 70% of the cane fields are burned before harvesting to facilitate the collection of stalks. After harvesting, the remaining burned residues (leaves, tops, etc.) are left on the field for soil replenishment, while the stalks are transported to the mill. In the sugar cane mill, cane is crushed and cane juice, bagasse, tops and leaves are extracted. The juice is used to produce sugar and ethanol, and the bagasse is partly used to produce steam in boilers and CHP plants and partly used as raw material in paper mills. The cane mill is mechanically driven by steam turbines fed with steam produced in bagasse-fuelled boilers. The cane juice is purified, filtrated and evaporated to produce molasses. This is followed by a crystallization and centrifugation process, in which sugar crystals are formed and separated from molasses. Molasses are then converted into bioethanol in a continuous process via microbial fermentation, distillation and dehydration. This is a mature, commercially available process that yields 0.093 tons of sugar and 0.019 tons of bioethanol per ton of sugar cane (without leaves) (BID-MME, Consorcio CUE, 2012). By-products of the ethanol production process include wastewater, vinasse and $CO_2$. While wastewater is treated via surface-aerated basins (lagoons) before release, $CO_2$ is vented into the atmosphere. Vinasse, on the other hand, is collected and concentrated by removing water, yeast and organic matter. Concentrated vinasse is then used for compost, while water, yeast and organic matter are recirculated into the fermentation reactor (BID-MME, Consorcio CUE, 2012). This process offers a significantly lower vinasse production (0.8-3 l-vinasse/l-ethanol) than the ferti-irrigation approach used in Brazil (8-12 l-vinasse/l-ethanol).

### B.2.5. Palm oil and biodiesel

Biodiesel was introduced in Colombia in 2008 through a blending mandate of 5% by volume (B5) in road transport diesel, which subsequently increased by 2013 to levels ranging from 8 to 10%, depending on the region. Blending proportions of biodiesel, tax incentives, quality standards and prices are regulated by the Ministry of Mines and Energy in a similar fashion to those regarding bioethanol. The production of biodiesel reached 276 mio liters in 2009 (208 kTOE), of which 223 mio liters (168 kTOE) were used in road transport and contributed to supplying 2.3% of the energy demand in that sector (UPME, 2011b). An installed production capacity of 1.8 mio liters per day is currently required to supply the growing biodiesel demand. Biodiesel is currently produced using palm oil as feedstock. Palm oil is widely cultivated across the country, but most representative plantations are located in the eastern, northern and central regions of the country. The cultivated area in 2009 accounted for 337 kha, of which 66% corresponds to full productive plantations and 34% to developing plantations not ready for exploitation (BID-MME, Consorcio CUE, 2012). The palm oil-cultivated area has been boosted since the introduction of the biodiesel blend mandate, and today Colombia is the fifth grower worldwide. Typical yields are about 20 tons of fresh fruit bunches (FFB) and 3.5 tons of oil per ha, which is higher than alternative oil crops (BID-MME, Consorcio CUE, 2012).

Fresh fruit bunches are cut from palm trees and transported by animal traction or by truck to palm oil extraction mills. In these mills, the fresh fruit bunches of the palm are crushed, producing palm oil and residues. Part of the residues (e.g. fiber, stone) is commonly used as fuel in steam boilers to provide heating, while the other part of the residues (e.g. rachis) is returned to the field for soil replenishment. The process of converting palm oil into biodiesel is commercially available and consists of oil refining, continuous transesterification and biodiesel purification steps. The reported biodiesel yield can be as high as 4530 liters per ha (BID-MME, Consorcio CUE, 2012). Sub-products of the palm oil extraction mill include palm kernel oil and meal, which are used as animal feed. Sub-products of the biodiesel conversion process include glycerol, soap and refined oil, which are used as feedstock in the cosmetics and pharmaceutical industries. Wastewater is produced at palm oil extraction mills and biodiesel production plants. Wastewater is treated via surface-aerated basins (lagoons), which significantly reduces the biochemical oxygen demand (BOD) but does not capture methane, which is released into the atmosphere causing a negative environmental impact.

### B.2.6. Biomass-based power generation & CHP

Today two main cases of biomass-based power generation and CHP exist in Colombia, i.e. cogeneration in the sugar cane and the palm oil industries. The first case relates to the use of steam turbine power plants using bagasse as a fuel to generate process steam and power. Steam is mainly used for two purposes: 1) to feed steam turbines driving knives, shredders and other equipment needed for processing and 2) to feed bioethanol distillation towers. The technology for cogenerating electricity at sugar cane facilities is well-established worldwide. In principle, it consists of power conversion technology entailing a bagasse-fired boiler, a steam turbine, a pump and a steam condenser. However, details of the process configuration vary from site to site. Various sugar mills use back-pressure steam turbines designed to meet power needs, in which steam exiting the turbine is extracted at pressures above atmospheric. This configuration is characterized by poor efficiencies that cover in-situ power needs but generate no surplus power (Macedo & Leal, 2001). In some cane mills, cogeneration power plants using condensing-extraction steam turbines are used. This is a superior configuration that has the capability of extracting steam at one or more points along the expansion path of the turbine to meet process needs. Non-extracted steam continues to expand to sub-atmospheric pressures, thereby increasing the efficiency and power generated compared to the back-pressure configuration. Electrical efficiencies range from 5 to 10% for the back-pressure configuration and from 10 to 30% for the condensing-extraction configuration. Today, the average electrical efficiency of bagasse-based power plants in Colombia is about 24%, while the CHP efficiency ranges between 45% and 65% (BID-MME, Consorcio CUE, 2012). The first cogeneration power plant at a sugar mill able to sell surplus power to the grid began operation in the Incauca sugar mill in the early 1990s, with a 9 MWe of installed capacity (XM, 2013). By 2009 there were six cogeneration power plants in operation and two planned, totaling 58 MW of installed capacity and generating 0.6 TWh (BID-MME, Consorcio CUE, 2012; XM, 2013)

The second case relates to the use of steam turbine power plants using palm residues in palm oil extraction mills. Steam is used in two processes: 1) sterilization of fresh fruit bunches (FFB) and 2) digestion of fruits in steam vessels with mechanical agitation to separate off the oil from the solid material. On the other hand, power is required to mechanically crush the FFB and separate oil from solid material as well as to drive other mechanical equipment. In this application, the most common technology is the back-pressure steam turbine cogeneration plant with a boiler fed with palm residues and occasionally with coal. In some sites no steam turbine is used. Instead, process steam is directly supplied by the boiler, while electricity is either bought from the grid or generated in a diesel engine. No data regarding palm oil extraction mills using condensing-extraction steam turbines is found. Depending on the configuration, typical electrical efficiencies range from 5 to 15% and CHP efficiencies range from 30% to 65%. The overall installed capacity is unknown, but the power generation in 2009 reached 0.2 TWh (BID-MME, Consorcio CUE, 2012).

# Chapter C. Method of assessing current biomass energy potential

## C.1. Overview

This chapter deals with one of the critical challenges to exploiting biomass in a country: how to estimate the current biomass energy potential. This challenge is further complicated in developing countries where the availability and quality of data are limited. A method to address uncertainty and improve reliability of the estimation of the biomass energy potential in countries with limited information is proposed. The proposed method is a bottom-up resource-focused approach with statistical analysis that uses a Monte Carlo algorithm to stochastically estimate the theoretical and the technical biomass energy potential. The proposed methodology improves the prediction reliability by following four steps: 1) using a simple accounting framework, 2) using a robust selection of probability density functions, 3) using a Monte Carlo simulation and a probabilistic propagation of uncertainty and 4) using sensitivity analysis to identify key variables contributing to uncertainty as well as a root cause analysis and a set of sub-models to improve estimation of key variables. The current biomass energy potential in Colombia is assessed following the proposed method and results are compared to existing assessment studies.

Potential advantages of the proposed method include transparency, reproducibility, low cost and possible adaptability to analyze other countries. This chapter is structured as follows: Section C.2 presents a literature review of state-of-the-art methodologies for assessing biomass energy and addressing uncertainty. Section C.3 describes the proposed method, while Section C.4 presents the application of the proposed method to the case study of Colombia. Finally, a summary and discussion are presented in Section C.5.

## C.2. Literature review

### C.2.1. State-of-the-art methods of assessing biomass energy potential

Detailed comparison of approaches, methodologies, key drivers and results of state-of-the-art biomass energy assessment for different countries are provided by (Batidzirai, Smeets, & Faaij, 2012; Heistermann , Müller, & Ronneberger, 2006; Berndes, Hoogwijk, & Van den Broek, 2003; Gnansounou & Panichelli, 2008; Van Schrojenstein Lantman, Verburg, Bregt, & Geertman, 2011). Batidzirai, Smeets & Faaij suggest three key elements to categorize state-of-the-art assessments: the type of potential, type of approach and type of method. The type of potential relates to the theoretical, technical, environmental and economic boundaries considered to perform the associated energy assessment, i.e. *what* is to be assessed. The type of approach relates to *how* the biomass resources are evaluated from a supply chain point of view, thus it can be demand-driven or supply-driven. On the other hand, the type of method relates to *how* the biomass resources are evaluated from an estimation technique point of view.

Four types of potential exist, namely theoretical potential (maximum amount of biomass), technical potential (fraction of the theoretical potential available at current conditions and constraints), the ecologically sustainable potential (fraction of technical potential under restrictions related to nature conservation and preservation of soil, water and biodiversity) and market potential (fraction of the technical potential that satisfies certain economic criteria).

Similarly, three types of approach are identified: resource-focused, demand-driven and integrated. While resource-focused approaches estimate the overall biomass resources and competition among different uses, demand-driven assessments investigate the cost competitiveness of biomass and bioenergy systems and evaluate biomass supply to meet exogenous targets. Integrated approaches combine features of both approaches and offer the possibility of evaluating multiple sustainability aspects. Finally, various types of methods are employed depending on the type of approach. Two main types of method are commonly employed in resource-focused approaches as defined by (Batidzirai, Smeets, & Faaij, 2012):

- Statistical analysis (non-spatial specific): it relies on statistical data to estimate the availability of biomass for energy conversion and other uses. Advantages include simplicity, transparency, reproducibility and low cost. However, it offers limited considerations for macro-economic impacts, environmental and social aspects.
- Spatially explicit analysis: it combines spatially explicit data and land use to assess biomass energy potential. The main advantage is the ability to

evaluate distribution of biomass and impacts at a local and regional level. Drawbacks include labor intensiveness and high complexity, which does not necessarily provide more accurate results and makes it difficult to replicate.

Two main types of methods are also employed in demand-driven assessments (Batidzirai, Smeets, & Faaij, 2012):

- Cost-supply analysis: it combines a biomass energy technical estimation with a cost evaluation of the biomass supply chain. It is a simple transparent, reproducible and inexpensive method. However, competition is not accurately modeled as it does not allow matching demand and supply through prices.
- Energy-system modeling: it simulates the behavior of energy markets and the competitiveness of biomass energy systems through application of economic optimization. Benefits include suitability to evaluate costs and effectiveness of policies. However, it lacks validation of land availability and agricultural yields and it uses economic correlations based on expert judgment.

While there is lack of a widely accepted and systematic approach to estimate current biomass energy potential, an ideal approach should consider key drivers and factors that influence the available biomass resource potential (Batidzirai, Smeets, & Faaij, 2012). Key drivers include land availability (or biomass production volumes), crop yields and reduction factors to avoid socio-economic and environmental impacts (Batidzirai, Smeets, & Faaij, 2012).

## C.2.2. Methods of assessing uncertainty in biomass energy potential

### C.2.2.1. Methods of addressing uncertainty in bioenergy

Various studies have recently proposed frameworks and structures to categorize the multiple types of uncertainties related to modeling the production of biomass. A notable example is given by Spiegelhalter and Riesch, who proposed a five-level structure for uncertainty associated with mathematical models in general (Spiegelhalter & Riesch, 2011). Levels 1 to 3 relate to uncertainties associated with unavoidable unpredictability of future events, limited information of model parameters and uncertainty regarding which model is best. Level 4 relates to uncertainty regarding known limitations of the mathematical model because of gaps in knowledge, computational limitations or methodological disagreements (i.e. indeterminacy). Finally, level 5 relates to uncertainty regarding unknown limitations of the mathematical model (i.e. ignorance).

The uncertainty framework described above was later applied by (Upham, Riesch, Tomei, & Thornley, 2011) to classify risks associated with the credibility of bioenergy certification and impacts of cultivation. They conclude that: a) not all uncertainties associated with bioenergy might be completely resolved (e.g. to a certain extent there is a lack of confidence in modeling to provide reliable data), b) some types of uncertainty cannot be tested empirically (i.e. indirect land use change) and c) many uncertainties are addressed diversely by different stakeholders resulting in indeterminacy and ignorance (e.g. various agro-economic models exist today, but necessary information to compare them is not even readily publicly available for independent researchers). (McDowall, Anandarajah, Dods, & Tomei, 2012) agree with these conclusions and further indicate that the scale of uncertainty and ignorance with respect to many energy crops and overall global potential is very large.

Another framework proposed by (Johnson, Willis, Curtright, Samaras, & Skone, 2011) categorizes the uncertainty in estimating the life cycle greenhouse gas (GHG) emissions from the production of biomass into three main types (Johnson, Willis, Curtright, Samaras, & Skone, 2011): model uncertainty, scenario uncertainty and data uncertainty. Model uncertainty is associated with the definition of the model structures, boundaries and overall assumptions, as well as temporal and spatial representation of the system. Scenario uncertainty is related to the definition of possible storylines, choices and assumptions. Data uncertainty relates to randomness, variability and systematic error.

Regarding ‘model uncertainty’, Johnson et al. discussed that there is a wide range of options for constructing models. Yet, there is uncertainty regarding which model is best - in other words, there is limited knowledge regarding the model structure (Johnson, Willis, Curtright, Samaras, & Skone, 2011). Johnson et al. pointed out that performing an inventory of the production of biomass does not necessarily require a sophisticated method to address the structural uncertainty, mainly because this process is composed of sequential and independent steps in a linear and additive form (Johnson, Willis, Curtright, Samaras, & Skone, 2011).

Regarding ‘data uncertainty’, Johnson et al. discussed that there are multiple sources of uncertainty associated with the data (Johnson, Willis, Curtright, Samaras, & Skone, 2011). There is uncertainty related to data availability and its quality, data variability, randomness, systematic error and to the unsuitability of some parameters to be mathematically described (Johnson, Willis, Curtright, Samaras, & Skone, 2011). Johnson et al. also describe the advantages and disadvantages of two approaches to addressing data uncertainty: boundary analysis and stochastic simulations. Boundary analysis has few requirements regarding data, assumptions and structure. However, it does not always identify rules for decision making and the less definitive results may be insufficient. In addition, it may produce misleading results in processes that are non-linear. They suggest that stochastic simulations provide a more descriptive representation of results and their likelihood compared to boundary analysis, but warn that a careful setup is required.

Regarding 'scenario uncertainty', Johnson et al. discussed that although scenarios are discrete possible storylines, they are the result of a combination of factors with associated uncertainties (Johnson, Willis, Curtright, Samaras, & Skone, 2011). As computational complexity increases with each scenario choice, they suggest reducing the number of scenarios to the minimum necessary. Furthermore, they suggest to estimate the probability of each scenario to be realized or, if that is not possible, to report outcomes separately for each scenario (Johnson, Willis, Curtright, Samaras, & Skone, 2011).

#### C.2.2.2. Uncertainty in biomass energy potential at national or regional levels

Smeets et al. have analyzed and compared various biomass energy potential assessments at regional and global levels (Smeets E. , Faaij, Lewandowski, & Turkenburg, 2007). They conclude that attention has been rarely paid to uncertainties and the impact of assumptions on the energy potential from forestry on a global scale. Smeets & Faaij define scenarios attempting to capture the uncertainty associated with the lack of data as well as the unpredictability of future events (Smeets & Faaij, 2007). They acknowledge that this approach provides rough estimations but it is a transparent method that identifies key variables and their related uncertainties. Böttcher et al. combine a scenario analysis with a stochastic simulation to estimate uncertainty in estimating forestry biomass in Thuringia (Germany) (Böttcher, Freibauer, Obersteiner, & Schulze, 2008). In that study, uncertainty is categorized and a coefficient of variation (i.e. standard deviation divided by mean) taken from literature or based on expert judgments is used to assign uncertainty to parameters. In addition, they perform a sensitivity analysis to identify key variables and the associated sources of variability, randomness or lack of knowledge. Another approach of addressing uncertainty in estimating the biomass energy potential is a boundary analysis, which produces limits on the potential by defining the minimum, maximum and most likely values for parameters. For example, (Richardson, Spies, Rigdon, York, Lieu, & Nacley, 2011) define uncertainty types (high, medium and low) associated with biomass production in the Yakama Nation (Washington, U.S.), to which an upper and lower bound multiplier is applied to modify a base case. Other examples of this approach include: a quantification the biomass energy from crop stalk resources in Inner Mongolia (China) (Liu, Wu, Liu, & Han, 2012) and a quantification of the biomass energy potential from heather in the UK (Worral & Clay, 2014).

Accuracy, appropriateness and complexity differ across the different approaches addressing uncertainty in biomass energy models at national or regional levels. While boundary analysis is a simple and clear technique, it might provide misleading results particularly for non-linear systems (Johnson, Willis, Curtright, Samaras, & Skone, 2011). Stochastic simulations might provide insights into the likelihood of the outcomes of a model but require a careful setup. Scenario analysis addresses uncertainty in future events by designing possible storylines. The selection of approach depends on the scope of the analysis and the availability of data and tools. (Roos & Rakos, 2000) recommend employing a transparent and rigorous approach that offers a balance between simplicity and realism. Furthermore, they suggest avoiding overly complex models that tend to lose credibility and acknowledging that there are factors that cannot be mathematically represented in models (Roos & Rakos, 2000).

### C.2.3. Gaps in knowledge

Uncertainty quantification is a topic that has not been a common practice in biomass energy assessments. When it was estimated, methods varied widely across studies. In developing countries, where availability and quality of data are limited, uncertainty quantification in biomass energy assessments has been even scarcer. In summary, there is a lack of a standard approach to address uncertainty in biomass energy assessments in countries where availability and quality of data are limited. The method proposed here aims at filling this gap.

## C.3. Method

A method to address uncertainty and improve reliability of the estimation of the biomass energy potential in countries with limited information is proposed. The proposed method aims at meeting the criteria defined in the introduction chapter, namely: 1) be transparent, easy to implement and replicable, 2) be inexpensive to adapt to constrained R&D budgets, 3) be built in well-known and generic platforms in order to increase the level of accessibility and 4) follow robust and state-of-the-art approaches (preferably bottom-up) to address the gaps in knowledge described above. Thus, a bottom-up resource-focused approach with statistical analysis is proposed for use, as it satisfies criteria 1, 2 and 4. To satisfy criterion 3, the method is built in Microsoft Excel and Crystal Ball.

In order to satisfy criterion 4, the proposed method is formulated in a generic manner and is composed of four steps, as shown in Figure 4. In a first step, it is proposed to use a simple, statistical (i.e. non-spatial specific), bottom-up accounting framework, to estimate the energy associated with different biomass categories (e.g. agricultural residues, forestry residues, animal waste, etc.). The accounting framework is based on an assessment of the key drivers of an ideal biomass energy potential as suggested by (Batidzirai, Smeets, & Faaij, 2012), i.e. biomass production volumes, crop yields and reduction factors to avoid socio-economic and environmental impacts. Boundary conditions and assumptions are then defined. An important boundary condition relates to the level of potential that is evaluated, which in the proposed method is limited to the theoretical potential and the technical potential. The ecologically sustainable potential and market potential are considered beyond the scope of this study. Next, a dataset is created with country statistics and technical data collected from available literature.

In a second step, a selection of appropriate probability density functions –PDF– (e.g. normal, discrete, etc.) for variables with sufficient available data and use of extended uniform distributions (EUD) for variables with limited data is proposed. In a third step, the use of a Monte Carlo algorithm that applies probabilistic propagation of uncertainty for evaluating the biomass energy potential and its associated uncertainty is proposed. For this purpose, a preliminary potential is stochastically calculated for each biomass category.

As this uncertainty might be substantial and might be associated to a large number of variables, the use of a sensitivity analysis for identifying key variables contributing to the overall uncertainty is proposed in a fourth step. This is very advantageous, as it reduces the number of variables that need to be re-assessed. Next, a reduction in uncertainty of the key variables is made by performing more thorough literature search and developing sub-models. These sub-models aim at describing more accurately key variables by doing: a) a root cause analysis and b) a disaggregation of variables into spatial or temporal sub-components. Finally, biomass energy potential is recalculated using the improved key variables and results are compared to those from the preliminary estimation.

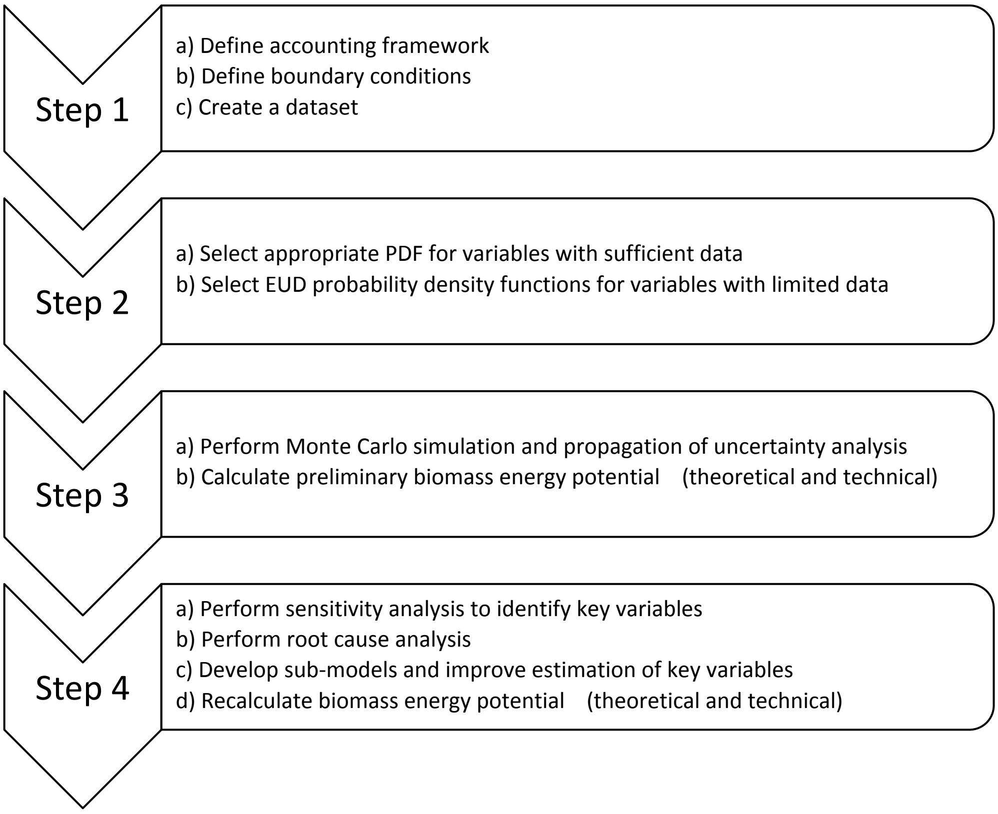

***Figure 4.*** *Method of assessing biomass energy potential and its associated uncertainty*

The novelty of the proposed approach is explained as follows. Step 1 is common practice in the bioenergy field. Step 2 has been proposed before, though not for bioenergy. Step 3 (uncertainty estimation) has been performed before, but it is not a common practice in biomass energy potential assessments. Instead, Step 4 is novel in the context of bioenergy. Combining Steps 1-4 in a comprehensive approach enables to fill the gap in knowledge described before. The most relevant aspects of each step of the proposed method are discussed in the following sections.

## C.3.1. Step 1

### C.3.1.1. Boundary conditions and assumptions

According to (Spiegelhalter & Riesch, 2011), the choice of the model structure, boundaries and assumptions is a pragmatic compromise between the credibility of results and the effort to create and analyze the model. Thus, clear definition of biomass categories based on the guidelines suggested by (Rosillo-Calle, de Groot, Hemstock, & Woods, 2007; Slade, Saunders, Gross, & Bauen, 2011) is proposed. The proposed definition should be regarded as general and should be used with caution as there is not a universally accepted definition. More site-specific sub-categories and boundaries can be determined for different countries or regions as needed. Firstly, biomass energy potential is defined as the amount of energy contained in biomass before any type of energy conversion. Bioenergy potential is defined as the energy associated with secondary energy resources/carriers such as electricity and biofuels after conversion losses (Slade, Saunders, Gross, & Bauen, 2011).

This method focuses only on the biomass energy potential and excludes the bioenergy potential. The reason for this is to avoid an inconsistent comparison between the potential associated with primary energy resources (e.g. residues and wastes) and secondary energy resources/carriers (e.g. biofuels and electricity). The biomass is further divided into terrestrial biomass and non-terrestrial biomass (e.g. algal biomass). This method focuses only on terrestrial biomass, which is classified into woody and non-woody biomass. Woody biomass comprises various sub-categories including natural forest and woodlands, forest plantations and energy plantations. On the other hand, non-woody biomass comprises sub-categories including agricultural crops, animal waste and urban waste. Under each of these sub-categories biomass is produced either for energy or non-energy purposes. Non-energy uses of biomass include supply for food and fiber as well as feedstock to the industrial sector. Current energy utilization is further divided into two categories: traditional use (wood fuel for cooking and heating) and modern use (use of bagasse and residues for heating, power generation and combined heat and power (CHP), biofuel production, etc.).

Four main biomass categories are considered:

- Forestry and wood industry: wood fuel, forestry residues and industrial residual wood.
- Agricultural residues: residues from agro-industry (e.g. bagasse) and crop residues (e.g. rice husk, cotton husk, etc.).
- Animal waste: manure from cattle, poultry, pork, etc.
- Urban waste: municipal solid waste producing landfill gas, residues from the wholesale market, demolition residues, residual methane from water treatment plants, pruning residues, etc.

The energy potential associated with biofuels is excluded to avoid an inconsistent comparison between the potential associated with primary energy resources (e.g. residues and wastes) and secondary energy resources/carriers (e.g. biofuels). In this sense and as discussed above, the present definition refers only to the biomass energy potential. The reason for excluding biofuels is that, in contrast to the four main biomass categories described above, they are not primary energy resources but secondary energy resources or energy carriers (i.e. substances that contain energy that can be directly used to produce mechanical work or heat or to operate chemical or physical processes (ISO, 1997)). As such, biofuels require primary and secondary energy resources and materials for their production, some of which are not renewable[4] (Slade, Saunders, Gross, & Bauen, 2011). For this reason, 1 MJ of biofuels is not the same as 1 MJ of primary energy resources (Slade, Saunders, Gross, & Bauen, 2011). Thus, a direct comparison between residues and wastes (i.e. primary energy resources) and biofuels (i.e. secondary energy resources) might be inconsistent and hence is avoided here.

For the category of animal waste, it is assumed that the energy potential derives from biogas produced from manure through a bio-digestion process (FAO, 1996). Two levels of biomass energy potential are evaluated, the theoretical potential and the technical potential. The theoretical potential is defined as the maximum amount of energy contained in biomass that can be used for energy purposes, explicitly excluding biomass used for food, fiber (e.g. round wood) and feedstock for industry (e.g. co-products).

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[4] For example, to produce 1 kg of bioethanol from sugar cane, it is required 3.3 kg of molasses, 0.5 kg of cane juice, 0.2 kg of $H_2SO_4$, 1.3 kg of cooling water, 3.9 kg of steam and 0.23 kWh of electricity (BID-MME, Consorcio CUE, 2012).

The technical potential is defined as the fraction of the theoretical potential that is available for energy production at current conditions and constraints, after considering current energy utilization and competition with other uses and various constraints.

Acknowledged limitations of the proposed system boundaries include the following considerations:

- They do not include the energy potential associated with the use of idle crop land and other uncultivated land.
- They do not include the potential for producing biofuels from primary biomass energy resources.
- They do not include the potential for producing secondary energy resources/carriers (e.g. electricity, heat, etc.) from primary biomass energy resources.

### C.3.1.2. Accounting framework

The accounting framework used to estimate the theoretical and technical biomass energy potential is a simple, bottom-up and non-spatial specific accounting framework. Firstly, it estimates the overall volume of biomass resources in a country using official statistics and public data. Secondly, it estimates the volume of residual biomass associated to biomass resources that could potentially be used for energy purposes. Finally, it estimates the energy associated by multiplying the volumes of said residual biomass on a dry basis by their corresponding lower heating value (LHV). This accounting framework is used to estimate the theoretical and technical biomass energy potentials.

The mathematical formulation of the accounting framework is presented below. The overall theoretical biomass energy potential is estimated as the sum of the potential associated with each biomass category, see Eq. 1. Similarly, the technical biomass energy potential is calculated by using Eq. 2.

Eq. 1 $Q = Q_{AR} + Q_{AW} + Q_F + Q_U$

Eq. 2 $Q^T = Q_{AR}^T + Q_{AW}^T + Q_F^T + Q_U^T$

The energy potential associated with agricultural residues is calculated using the crop production $P_i$, by-product to crop ratio $k_{i,j}$, moisture content $M_{i,j}$ and the lower heating value $LHV_{i,j}$, as shown in Eq. 3 and Eq. 4.

Eq. 3 $Q_{AR} = \sum_i \sum_j P_i \cdot k_{i,j} \cdot (1 - M_{i,j}) \cdot LHV_{i,j}$

Eq. 4 $Q_{AR}^T = \sum_i \sum_j P_i \cdot k_{i,j} \cdot (1 - M_{i,j}) \cdot LHV_{i,j} \cdot a_{i,j}$

The energy potential of animal waste is calculated from the amount of biogas produced from manure from the different *m* type of animal (e.g. pigs, chicken, cows and horse) and *n* sub-type of animal (e.g. young pig, boar and sow) through a bio-digestion process:

Eq. 5 $Q_{AW} = \sum_m \sum_n H_{m,n} \cdot f_{m,n} \cdot b_{m,n} \cdot LHV_{m,n}$

Eq. 6 $Q_{AW}^T =$
$$\sum_m \sum_n H_{m,n} \cdot f_{m,n} \cdot b_{m,n} \cdot LHV_{m,n} \cdot a_{m,n}$$

The energy potential of the category of forestry and wood industry is calculated using Eq. 7 and Eq. 8. In these equations $P_r$ represents the production of the r-th forestry resource (e.g. wood fuel, round wood, etc.), $c_r$ represents the by-product to product ratio in forestry, $\rho_r$ symbolizes the density (t/m$^3$, dry basis) and $LHV_r$ the lower heating value.

Eq. 7 $Q_F = \sum_r P_r \cdot c_r \cdot \rho_r \cdot LHV_r$

Eq. 8 $Q_F^T = \sum_r P_r \cdot c_r \cdot \rho_r \cdot LHV_r \cdot a_r$

Finally, for the urban waste category the energy potential is calculated using Eq. 9 and Eq. 10 by multiplying the production volume of each urban waste type $P_x$ by the lower heating value $LHV_x$.

Eq. 9 $Q_U = \sum_x P_x \cdot LHV_x$

Eq. 10 $Q_U^T = \sum_x P_x \cdot LHV_x \cdot a_x$

The availability factor for each biomass resource (viz. $a_{i,j}$, $a_{m,n}$, $a_r$, $a_x$) is calculated using Eq. 11-Eq. 14. Constraint factors $\propto_1$ to $\propto_5$ represent, respectively, geographical, market, technical, environmental and special constraints associated with the different biomass resources. These constraint factors are highly site-specific and depend on numerous variables that need to be analyzed carefully. For the study case of Colombia, the analysis of the constraint factors is presented in Section C.4.4.

Eq. 11 $a_{i,j} = [\propto_1 \cdot \propto_2 \cdot \propto_3 \cdot \propto_4 \cdot \propto_5]_{i,j}$

Eq. 12 $a_{m,n} = [\propto_1 \cdot \propto_2 \cdot \propto_3 \cdot \propto_4 \cdot \propto_5]_{m,n}$

Eq. 13 $a_r = [\propto_1 \cdot \propto_2 \cdot \propto_3 \cdot \propto_4 \cdot \propto_5]_r$

Eq. 14 $a_x = [\propto_1 \cdot \propto_2 \cdot \propto_3 \cdot \propto_4 \cdot \propto_5]_x$

### C.3.1.3. Create a dataset

Next, a dataset is created with country statistics and technical data collected from available literature.

## C.3.2. Step 2

Ideally, if the data required for computing the equations described in Section C.3.1.2 were available and fully accurate, estimating biomass energy potential would be straightforward. However, in reality there are multiple sources of uncertainty associated with the data.

But how can stochastic simulations be performed when the quality and availability of data are insufficient to parameterize probability distributions? Use of a pragmatic approach is proposed - use detailed probability functions for parameters with sufficient available data and use an extended uniform distribution (EUD) for those parameters with limited available information. As described by (Goulet & Smith, 2011; Goulet, Michel, & Smith, 2012), the extended uniform distribution is a simple technique to describe errors in the absence of more precise information. It provides a probability density function that considers multiple orders of uncertainty in a more representative way than uniform or curvilinear distributions. Goulet and Smith suggest that this distribution contributes to increase the robustness of models by better describing an incomplete knowledge of parameters. In the EUD distribution the zero-order uncertainty is described by a uniform distribution with lower and higher bounds (i.e. A and B). As there is uncertainty regarding the exact position of each bound, this uncertainty is described by a first-order uniform distribution with lower and higher bounds. The width of the first-order distribution is defined as $\beta \cdot (B - A)$, where $\beta \in [0,1]$. As the knowledge regarding the lower and higher bounds of the first-order distribution is incomplete, its uncertainty is described by a second-order uniform distribution. The width of this distribution is defined as $\beta^2 \cdot (B - A)$. This process can continue to several orders of uncertainty with the width of further distributions defined as $\beta^\gamma \cdot (B - A)$, where $\gamma$ is the order of uncertainty. For engineering applications such as the one presented in this study, (Goulet & Smith, 2011) indicate that two or three orders of uncertainty may be sufficient. For simplicity, two orders of uncertainty are therefore selected. If $\beta = 1$ the shape obtained is close to a normal distribution, while if $\beta = 0$ the shape obtained is a standard uniform distribution. Following procedures suggested in (Goulet, Michel, & Smith, 2012; Goulet & Smith, 2010) for applied engineering applications, a value of $\beta = 0.3$ is chosen. An example of the shape of the assumed extended uniform distribution for [-1, 1] is shown and compared to a standard uniform distribution in Figure 5.

## C.3.3. Step 3

A Monte Carlo simulation to evaluate the accounting framework is proposed. A Monte Carlo simulation performs a random sampling of input parameters and a deterministic calculation of each trial to produce thousands of possible outcomes. Next, a probabilistic propagation of uncertainty analysis is performed in order to determine the uncertainty of model outputs from random sampling of probability distributions of input parameters. This combination of Monte Carlo simulation and propagation of uncertainty is then used to preliminary evaluate the biomass energy potential at two levels: a) theoretical energy potential and b) technical energy potential.

## C.3.4. Step 4

### C.3.4.1. Sensitivity analysis to identify key variables

In many cases a more comprehensive search of literature might well help to reduce the uncertainty associated with a parameter. However, performing a thorough literature search might be challenging and non-practical when the number of variables is large, as is the case of the accounting framework described in Section C.3.1.2. Thus, a sensitivity analysis to identify key contributors is proposed. For this purpose, the abovementioned method of propagation of uncertainty is used. This method performs a variance-based sensitivity analysis, in which the contribution of each input to the uncertainty in outputs is probabilistically quantified. While a sensitivity analysis is not a method of addressing uncertainties per se, it is a powerful technique that indicates which variables should be the focus of attention in order to reduce overall uncertainty. For the sake of brevity, fundamentals of error analysis are not shown here but can be found in (Taylor, 1982; Coleman & Steele, 2009).

### C.3.4.2. Improved estimation of key variables

Once key variables contributing to uncertainty are identified, the next step is to improve their estimation. The estimation of these key contributors is improved by making a more thorough search of literature and by disaggregating variables into spatial or temporal sub-models. Sub-models aim at describing more accurately key variables by doing: a) root cause analysis and b) disaggregation of variables into spatial or temporal sub-components. Firstly, root cause analysis is employed to identify the most important sub-components that affect each one of the key variables. Once these sub-components are identified, a more detailed search of information for each of these sub-components is performed. It is expected that a better estimation of key variables can be achieved by having a more detailed representation of sub-components.

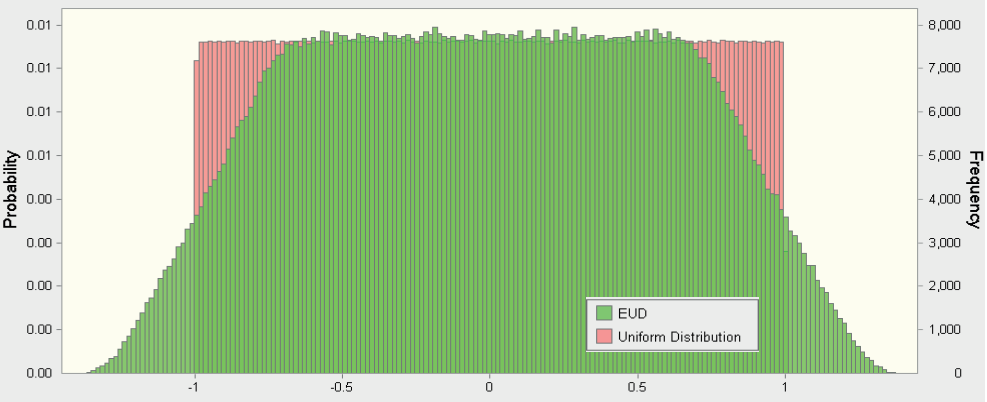

***Figure 5.*** *Extended uniform distribution (EUD) compared to uniform distribution*

For this reason, and depending on data available, sub-components of key variables are disaggregated into spatial or temporal sub-components. An example is provided as follows. Let's assume the density of woodfuel at a country level involves a very large uncertainty. An option might be to express the density as a function of the type of tree species and region, if more information for those sub-components is available. The weighted mean of the density can be computed as follows:

Eq. 15 $$\bar{\rho} = \sum_r (\rho_r) \cdot (w_r) = \sum_r f\left(\rho_{r,s1}, \rho_{r,s2}, \dots, \rho_{r,sn}\right) \cdot \left(\frac{PW_r}{\sum_r PW_r}\right)_r$$

Where $\bar{\rho}$ is the weighted mean of the density, $\rho_r$ is the density of wood fuel in a particular geographical region *r*, $\rho_{r,s}$ is the density of wood fuel of specie of tree *s* (1,2,…,n) in a region *r, $w_r$* is the weight factor and $PW_r$ is the production of wood fuel by region. The density of wood fuel in a particular region ($\rho_r$) is a function of the density of the different species of trees in that region ($\rho_{r,s1}, \rho_{r,s2}, \dots, \rho_{r,sn}$), which can for example be defined with a discrete probability distribution. This distribution assigns the same probability of occurrence to the densities of each of the different species of trees existing in that particular region. Then, the regional density of wood can be weighted by its contribution to the overall wood fuel production and the weighted mean can be computed. Estimation of other key variables can be improved following a similar approach.

#### C.3.4.3. Recalculate biomass energy potential

The theoretical and technical biomass energy potential is then recalculated using the improved estimation of sub-components of key variables through spatial or temporal disaggregated sub-models. Finally, the preliminary and recalculated estimations of the biomass energy potential are compared and analyzed.

### C.3.5. Limitations of the proposed method

The method proposed here should not be regarded as definitive and unambiguous. It is an attempt to find a balance between simplicity and realism, avoid overly complex models that tend to lose credibility and acknowledge that there are factors difficult to model mathematically, as suggested by (Roos & Rakos, 2000). Following the suggestions of (Spiegelhalter & Riesch, 2011; Johnson, Willis, Curtright, Samaras, & Skone, 2011; Roos & Rakos, 2000), the limitations of the proposed method are acknowledged (Figure 6).

#### C.3.5.1. Limited knowledge about the model structure

It is important to mention that while the accounting framework described above is acknowledged in scientific literature (Rosillo-Calle, de Groot, Hemstock, & Woods, 2007; Elbersen, Startisky, Hengeveld, Schelhaas, Naeff, & Böttcher, 2012; Ralevic & Layzell, 2006; Jingjing, Xing, DeLaquil, & Larson, 2001), there are alternative methods for quantifying biomass production and its associated energy potential. Examples include: a) top-down demand-driven methods to estimate biomass energy potential based on supply curves, b) the use of agriculture residue yields (kg/ha), which can be measured or estimated as a function of crop yields (Bentsen, Felby, & Thorsen, 2014) and c) the use of higher heating value (HHV) (Smeets & Faaij, 2007; Slade, Saunders, Gross, & Bauen, 2011; GCEP, 2005). The proposed accounting framework presents various differences compared to these alternatives. Firstly, in contrast to demand-driven studies that provide little insight into the size of the technical biomass potential and its calculation (Slade, Saunders, Gross, & Bauen, 2011), it offers a consistent approach that fully relies on official statistics and public data (Slade, Saunders, Gross, & Bauen, 2011). However, the proposed method does not offer insights into the demand of biomass resources.

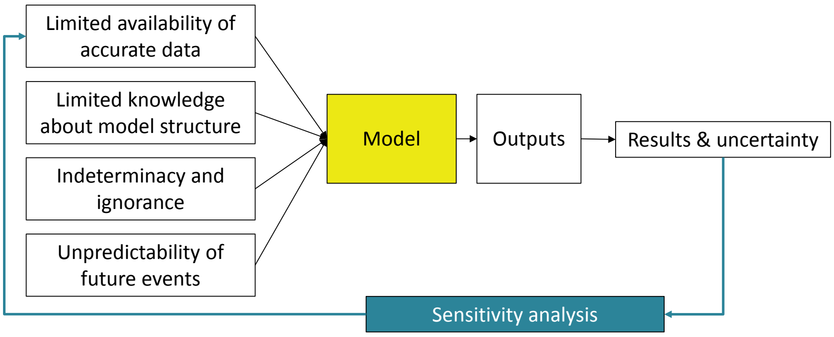

***Figure 6.*** *Limitations of the proposed method*

Secondly, agriculture residue yields are not readily available and as (Bentsen, Felby, & Thorsen, 2014) suggest, they can be derived from crop yields. However, it is unclear whether the overall uncertainty associated with crop yields and derivation methods is smaller than the uncertainty of the typical by-product to crop ratio technique. Regarding the use of the lower heating value (LHV) rather than the higher heating value (HHV), the former is smaller as it does not include two forms of heat energy released during biomass combustion: a) the energy to vaporize water contained in the fuel (latent heat) and b) the energy to form and vaporize water from hydrogen contained in hydrocarbon molecules (Rosillo-Calle, de Groot, Hemstock, & Woods, 2007). The selection of LHV over HHV is consistent with most international energy statistics and balances which are based on LHV, because most current energy technologies are not able to recover the latent heat (GEA, 2012). However, it should be noted that according to some sources, using HHV and dry biomass amounts may help reducing the uncertainty, since biomass moisture content varies depending on harvesting technologies and local conditions.

In summary, there is no definitive and unambiguous accounting method, but the abovementioned reasons suggest that the proposed accounting framework is appropriate. It is possible that other authors might disagree with the logic described above, which would lead to uncertainty (Spiegelhalter & Riesch, 2011). No particular technique to quantify this uncertainty is proposed, but rather it is acknowledged that differences in results might arise by selecting alternative accounting methods.

#### C.3.5.2. Limited availability of accurate data

In the proposed model there is uncertainty related to data availability and its quality, data variability, randomness, systematic error and to the unsuitability of some parameters to be mathematically described. While using EUD probability density functions would contribute to reduce the uncertainty associated with variables with limited data, it will not eliminate uncertainty associated with indeterminacy and ignorance (see Section C.3.5.4). Similarly, improving the estimation of key variables would reduce to certain extent their uncertainty, but would not eliminate uncertainty associated with data variability, randomness, indeterminacy and ignorance.

#### C.3.5.3. Unpredictability of future events

There are future events that cause uncertainty in the estimation of the technical biomass energy potential. To address this uncertainty, a scenario analysis is highly recommended. With this technique, various scenarios can be defined to evaluate the technical potential under different possible storylines. Despite its multiple advantages, a scenario analysis has not been included here and is proposed as a topic for further investigation.

#### C.3.5.4. Indeterminacy and ignorance of the proposed accounting framework

Indeterminacy relates to the uncertainty regarding the known inadequacies of the applied model. There are four main known model limitations: 1) there might be unknown correlations of model parameters, 2) the model does not improve the estimation of non-key parameters, 3) the method does not include idle land to estimate the biomass energy potential and 4) the method does not consider biomass for final human usage to estimate the biomass energy potential. Two limitations are associated with the approach addressing data uncertainty (#1 and #2) and two are associated with boundaries (#3 and #4).

Limitation #1 relates to the assumption that all parameters are uncorrelated. However, there might be unknown correlations of these parameters which are likely to have an important influence on the confidence in estimates. Some correlations are found in literature, for instance between the agriculture residue yield and the crop yield (Bentsen, Felby, & Thorsen, 2014). However, for the parameters described in Section C.3.1.2 no correlations were found. Limitation #2 relates to the fact that the model does not improve the estimation of non-key parameters. While estimation of key parameters is improved through disaggregation and comprehensive data collection, non-key parameters are left with a non-improved EUD probability distribution. This limitation has a moderate impact on estimates, and might be mitigated by performing a second-round sensitivity analysis to identify secondary key parameters and improve their estimation.

Limitation #3 relates to the exclusion of idle land to estimate the biomass energy potential. The inclusion of idle land is mostly employed in future biomass energy potential assessments to illustrate how much biomass can be used for energy purposes without jeopardizing food supplies (IEA, 2011b; Dornburg, et al., 2008). While the present method focuses on current biomass energy potential, excluding idle land is likely to have an important impact and may change the estimate. Finally, limitation #4 relates to the exclusion of biomass for final human usage in the estimation of the biomass energy potential. By definition the biomass used for final human usage (e.g. food, fiber, wood fuel, etc.) cannot be employed for energy purposes. Since the current biomass used for final human usage contributes to about 7-8% of the terrestrial biomass according to (GCEP, 2005), its impact is unlikely to change the confidence of the estimate. In summary, Limitations #1-#3 are considered of moderate quality according to the GRADE scale (Spiegelhalter & Riesch, 2011), and therefore further research is likely to have an important impact on the confidence in the estimate and may change the estimate. Limitation #4 is considered of high quality and thus, further research is highly unlikely to change confidence in the estimate and may change the estimate.

## C.4. Study case: Colombia

The method of estimating the biomass energy potential and its associated uncertainty when quality and availability of data are limited is applied to a case study of Colombia. Similarly to other developing countries, Colombia has an obvious interest in biomass: it is the second largest renewable energy resource after large hydro. In 2009, biomass contributed to 67% (3.4 PJ, excluding large hydro) of the renewably generated electricity, to 4.2% (15.7 PJ) of the energy supply in the transport sector and to 3.9% (193.5 PJ) of the overall primary energy supply (4.93 EJ according to UPME) (UPME, 2011b). Earlier studies indicate that nearly half of the country's available biomass energy potential remains untapped.

### C.4.1. Prior art

Five studies estimating the current biomass energy potential in Colombia are available in literature, i.e. (UPME, 2011b; AENE, 2003; Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011; Arias Chalico, et al., 2009; Kline, Oladosu, Wolfe, Perlack, Dale, & McMahon, 2008). The Mining and Energy Planning Unit (UPME), an affiliate of the Ministry of Mines and Energy, has been particularly active in the process of assessing the biomass energy potential. To date, UPME has developed one biomass energy estimation (UPME, 2011b) and has participated in and sponsored two additional studies (AENE, 2003; Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011). Independent estimations have been created by foreign institutions or project consortiums and examples include the reports from the Oak Ridge National Laboratory (Kline, Oladosu, Wolfe, Perlack, Dale, & McMahon, 2008) and the collaborative European-Latin American project consortium BioTop (Arias Chalico, et al., 2009). A comparative overview of the year of estimation, considered biomass categories, type of potential, type of approach and type of method for the different studies is presented in Table 1. In general, all estimations have been published in the last seven years except the AENE report, which was released in 2003. All studies have estimated the theoretical biomass energy potential while only three reports also evaluated the technical potential.

Among the studies, five biomass categories are considered relevant to Colombia: agricultural residues, animal waste, forestry and wood industry, biofuels and urban waste. Although biofuels are secondary energy carriers derived from biomass resources, in some of these studies they are indistinctly treated compared to primary biomass energy resources (residues, wastes, etc.). While most studies evaluate the energy potential of at least three of these categories, the entire energy potential of all biomass categories has not been reported.

Uncertainty in predictions has not been reported in any of the assessments. Regarding the theoretical potential of the forestry and wood industry, most of the studies evaluated the residual biomass associated with the production of round wood. However, the biomass potential evaluated using above-ground biomass in forests has not been reported. The preferred method throughout studies is the resource-focused approach employing statistical analysis. This method has been employed in four reports and it has been notably combined with a spatially explicit analysis to offer regional results in (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011). The method used by UPME has not been reported. Generally speaking, the approach employed in all existing studies is characterized by a three step process to estimate biomass energy potential:

1. Use available statistics to define production volumes and yields of primary agricultural and forestry biomass resources including dedicated

crops, energy crops, animal production and forestry and wood industry.

2. Use available statistics to define production volumes (i.e. by using by-product to product ratios) and the heating value of by-products associated with primary biomass resources. At this step the theoretical biomass energy potential for each biomass category is estimated by multiplying the heating value by the production volume. With the exception of the AENE report, all other reports estimated the theoretical energy potential of biomass on a dry matter basis.

3. Assume or estimate an availability factor for the primary biomass resources and the associated by-products to produce energy. At this step the technical biomass energy potential for each biomass category is estimated by multiplying the theoretical potential with a corresponding availability factor.

Although similar approaches are used across studies, non-reported methodologies, omissions and inconsistencies in assumptions and data are found. In order to allow a meaningful comparison of results in further sections, a comparative summary of the assumptions taken from different studies is presented in Table 36 in the Appendix.

### C.4.2. Site-specific boundary conditions and assumptions

The boundary conditions and assumptions defined in Section C.3.1 are applied to the specific case of Colombia (see Figure 7). Non-energy uses of biomass (yellow area in Figure 7) include supply for food and fiber as well as feedstock to the industrial sector.

Current biomass energy utilization in Colombia (blue area in Figure 7) is divided into two categories: traditional use (wood fuel for cooking and heating) and modern use (use of bagasse and palm oil residues for heating, power generation and combined heat and power (CHP)). Four main biomass categories are considered: forestry and wood industry, agricultural residues, animal waste and urban waste. Biomass resources associated with these four categories are primary energy resources, i.e. residues and wastes. Biofuels are excluded from the assessment.

Two levels of biomass energy potential are evaluated - the theoretical potential (green area in Figure 7) and the technical potential (grey area in Figure 7). Nearly half of the land in Colombia is covered with forests (58.6 mio ha), of which 16% are protected areas and about 70-75% are tropical forests with high biodiversity and carbon pools (Phillips, et al., 2011; Corredor, 2011). The theoretical biomass energy potential is evaluated on two scales: a) one including the entire above-ground biomass in forests but excluding protected areas and b) one including only the biomass associated with the production of round wood. The first case is estimated only for comparative purposes, as from a sustainability and ecological point of view the use of biomass from tropical forests is prohibitive. The second case is considered more attainable and is further used to calculate the technical biomass energy potential.

***Table 1.*** *Comparative overview of existing estimations of biomass energy in Colombia*

| Study | Year of publication/ estimation | Potential | Approach | Method | Considered biomass categories | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Agricultural residues** | **Biofuels** | **Animal waste** | **Forestry & wood industry** | **Urban waste** |
| UPME [1] | 2011/2009 | Theoretical potential and energy currently used | Resource-focused | Not reported | ✓ | ✓ | ✗ | ✓ | ✗ |
| AENE [2] | 2003/2003 | Theoretical and technical potential | Resource-focused | Statistical analysis | ✓ | ✓ | ✗ | ✓ | ✗ |
| Escalante et al [3] | 2011/2010 | Theoretical potential | Resource-focused | Statistical analysis and spatially explicit analysis | ✓ | ✗ | ✓ | ✗ | ✓ |
| Arias et al [4] | 2009/2008 | Theoretical and technical potential | Resource-focused | Statistical analysis | ✓ | ✓ | ✓ | ✓ | ✗ |
| Kline et al [5] | 2008/2007 | Theoretical and technical potential | Resource-focused | Statistical analysis | ✓ | ✓ | ✗ | ✓ | ✗ |

Notes:
[1] (UPME, 2011b)
[2] (AENE, 2003)
[3] (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011)
[4] (Arias Chalico, et al., 2009)
[5] (Kline, Oladosu, Wolfe, Perlack, Dale, & McMahon, 2008)

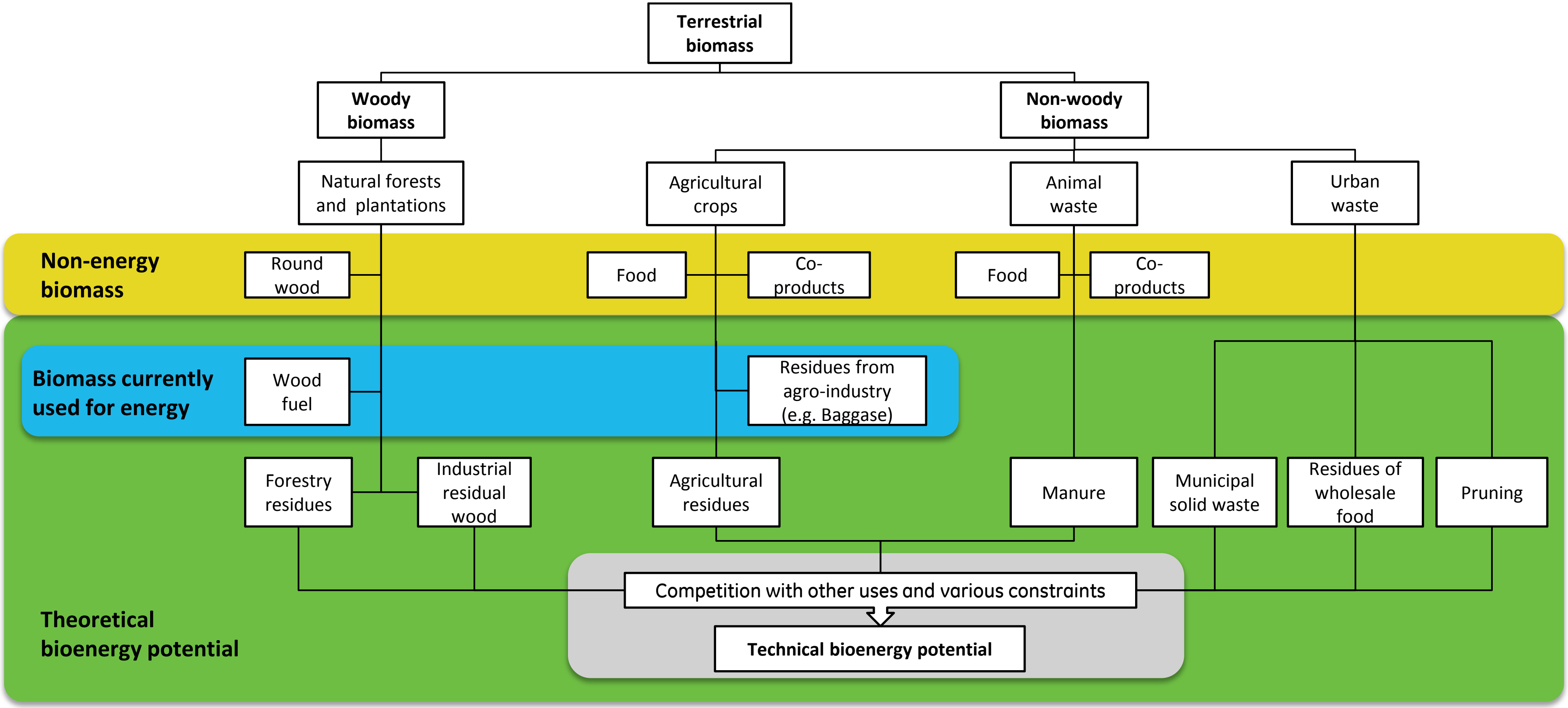

***Figure 7.*** *Boundary conditions specific for Colombia*

### C.4.3. Calculation of the theoretical potential

Country statistics and technical data are collected from available literature. Given the heterogeneity of the data found in literature, a priority order of the different sources of information is set. As suggested by (Arias Chalico, et al., 2009), first priority is given to official statistics from the government, second priority to data provided by international agencies and third priority to scientific papers. This order of preference is not definitive and the reasons for using it are explained as follows. Official statistics from the government are considered reliable, particularly at a country level, owing to well-structured national agricultural statistical systems and national statistical systems (Acosta Moreno & Pérez Gómez, 2011). These national statistical systems offer data collected from well-coordinated national agriculture surveys and measurements using methods and technologies generally accepted by the scientific community (particularly in recent years), e.g. advanced database systems, geographic information systems, satellite imagery, digital photogrammetry, etc. (Acosta Moreno & Pérez Gómez, 2011). In addition, the national statistical systems follow guidelines and recommendations from the Food and Agriculture Organization for the United Nations (FAO), the U.S. Department of Agriculture (USDA), European Statistical System (EUROSTAT) and the organization for Economic Co-operation and Development (OECD) (Acosta Moreno & Pérez Gómez, 2011). However, the national statistical systems also present some drawbacks. Firstly, agricultural and forestry statistics are not commonly available at regional or county level. Secondly, methodologies, boundary conditions and assumptions for creating statistics vary throughout the years, causing a lack consistency and clarity and potentially heading to bias (Acosta Moreno & Pérez Gómez, 2011).

When data was not available in official statistics, or when it was considered unreliable, the procedure was to firstly use data from international organizations and secondly from technical papers. This procedure ensures that most reliable and accurate data is always used. However, it does not solve the problem of having heterogeneity of data collected from multiple sources.

While country statistics are generally available in at least one of the three main data sources described above (i.e. official statistics, international agencies and scientific papers), site-specific technical data associated with biomass resources in Colombia was not always readily accessible. To overcome this challenge, the following approach was employed. For the preliminary estimation of the theoretical potential, data corresponding to Colombia was used to the maximum extent. However, when it was not available, data corresponding to countries other than Colombia was used. Examples include the by-product to product ratio for some crops, the manure production per head for some animals, etc. Once key variables were identified through a sensitivity analysis, the theoretical potential was re-calculated by performing a thorough search of site-specific data for these key variables. A criterion proposed by (Thompson, 1935) for rejecting outlying observations was used to filter and exclude suspiciously high or low values found in literature. The dataset for the different biomass categories is presented as follows.

Agricultural residues

The dataset for agricultural residues is shown in Table 29 in the Appendix. The production volumes of agricultural crops are taken from the Ministry of Agriculture and Rural Development (MADR, 2012), which in turn estimates it through a survey based on a multiple-frame sampling method described in National Agriculture Surveys (DANE, 2010a; DANE, 2000; DANE, 1997; DANE, 2009). This method combines a two stage area-frame sampling with a list-frame sampling to estimate production volumes of the samples and through statistical methods to infer the production volumes of the entire population (DANE, 2010a; DANE, 2000; DANE, 1997; DANE, 2009). The method involves a sample error (i.e. a coefficient of variability) associated with the degree of approximation, which according to the National Administrative Department of Statistics (DANE) is normally distributed (DANE, 2010a; DANE, 2000; DANE, 1997; DANE, 2009).

It was found that the National Agriculture Survey of 2010 does not include the coefficient of variability of various crops and therefore the survey of 2009 that includes data for most crops was used (DANE, 2009). Unfortunately, this survey does not report data for cotton, cane (large-scale) and palm oil. For these crops data is scarce and some assumptions were made. For cotton, the coefficient of variability reported in the National Agriculture Survey of 2000 (DANE, 2000) was used, for palm oil the coefficient of variability reported in the survey of 1997 (DANE, 1997) was used and for cane (large-scale) the uncertainty in measuring bagasse reported by a typical sugar mill with cogeneration under a CDM project (UNFCCC, 2009) was used. The probability distributions used are normal for the production volumes of crops and EUD for the by-product to crop ratio, moisture content and lower heating value.

Animal waste

The dataset for animal waste is shown in Table 30 in the Appendix. The inventory of cattle, swine, poultry and equine is taken from the Ministry of Agriculture and Rural Development (MADR, 2012), which in turn estimates it through the National Agriculture Surveys (DANE, 2010a; DANE, 2000; DANE, 1997; DANE, 2009). According to the National Administrative Department of Statistics (DANE), the sample error in inventorying animals is normally distributed (DANE, 2010a; DANE, 2000; DANE, 1997; DANE, 2009). To be consistent with the assumptions made for agricultural residues, the normally distributed coefficient of variability associated with each of the animal types is taken from the National Agriculture Survey of 2009 (DANE, 2009). Data on biogas yield from manure is available for the different animal types but is not disaggregated by animal sub-type (i.e. young, boar and sow for pigs). Therefore, the biogas yield from manure for each animal type is assumed to remain constant for the different animal sub-types. The lower heating value of biogas is not commonly reported and instead the ranges of chemical components (e.g. $CH_4$, $CO_2$) of biogas from manure are published. However, these ranges are not disaggregated by animal type and sub-type. Therefore, it is assumed that the lower heating value ($MJ/m^3$) of biogas is the same for all animal types and subtypes. It is calculated using Aspen Hysys® at 1 bar and 15°C, based on the methane content in biogas ranging from 50% to 75% by volume (Farret & Godoz Simoes, 2006; Al Seadi, Rutz, Prassl, Köttner, & Finsterwalder, 2008). The probability distributions used are normal for the inventory of animals and EUD for the manure production per head, the biogas yield from manure and the lower heating value.

Forestry and wood industry

The dataset for forestry and wood industry (excluding above-ground biomass) is shown in Table 31 in the Appendix. As mentioned above, the theoretical biomass energy potential is evaluated at two scales: a) including the entire above-ground biomass in forests but excluding protected areas and b) including only the biomass associated with the production of round wood. This dataset allows the calculation of the biomass energy potential associated only with the production of round wood. The volumes of wood fuel, round wood and industrial round wood are taken from FAOSTAT (FAO, 2012b). FAOSTAT does not report the sampling error and therefore some assumptions are taken. It is assumed that the sampling error is equal to that of the current land used for forestry in Colombia, which is available in the National Agriculture Survey of 2009 (DANE, 2009). It is found that the density of wood fuel varies widely depending on the species. Thus, 60 different species of trees producing wood in Colombia are identified based on data from (AENE, 2003) and the corresponding density per species is taken from (IPCC, 2006a). Nevertheless, this density varies widely from 0.33 to 0.87 dry ton per cubic meter. The density of forest field residues was not found in literature. Therefore, it is assumed that density of forest field residues is equal to the density of wood fuel. Similarly, the lower heating value of industrial residual wood is assumed to be equal to that of forest field residues. The probability distributions used are normal for the production of forestry resources (i.e. wood fuel, round wood, etc.) and EUD for the density, the by-product to product ratio and the lower heating value.

Above-ground biomass

The dataset for above-ground biomass calculations is shown in Table 32 in the Appendix. This dataset allows the calculation of the biomass energy potential associated with the above-ground biomass in forests but excluding protected areas. The estimation of overall above-ground biomass found in forests in Colombia is taken from the national inventory of carbon reserves in forests in Colombia by IDEAM (Phillips, et al., 2011), while the estimation only for protected forests is taken from UAESPNN (Corredor, 2011). For each forest type, the IDEAM study reports the area (ha), the biomass yield (dry t/ha) and a normally distributed standard deviation. Similarly, for each forest type, the UAESPNN study reports the size of the protected area (ha) and the biomass yield (dry t/ha). However, this study does not report the variability in biomass yield, therefore some assumptions are made. It is assumed that the coefficient of variability of the biomass yield in protected areas is equal to that of forest areas published by IDEAM (Phillips, et al., 2011). It is also assumed that the uncertainty associated with the size of protected areas (ha) can be represented by the sampling error associated with the current land used for forestry in Colombia (DANE, 2009). The uncertainty of the biomass produced in protected areas is then estimated using a model in Oracle® Crystal Ball 11.1.2.1. The biomass produced in forests in Colombia excluding protected areas is calculated and shown in Table 32 in the Appendix. From this biomass two products are produced: round wood and forestry residues. The production fractions for each one are calculated using the data shown in Table 31 in the Appendix, e.g. the fraction of forestry residues per unit of round wood. The probability distributions used are normal for the biomass produced in forests in Colombia excluding protected areas, and EUD for the density, the by-product to product ratio and the lower heating value.

Urban waste

Finally, the dataset for urban waste is shown in Table 33 in the Appendix. The range of production of municipal solid waste (MSW) per capita is taken from various reports published by the Colombian Administration of Public Services (Superservicios, 2009; Superservicios, 2011; Superservicios, 2012). This data is multiplied by the country population in 2010 (taken from the National Administrative Department of Statistics (DANE, 2005)), to obtain the overall production volume of MSW. Subsequently, the MSW volume is used as an input in the Colombia Landfill Gas Model Version 1.0 (MADR, 2012; SCS Engineers, 2010) to estimate the amount of landfill gas that can be generated in landfill applications. The model calculates landfill gas generation by using a first order decay equation, specific data of climate, waste composition and disposal practices in each of the 33 departments in Colombia. It is assumed that the type of landfill is engineered or sanitary, that the start year of the landfill is 2005[5] and that the projected closure year is 2030. The lower heating value of the landfill gas is estimated using Aspen Hysys® at 1 bar and 15°C, based on the methane content in landfill gas ranging from 30% to 60% by volume (Al Seadi, Rutz, Prassl, Köttner, & Finsterwalder, 2008; CREDP, 2010; Dudek, Klimek, Kolodziejak, Niemczewska, & Zaleska Bartosz, 2010). The production volumes of residues from the wholesale food market and pruning are only available in one reference, i.e. (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011). Based on personal communication with experts on waste disposal in Colombia, it was assumed that these production volumes might vary within a range of ±15% similarly to the variability of MSW production. EUD distributions are used for all the variables related to urban waste.

### C.4.3.1. Preliminary calculation of the theoretical biomass energy potential

The theoretical biomass energy potential is calculated using the method described in Section C.3 and the datasets shown in Table 29 to Table 33 in the Appendix as inputs. The uncertainty calculation and sensitivity analysis in this investigation are conducted in Oracle® Crystal Ball 11.1.2.1 using 50,000 trials and a Latin Hypercube sampling methods using 1,000 bins. Results for the theoretical potential including and excluding above-ground biomass in forests are shown in Table 2. As mentioned before, the results for the theoretical potential including the above-ground biomass are shown only for comparative purposes. Results for theoretical potential including the above-ground biomass show the vast potential (220 EJ) of forestry resources in the country. However, most of this potential is associated with tropical forests, which from a sustainability and ecological point of view is prohibitive.

There is a large uncertainty in this estimation (±46%), partly as a result of a considerable uncertainty in the prediction of the above-ground biomass in forests in the country (±23%). In comparison, the theoretical potential including only the forestry resources associated with the current wood exploitation is three orders of magnitude lower (0.75 EJ) and with a lower associated uncertainty (±19%). The theoretical potential excluding above-ground biomass is considered more attainable and is further used to calculate the technical biomass energy potential. The categories that contribute the most to this theoretical potential include agricultural residues with 52.8%, forestry residues with 25.2% and animal waste with 20.6%. The contribution from urban waste is marginal and accounts for 1.3% of the theoretical potential.

A sensitivity analysis using the propagation of uncertainty is performed to the preliminary theoretical potential and results are shown in Figure 8. Results indicate that in a model of 116 variables, 11 contribute to nearly 90% of the uncertainty: the density of wood fuel (44%), the by-product to product ratio of forestry residues (13%), the LHV of biogas from manure (6%), the moisture of cane leaves and tops (6% for large-scale and 5% for small-scale), the biogas yield from cattle manure (6%), the manure production for cattle > 36 months (5%), the by-product to product ratio for cane leaves and tops (2% for large-scale and 1% for small-scale) and finally the LHV for wood fuel (2%) and cane leaves and tops (1%).

These variables can be grouped into parameters describing: a) forestry residues (density, by-product to product ratio and LHV), b) cattle manure (LHV, biogas yield, manure production) and c) cane leaves and tops (moisture, by-product to product ratio and LHV). A more thorough search of literature is performed for these groups of variables aiming at improving their estimation and reducing the associated uncertainty. This procedure is shown in next section.

### C.4.3.2. Re-calculation of the theoretical biomass energy potential

First, a more thorough search of literature is performed for the following groups of variables: forestry residues, cattle manure and cane leaves and tops. A root cause analysis is then carried out to identify sub-components affecting key variables (see Figure 9). Then, further disaggregation of variables into spatial or temporal sub-models is performed. Sub-models include: a dedicated model of the forest residues disaggregated by specie and geographical region, a model of the production of bagasse and cane residues (both for sugar cane and jaggery cane) disaggregated by cane variety and region and a model of palm oil residues disaggregated by region. For simplicity, a general description of the mathematical framework of sub-models is presented only for forest residues, but can be flexibly extended to the other sub-models.

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[5] Resolution 1045 and 1390 from Ministry of Environment, Housing and Territorial Development forbid the use of unmanaged waste disposal sites in Colombia as of 2005.

***Table 2.*** *Results of the theoretical biomass energy potential including and excluding above-ground biomass in forests*

| **Biomass categories** | **Theoretical potential including above-ground biomass** | | | **Theoretical potential excluding above-ground biomass** | | |
|---|---|---|---|---|---|---|
| | **Mean (EJ)** | **Confidence interval (95% probability)** | | **Mean (EJ)** | **Confidence interval (95% probability)** | |
| Agricultural residues | 0.40 | -14.9% | 17.4% | 0.40 | -14.9% | 17.4% |
| Animal waste | 0.15 | -31.1% | 40.5% | 0.15 | -31.1% | 40.5% |
| Forestry | 219.32 | -45.4% | 46.3% | 0.19 | -48.7% | 61.1% |
| Urban waste | 0.01 | -35.7% | 40.4% | 0.01 | -35.7% | 40.4% |
| Total | 219.88 | -45.5% | 46.0% | 0.75 | -17.0% | 19.3% |

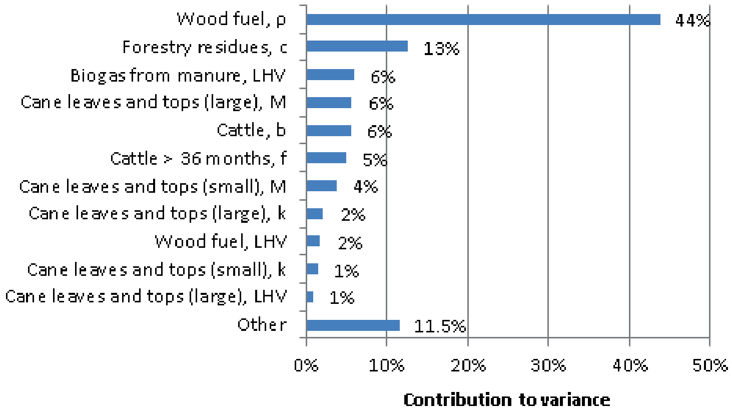


***Figure 8.*** *Sensitivity analysis for the theoretical biomass potential excluding above-ground biomass in forests*

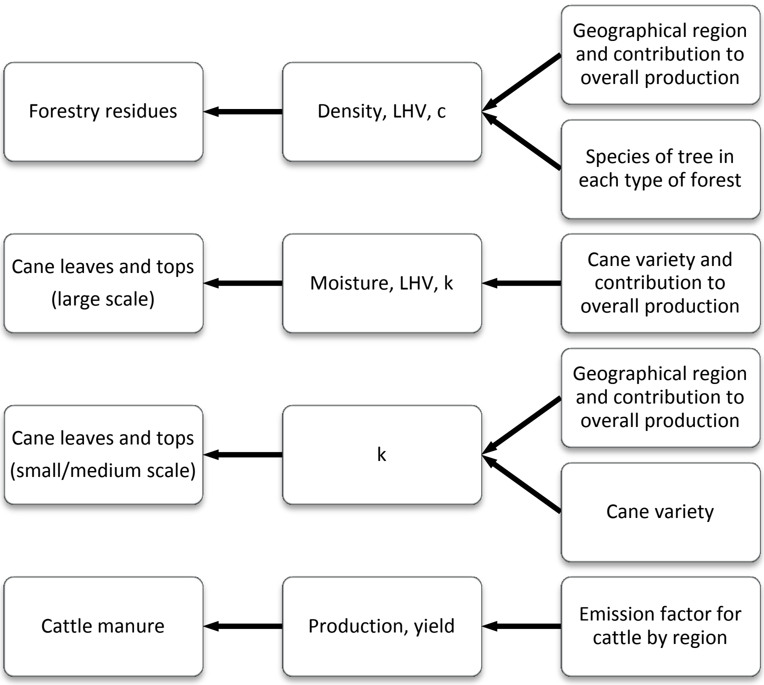


***Figure 9.*** *Root cause analysis to identify sub-components affecting key variables to the theoretical potential*

### Forestry residues

AENE reports the species of trees, the biomass yields, the residue to product ratio and the area covered with forest disaggregated by geographical region (AENE, 2003). The computation of the weighted mean of the density and the residue to product ratio is proposed:

Eq. 16 $$\bar{\rho} = \sum_r (\rho_r) \cdot (w_r) = \sum_r f\left(\rho_{r,s1}, \rho_{r,s2}, \dots, \rho_{r,sn}\right) \cdot \left(\frac{PW_r}{\sum_r PW_r}\right)_r$$

Eq. 17 $$\rho_r = f\left(\rho_{r,s1}, \rho_{r,s2}, \dots, \rho_{r,sn}\right)$$

Eq. 18 $$\overline{RTP} = \sum_r (RTP_r) \cdot (w_r) = \sum_r (RTP_r) \cdot \left(\frac{PW_r}{\sum_r PW_r}\right)_r$$

Where $\bar{\rho}$ is the weighted mean of the density, $\rho_r$ is the density of wood fuel in a particular geographical region *r*, $\rho_{r,s}$ is the density of wood fuel of specie of tree *s* (1,2,…,n) in a region *r*, $\overline{RTP}$ is the weighted mean of the residue to product ratio, $RTP_r$ is the residue to product ratio in a region *r*, $w_r$ is the weight factor and $PW_r$ is the potential production of wood fuel by region as defined by AENE in (AENE, 2003). According to prior art, the country can be divided into thirteen geographical regions according to type of forest (AENE, 2003). In these regions, more than 60 tree species are typically used for wood production. The density of wood fuel in a particular region ($\rho_r$) is a function of the density of the different species of trees in that region $\rho_r = f\left(\rho_{r,s1}, \rho_{r,s2}, \dots, \rho_{r,sn}\right)$ and is defined with a discrete probability distribution. This distribution assigns the same probability of occurrence to the densities of each of the different species of trees existing in that particular region (densities are taken from (IPCC, 2006a)). Then, the regional density of wood is weighted by its contribution to the overall potential wood fuel production (taken from AENE in $m^3$ (AENE, 2003)). Finally, the weighted mean is computed. The procedure to estimate the weighted mean of the residue to product ratio is similar, although ranges of data are not available per specie but per region. Thus, an EUD distribution is employed to define the residue to product ratio by region ($RTP_r$). The data used to calculate the weighted mean of these parameters is shown in Table 34 in the Appendix, and the results of the estimated weighted mean for the density and the residue to product ratio are shown in Figure 99 in the Appendix.

### Cane residues on a large-scale

Sugar cane for large-scale production of sugar and bioethanol is concentrated in ~200 kha in the Valley of the Cauca River. Data disaggregated by cane variety and composition of residues is published by the Research Center on sugar cane (Cenicaña) and the Federal Association of sugar cane growers (Asocaña). Calculation of the mean of the by-product to crop ratio weighted by cane variety is proposed along with the mean of the moisture and LHV of leaves and tops weighted by the composition of the residue. The procedure used is similar to the one described above for forestry residues.

The contribution per cane variety to the harvested area and the corresponding range of by-product to crop ratio are shown in Figure 101 in the Appendix. An EUD distribution is assigned to the by-product to crop ratio for each sugar cane variety and is then weighted by the corresponding contribution to the harvested area. The result of the weighted mean of the by-product to crop ratio is also shown in Figure 101. On the other hand, disaggregation of the data on cane leaves and tops by the type of residue (i.e. dry leaves, green leaves and tops) is proposed to estimate the weighted mean of moisture and LHV (see Figure 102 in the Appendix). Value ranges of mass fraction, moisture and LHV for cane leaves and tops is based on data published by (Cenicaña, 2006a) in Colombia and UNDP-CTC in Brazil (Hassuani, Leal, & Macedo, 2005). EUD distributions are then assigned to the moisture and LHV for each type of residue and weighted by the mass fraction.

### Cane residues on a small- and medium-scale

Sugar cane for small- and medium-scale production of jaggery covers more than 200 kha, but it is highly spread across the country. Disaggregation of the production of cane on a small and medium scale by variety and region is proposed, followed by the computation of the weighted mean of the by-product to product ratio (see Figure 103 in the Appendix). The procedure used is similar to the one described above for other residues.

First, the different varieties of cane are identified for each region. The by-product to product ratio in a particular region is defined with a discrete probability distribution. This distribution assigns the same probability of occurrence to the ratios of each of the different cane varieties existing in that particular region. The by-product to product ratio for the different cane varieties is taken from (Cenicaña, 2006a; Universidad de Pamplona & Corpoica, 2012). The regional by-product to product ratio is then weighted by its contribution to cane production (taken from the Ministry of Agriculture and Rural Development (MADR, 2012)). Finally, the weighted mean is computed. As the composition of residues does not widely vary for different cane varieties (Cenicaña, 2006a), it is assumed that the moisture and LHV of leaves and tops for small-scale cane is equal to those of large-scale cane.

### Cattle manure

In 2009, the Institute for Hydrology, Meteorology and Environmental Sciences (IDEAM) published a study that inventoried the sources and sinks of greenhouse gas emissions in Colombia. This study provides a methane emission factor for cattle (kg $CH_4$ / head /year) from enteric fermentation disaggregated by region (Nieves & Olarte, 2009), which allows the possibility of directly estimating the energy potential. Therefore, the multiplication of these emission factors by the amount of cattle heads in each region is proposed in order to obtain the overall theoretical potential. According to IDEAM, the uncertainty in the prediction of the emission factors is normally distributed with a coefficient of variation of 22.63% (Castillo Díaz, 2009). On the other hand, according to the National Agriculture Survey of 2009 (DANE, 2009), the uncertainty in accounting the cattle heads is also normally distributed with a coefficient of variability of 2.3%, as already shown in Table 30 in the Appendix. The theoretical potential associated with cattle manure is then calculated (not shown) and totals 0.129 EJ with a confidence interval of ±15.8% (95% probability).

Preliminary vs. recalculated theoretical potential

The theoretical potential is recalculated using the improved estimated parameters discussed above. Results are then compared to the preliminary estimation and shown in Table 3 and in Figure 14. It can be observed that while both estimations have an almost identical mean, the uncertainty associated with the recalculated estimation is significantly lower. In fact, the preliminary calculation estimates a theoretical potential of 0.748 EJ with a C.I. of -17.0%, 19.3% (slightly positively skewed), while the recalculated evaluation estimates a theoretical potential of 0.744 EJ with a C.I. of -7.2%, 7.8%. A particular reduction in uncertainty is obtained for the categories of forestry, animal waste and agricultural residues. Results also show the effectiveness of the sensitivity analysis followed by an improved estimation of key parameters.

## C.4.4. Calculation of the technical biomass energy potential

The technical biomass energy potential is calculated at current conditions and constraints following the method explained in Section C.3.1.2.

The technical potential for each biomass category is obtained by multiplying the theoretical potential by the corresponding availability factor. The availability factor for these biomass resources is evaluated considering various constraints and excluding the fraction that is already used for energy production (heat, CHP, etc.). Firstly, the availability factors and the technical biomass energy potential are preliminarily calculated. Key parameters are then identified through a sensitivity analysis. Subsequently, estimation of key parameters is improved through a thorough data search and disaggregated into sub-models in a similar manner as that shown for the theoretical potential in Section C.4.3. Finally, the availability factors and the technical potential are recalculated. The following sections discuss the methods to preliminarily estimate and recalculate the technical biomass energy potential.

### C.4.4.1. Preliminary calculation of the technical biomass energy potential

Most agricultural residues are currently used for animal feed, soil fertilization and to provide heat (see Table 35 in the Appendix). One special case is sugar cane on a large scale, in which bagasse is used to provide heat and power to the sugar and bioethanol industry (UPME, 2011b). Only rachis of the palm oil tree, cane leaves and tops (large-scale) and rice husk are potentially available for energy production. The rachis or empty fruit bunch (EFB) is a solid residue from the palm oil tree resulting from the processing mills. The use of rachis varies widely by field and by region in Colombia (BID-MME, Consorcio CUE, 2012). In some fields it is completely left on the field for mulching, while in others it is partially or totally collected for various purposes (composting, burning in boilers, etc.). In the scientific literature, various studies show availability factors ranging from 0 to 100% and compare the use of rachis for mulching to replace fertilizers and for energy production (Panapanaan, Helin, Kujanpää, Soukka, Heinimö, & Linnannen, 2009; Schmidt, 2007).

***Table 3.*** *Preliminary vs. recalculated theoretical potential*

| **Biomass categories** | **Theoretical potential (preliminary)** | | **Theoretical potential (recalculated)** | |
|---|---|---|---|---|
| | **Mean (EJ)** | **C.I. (95%)** | **Mean (EJ)** | **C.I. (95%)** |
| Agricultural residues | 0.396 | -14.9%, 17.4% | 0.394 | -9.0%, 9.3% |
| Animal waste | 0.154 | -31.1%, 40.5% | 0.176 | -14.1%, 14.6% |
| Forestry | 0.189 | -48.7%, 61.1% | 0.164 | -17.9%, 23.4% |
| Urban waste | 0.010 | -35.7%, 40.4% | 0.010 | -35.7%, 40.2% |
| Total | 0.749 | -17.0%, 19.3% | 0.744 | -7.3%, 7.8% |

The availability factor of rachis is preliminarily estimated through a uniform distribution with limits of between 0-100%. About 70% of the cane fields in Colombia are currently burned before harvesting to facilitate the collection of stalks (BID-MME, Consorcio CUE, 2012). After harvesting, the remaining burned residues (leaves, tops, etc.) are left on the field for soil replenishment, while stalks are transported to the mill. If cane were unburned, part of the cane leaves and tops might be available for energy production. In literature, availability factors accounting for the fraction of residues that should be left on field range from 0-50% (Hassuani, Leal, & Macedo, 2005; BID-MME, Consorcio CUE, 2012; Pankhurst, 2005). Thus, the preliminary availability factor for cane leaves and tops is described by an EUD distribution using 0-50% as limits. Rice husk is currently used as a fertilizer in the flower industry and as a feedstock in poultry sheds. AENE reports that only large mills producing more than 100 tons of husks daily can afford the costs of exploiting rice husk for energy production (AENE, 2003). 44% of the production of husk corresponds to mills with these characteristics. Therefore, the preliminary availability factor for rice husk is described as an EUD distribution using 0-44% as limits.

In the category of animal waste, manure from poultry is currently used as a fertilizer in agricultural crops and is not expected to be available in the short-term. Manure from equine is currently wasted but it is not expected to become available for energy generation given its decentralized production. Manure from cattle and pork is currently wasted and might be potentially used for energy purposes (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011; Arias Chalico, et al., 2009). Data on the availability of manure from cattle or pork in Colombia is scarce. As a preliminary estimation, EUD distributions are created using the limits shown in (Gonzalez-Salazar, et al., 2013). The preliminary availability factor for manure from cattle is described by an EUD distribution using 11.7-23.5% as the limits, while for manure from pork another EUD distribution uses 7-14.5% as the limits.

In the category of forestry and wood industry, significant availability is expected from forestry residues. Forestry residues are currently left for soil replenishment or simply as waste (AENE, 2003), whereas industrial residual wood is a marketable by-product not currently available. The availability factor for forestry residues ranges in literature from 0% to 50% (AENE, 2003; Arias Chalico, et al., 2009; Kline, Oladosu, Wolfe, Perlack, Dale, & McMahon, 2008). Therefore, the preliminary availability factor for forestry residues is described by an EUD distribution using 0-50% as limits.

In the category of urban waste, residues from pruning and from the wholesale food market are currently used for animal feed and are not considered available. Landfill gas is currently produced in waste disposal sites and is either flared or vented. The availability of landfill gas depends mainly on the technical characteristics of the landfill site, including site management practices, collection system coverage, waste depth, cover type and extent, landfill liner, etc. (SCS Engineers, 2010). SCS Engineers estimate that the collectability of landfill gas ranges between 50-90%. Thus, the technical constraint factor is described by an EUD distribution using these limits.

The preliminary biomass energy technical potential is then calculated in Oracle® Crystal Ball 11.1.2.1 using 50,000 trials and a Latin Hypercube sampling methods using 1,000 bins. Results of the preliminary estimation of the technical biomass energy potential and its associated sensitivity analysis are shown in Table 4. The preliminary technical potential totals 78,607 TJ with an uncertainty of -36%, +39% which is significantly high. Results of the sensitivity analysis by propagation of uncertainty show that four parameters account for 85% of the overall uncertainty (see Figure 10). The four parameters are the availability of forestry residues (43%), availability of cane leaves and tops (25%), availability of rachis (9%) and availability of cattle manure (9%). In order to better estimate these parameters, a more thorough search of literature is combined with the development of more detailed sub-models.

***Table 4.*** *Preliminary technical biomass energy potential and associated uncertainty*

| **Biomass categories** | **Preliminary technical potential** | | |
|---|---|---|---|
| | **Mean (TJ)** | **Confidence interval (95% probability)** | |
| Agricultural residues | 25642 | -67% | 76% |
| Animal waste | 23202 | -37% | 41% |
| Forestry | 23040 | -73% | 92% |
| Urban waste | 6722 | -46% | 60% |
| Total | 78607 | -36% | 39% |

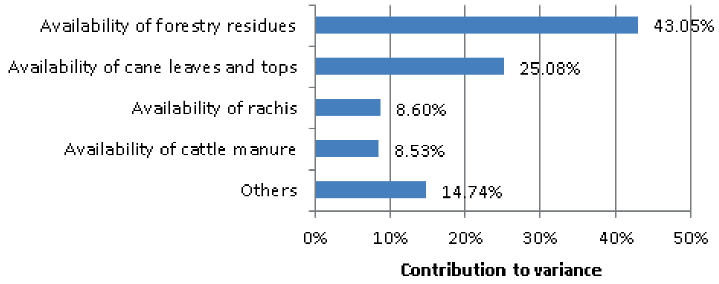


***Figure 10.*** *Sensitivity analysis for the preliminary technical biomass energy potential*

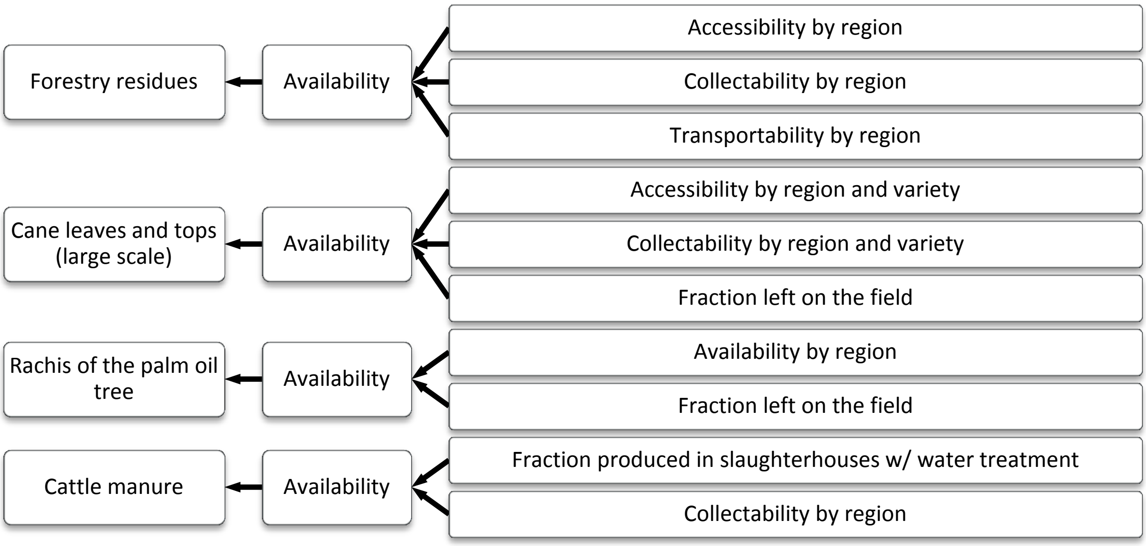


***Figure 11.*** *Root cause analysis to identify sub-components affecting key variables to the technical potential*

### C.4.4.2. Re-calculation of the technical biomass energy potential

The application of the method to better estimate the parameters that mostly influence the overall uncertainty (availability factors of forestry residues, cane leaves and tops, rachis of the palm oil tree and cattle manure) is documented below. The procedure to estimate the availability factor for the different biomass resources follows the same guidelines as those described for the theoretical potential, e.g. disaggregate variables into spatial or temporal sub-models.

Rachis of the palm oil tree

The use of rachis varies widely by field and by region in Colombia (BID-MME, Consorcio CUE, 2012). In some fields it is completely left on the field for mulching, while in others it is partially or totally collected for various purposes (composting, burning in boilers, etc.). The fraction of rachis not employed for mulching is defined as a special constraint factor and the use of a discrete distribution per region is proposed to estimate it. This distribution assigns the same probability of occurrence to the different availability factors reported in (BID-MME, Consorcio CUE, 2012) by field for different regions. On the other hand, rachis is not available in all regions and a geographical constraint factor is required. This factor is estimated as the fraction of the total harvested area in which rachis residues are available. It accounts for the harvested area in the eastern region (98,500 ha), the northern region (99,000 ha) and the central region (66,300 ha) but excludes the western region (20,530 ha) due to unreliable production, as described in (BID-MME, Consorcio CUE, 2012). The calculated geographical constraint factor is 0.93 ± 0.01 (95% prob.), which takes into account a coefficient of variation of 5% for the estimation of the regional harvested area (taken from Table 29 in the Appendix). The improved availability factor of rachis is shown in Figure 104 in the Appendix.

Cane leaves and tops (large-scale)

The availability of cane leaves and tops depends on technical, environmental and other special constraints. Firstly, not all the fields can be harvested with machines that collect cane leaves and tops. Today, 33% of the total area is harvested with machines (BID-MME, Consorcio CUE, 2012) and Cenicaña estimates that up to 98% of the area is suitable for mechanical harvesting (Cenicaña, 2006a). Thus, the technical constraint factor is described by an EUD distribution using 33% and 98% as limits.

Secondly, part of the cane leaves and tops should be left on the field for soil replenishment and agronomic purposes. In literature it is reported that 70-100% of the cane leaves and tops should be left on the field (Hassuani, Leal, & Macedo, 2005). The environmental constraint factor is then described by an EUD distribution using 0-30% as limits. Thirdly, some cane varieties and particularly the variety V 71-51 (a variety developed in Venezuela) have very large by-product to crop ratios that complicate the collection of residues with harvest machines (Cenicaña, 2006a). The special constraint factor estimates the fraction of the total cane fields that are not cultivated with the variety V 71-51. This factor is then described by an EUD distribution using the minimum and maximum areas apart from variety V 71-51 in the last five years reported by (Cenicaña, 2012). The improved availability factor of cane leaves and tops is shown in Figure 104 in the Appendix.

Cattle manure

The cattle industry is widely spread across the country, which complicates the collection and exploitation of manure for energy purposes. However, it is technically feasible to collect and exploit manure in slaughterhouses. The technical availability factor is the fraction of manure produced only in slaughterhouses. First, the number of sacrificed animals and its normally distributed uncertainty is taken from (MADR, 2012). The manure produced in slaughterhouses by region is then estimated following the method described in Section C.4.4.1 and compared to the corresponding regional manure production. The result is a normal distribution with a mean of 0.13 ± 0.01 (95% probability). The special constraint factor relates to the fraction of slaughterhouses having water treatment plants to treat manure. It is estimated by region based on technical and regional data reported in (CNPML, 2009). The resulting curve is a beta probability distribution with a mean of 0.91, a minimum of 0.73, a maximum of 0.99, $\alpha = 12.14$ and $\beta = 5.352$. The improved availability factor of manure from cattle is shown in Figure 104 in the Appendix.

Pork manure

The availability factors for pork manure are calculated using the same procedure as for cattle manure. The technical constraint factor is the fraction of manure produced only in slaughterhouses and is described by a normal distribution with a mean of 0.6 ± 0.04 (95% probability). A special constraint factor describes the fraction of manure that can be collected in slaughterhouses through a manure management system, which is described by a normal distribution with a mean of 0.97 ± 0.01 (95% probability).

Forestry residues

Forestry residues are currently left on the field for soil replenishment or simply as waste. The availability of these residues depends on geographical, technical and special constraints. The geographical constraint factor relates to the fraction of residues that are accessible. Accessibility widely varies by region as described by (AENE, 2003). The geographical constraint factor is then calculated as the weighted mean of accessibility factors by region using AENE data. The result is a trapezoidal probability distribution with a min = 0.91, max = 1, and modes 0.94 and 0.97. The special constraint factor relates to the fraction of residues that can be collectable. It is calculated as the weighted mean of the collectable fraction of residues by region, with a collectable fraction of 0.4-0.9 in forest plantations and of 0.4-0.5 in forests. The result is a non-uniform distribution (Figure 100) ranging between 0.51 and 0.64. Finally, the technical constraint factor relates to the fraction of residues that can be transported by road given a constrained transport capacity by region. It is calculated as the weighted mean of the transportable fraction of residues by region. First, the production of forestry residues is disaggregated by region. The transport capacity by region reported by the Ministry of Transport (MinTransporte, 2005) is then used to estimate the transportable fraction of residues. The result is a normal probability distribution with a mean of 0.47 ± 0.06 (95% probability). The improved availability factor of forestry residues is shown in Figure 104 in the Appendix.

Preliminary vs. recalculated technical potential

The technical potential is recalculated using the improved estimated parameters discussed above and compared to the preliminary estimation (see Table 5 and Figure 14). Results for the recalculated potential (58,904 TJ) are 25% lower than results for the preliminary potential (78,607 TJ). In addition, the uncertainty associated with the recalculated case is significantly lower (-22%, +24%) than that of the preliminary case (-36%, +39%). This is a consequence of better estimation of the availability factors, which after a thorough literature search and improved models tends to be lower and with a smaller associated uncertainty than in the preliminary estimation. While an important reduction in uncertainty is obtained particularly for the categories of animal waste (from 37-40% to 19%) and forestry residues (from 73-92% to 29-37%), this reduction is marginal for agricultural residues (from 67-76% to 60-69%). One of the reasons for this marginal reduction is the large uncertainty in estimating the volume of residues currently used for non-energy purposes, which is the case of the rachis of the palm oil tree. Nevertheless, results also show the effectiveness of the sensitivity analysis followed by an improved estimation of key parameters.

### C.4.5. Calculation of the current biomass energy utilization

The current biomass energy utilization is estimated as the theoretical potential associated with certain biomass categories used for energy production. These categories include cane bagasse on a large- and small-scale, stone and fiber of the palm oil tree and wood fuel (see Figure 13). It totals 211 PJ with a confidence interval of -11.4%, +12.5% at 95% probability.

### C.4.6. Re-evaluation of other studies

Results of other studies were re-evaluated using the method explained before and the published assumptions. Information from the dataset presented in Section C.4.3 and in the Appendix has been employed in cases where the method or assumptions used by the different reports are either not published or inconsistent. Examples include the calculation method used in the AENE and UPME report as well as some assumptions in the reports by Escalante et al., Arias et al. and Kline et al. Results are reported in Figure 12 and Figure 13. According to the hypotheses made, this study predicts a mean theoretical energy potential of 0.744 EJ with a confidence interval of -7.3%, +7.8% at 95% probability. This value is higher than the re-evaluated results of other studies. The main reasons for a higher estimation include: 1) this study includes agricultural residues, animal waste, forestry and urban waste, while most former studies evaluated only three of these categories, 2) this study includes both wood fuel and forestry residues, while previous reports considered one of the two and 3) it assesses the potential for a more recent year (2010) compared to some of the previous studies. Most relevant categories for the theoretical biomass energy potential include agricultural residues (53%), forestry and wood industry (22%) and animal waste (24%). Contribution from urban waste is marginal and accounts for 1% of the theoretical potential.

The predicted maximum technical potential is 58,984 TJ with a confidence interval of -22%, +24% at 95% probability. The most relevant biomass categories for the technical potential are agricultural residues (29%), forestry (31%) and animal waste (29%), while urban waste contributed to the remaining 11%. The estimated technical potential is lower than three of the four existing studies due to various reasons. Firstly, this study does not include the potential of biofuels (secondary energy resources/carriers). Secondly, biomass resources that currently compete with other uses are not accounted. Thirdly, it attempts at describing more accurately the availability factors for the different biomass resources, which resulted in lower values compared to Arias et al. and AENE. Re-evaluated results from other studies do not always match published results. The main reason for this discrepancy can be attributed to the use of different assumptions and methodologies that were not originally available in previous reports.

A notable mismatch is found for the predictions of AENE and Arias et al. (for the latter, particularly in the category of animal waste). In summary, compared to prior art, the theoretical biomass energy potential estimated in this study might be considered all-embracing, while the estimated technical biomass energy potential might be considered fairly conservative. The current biomass energy utilization estimated in this study (211 PJ) is higher than three of the existing studies but is very similar to the official value (209 PJ) reported by the Mining and Energy Planning Unit (UPME). The estimated current biomass energy utilization accounts for 4.2% of the current primary energy supply (4.93 EJ). This contribution can increase to 5.47% (270 PJ) by exploiting the technical potential. Moreover, the amount of biomass not available for energy production at current conditions and constraints totals 479 PJ, which is 64% of the technical biomass energy potential in the country (excluding above-ground biomass in forests).

## C.5. Summary and discussion

This chapter presents a method of estimating the biomass energy potential and its associated uncertainty at a country level when quality and availability of data are limited. The proposed method is a bottom-up resource-focused approach with statistical analysis that uses a Monte Carlo algorithm to stochastically estimate the theoretical and the technical biomass energy potential. It includes a proposed approach to quantify uncertainty combining a probabilistic propagation of uncertainty, a sensitivity analysis and a set of disaggregated sub-models to estimate the reliability of predictions and reduce the associated uncertainty.

The current biomass energy potential in Colombia is assessed following the proposed method and results are compared to existing assessment studies. Obtained results show that it is possible to envision a theoretical energy potential of 0.744 EJ with a confidence interval of -7.3%, +7.8% at 95% probability, which might be considered all-embracing. However, this potential excludes the above-ground biomass in forests. If above-ground biomass in forests is included, then the theoretical potential can grow to 219.88 EJ. However, a high uncertainty in this estimation is evidenced by a confidence interval of -45.5%, +46.0% at 95% probability.

***Table 5.*** *Preliminary vs. recalculated technical potential*

| Biomass categories | Preliminary technical potential | | Recalculated technical potential | |
|---|---|---|---|---|
| | **Mean (TJ)** | **C.I. (95%)** | **Mean (TJ)** | **C.I. (95%)** |
| Agricultural residues | 25642 | -67%, 76% | 16854 | -60%, 69% |
| Animal waste | 23202 | -37%, 41% | 17229 | -19%, 19% |
| Forestry | 23040 | -73%, 92% | 18185 | -29%, 37% |
| Urban waste | 6722 | -46%, 60% | 6716 | -45%, 60% |
| Total | 78607 | -36%, 39% | 58984 | -22%, 24% |

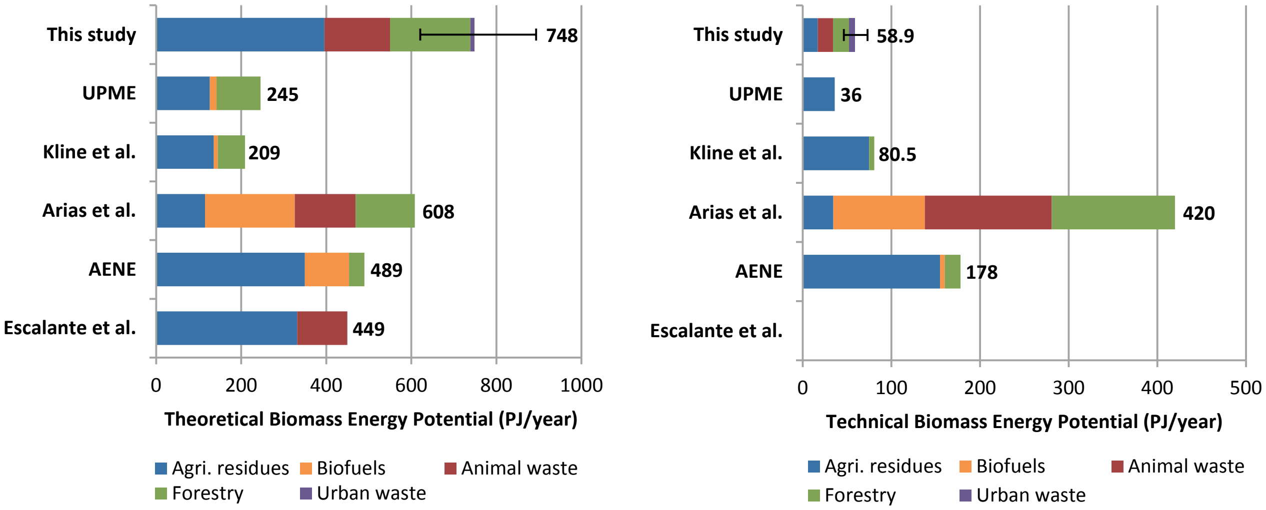


***Figure 12.*** *Comparison of the theoretical and technical biomass energy potential (C.I. of 95% probability)*

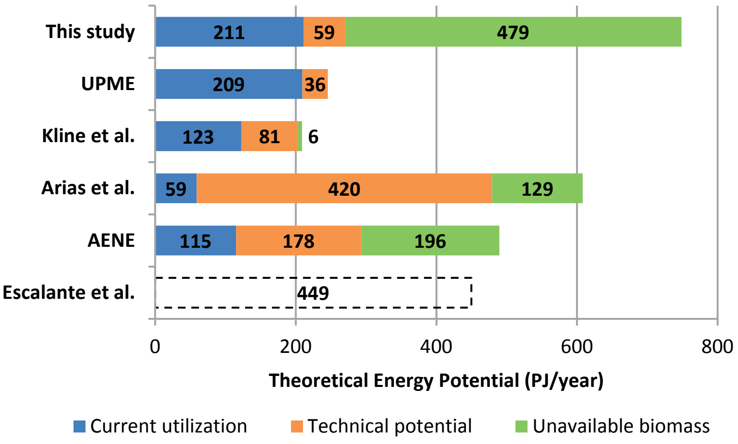
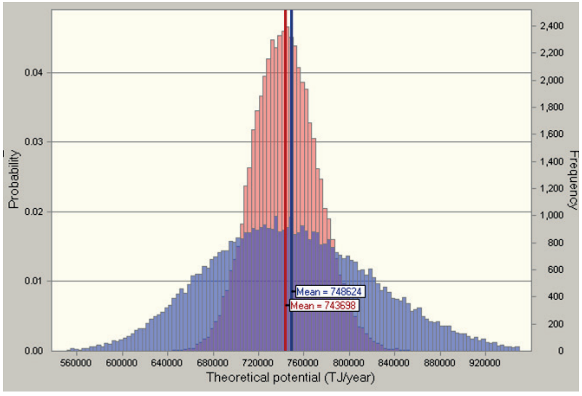
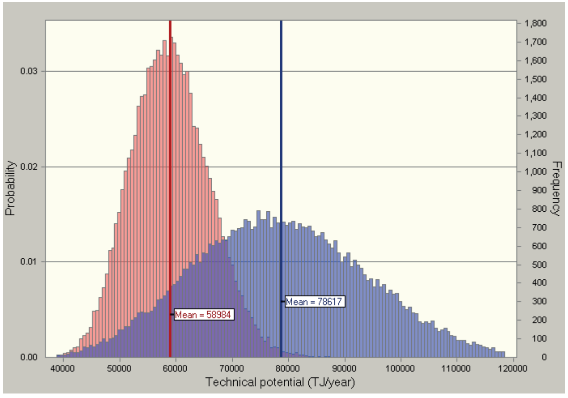


***Figure 13.*** *Comparison of the current biomass energy utilization and the technical potential*

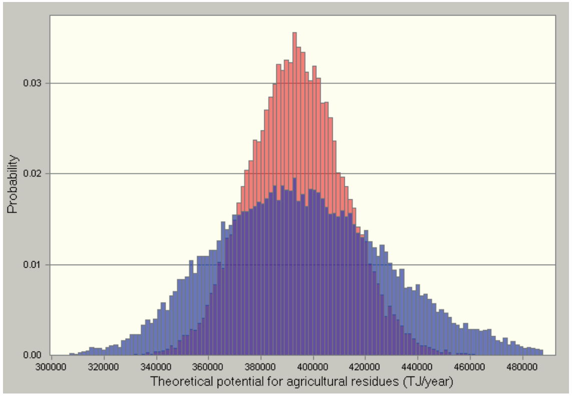
**Overall theoretical potential**



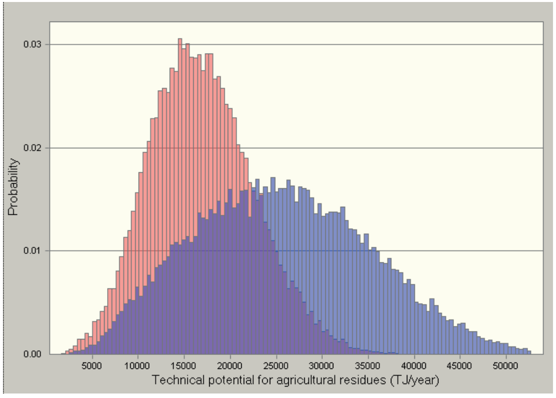
**Overall technical potential**



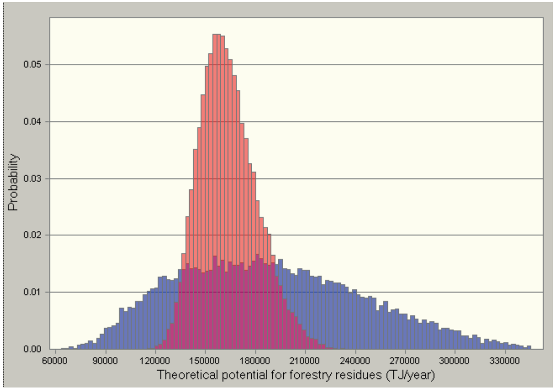
**Theoretical potential for agricultural residues**



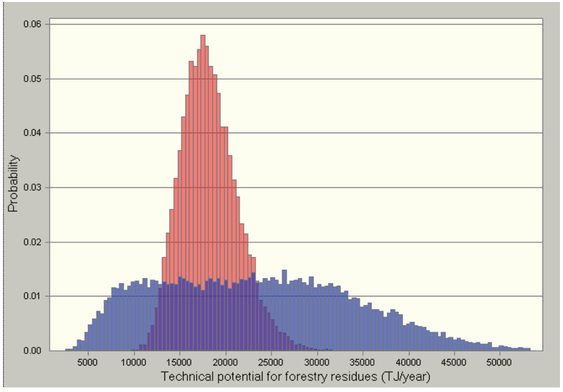
**Technical potential for agricultural residues**



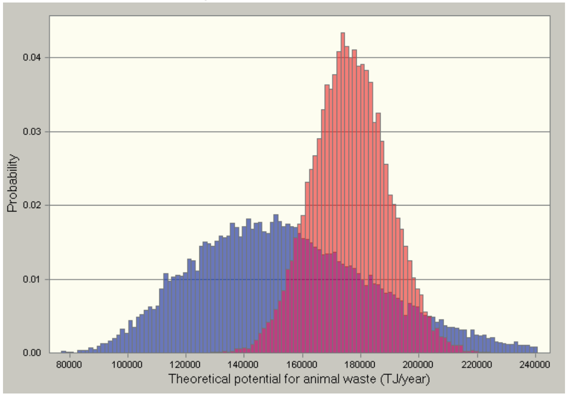
**Theoretical potential for forestry residues**



**Technical potential for forestry residues**



**Theoretical potential for animal waste**



**Technical potential for animal waste**

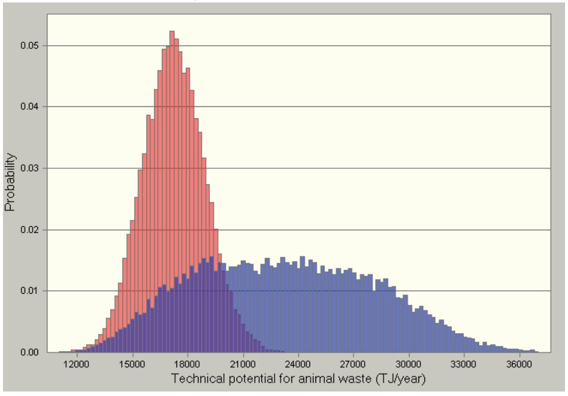


***Figure 14.*** *Theoretical (left) and technical biomass energy potential (right) for different biomass categories. Blue areas describe the preliminary estimation, while read areas describe the improved estimation.*

The predicted maximum technical potential is about 59,000 TJ with a confidence interval of -22%, +24% at 95% probability. The effectiveness of the proposed method was proved by significantly reducing the uncertainty in predicting the theoretical and the technical biomass energy potential.

Results from previous studies are re-evaluated and compared following the proposed method. Despite large differences in results, there is agreement across studies that most relevant biomass categories include agricultural residues, residues from forestry and wood industry and animal waste. As a conclusion, this chapter provides a complete and detailed framework for estimating the biomass energy potential at a country level and is applied to a case study of Colombia. This method is characterized by its transparency, reproducibility, low cost and possible adaptability to other countries. Various aspects require further attention in future work, e.g. scenario analysis to understand the influence of technology deployment on the technical potential, as well as dedicated measurement campaigns to assess the availability of biomass resources (e.g. rachis of palm oil tree, cane leaves at tops, forestry residues, etc.) on a local scale.

# Chapter D. Method of assessing future biomass energy potential

## D.1. Overview

Global interest in bioenergy as the largest renewable resource today (IEA, 2012c) with the potential to reduce dependency on fossil fuels and decrease greenhouse gas emissions continues to grow. While most R&D activities on bioenergy have so far been carried out in industrialized countries and in few large economies, the largest growth in biomass for power and biofuel production is actually expected in emerging economies and developing countries (Eisentraut, 2010; IEA, 2011b; IEA, 2012c). Despite a vast potential, developing countries face several challenges to using biomass resources sustainably. Hurdles include limited industrial experience, constrained investment in R&D and absence of support policies. Strategic planning is therefore required to ensure that appropriate measures are taken to exploit bioenergy. This chapter deals with one of the critical challenges of strategic planning: how to estimate future biomass energy potential in a country.

Assessing the future biomass energy potential is important not only to understand the magnitude and significance of bioenergy to the future energy mix of a country, but also to analyze associated changes in land use and ecological impacts. Ultimately, it is critical to design sound policies that ensure sustainable operation and environmental benefits. Several reviews have recently compared approaches, methodologies, key drivers and results of future biomass energy potential assessment for different countries (Batidzirai, Smeets, & Faaij, 2012; Thrän, Seidenberger, Zeddies, & Offermann, 2010; Smeets E. , Faaij, Lewandowski, & Turkenburg, 2007; Berndes, Hoogwijk, & Van den Broek, 2003). Most reviews agree that while there is a lack of a widely accepted and systematic approach to estimating future biomass energy potential, an ideal approach should consider demographic data, market data (food, energy, others), land use, macro-economic effects and environmental impacts (Batidzirai, Smeets, & Faaij, 2012; Thrän, Seidenberger, Zeddies, & Offermann, 2010; Smeets E. , Faaij, Lewandowski, & Turkenburg, 2007; Berndes, Hoogwijk, & Van den Broek, 2003; Van Vuuren, Van Vliet, & Stehfest, 2009; Heistermann , Müller, & Ronneberger, 2006; Van Schrojenstein Lantman, Verburg, Bregt, & Geertman, 2011; Gnansounou & Panichelli, 2008). Regarding the country of analysis, the majority of bioenergy assessments target industrialized countries and emerging economies (e.g. BRICS) while a limited number of studies aim at developing countries. Compared to industrialized countries, studies for developing countries are often less comprehensive and offer a limited level of detail in data and analysis (Batidzirai, Smeets, & Faaij, 2012).

The aim of this chapter is to present a method of estimating the future biomass energy potential in countries with domestic markets unable to influence international markets. The proposed method is a combination of resource-focused and demand-driven approaches in which the biomass energy potential is influenced by the demand and land use under different global scenarios selected from literature. The fundamental driver of land use and trade is the maximization of the profit that can be perceived by local actors. Competition is considered at three levels: food vs. biofuels, residues for energy vs. other uses and local production vs. imports, although an exhaustive representation of all economy sectors and international trade is beyond the scope of this study.

Potential advantages of this method include a simple approach that is easy to implement and relies on official statistics and public data. Simultaneously, it offers a significant level of detail in terms of land use, production of commodities and biomass categories compared to existing studies for developing countries. These features are expected to be particularly relevant for countries like Colombia, where no future bioenergy assessments are available.

This chapter is structured as follows: Section D.2 describes the proposed method, modeling approach and optimization algorithm for evaluating future biomass energy potential; assumptions, model validation and results for the particular case of Colombia are presented in Section D.3, and finally a summary and discussion are presented in Section D.4.

## D.2. Method

### D.2.1. State-of-the-art

A literature review of state-of-the-art approaches to estimating biomass energy potential is already presented in Section C.2.1.

### D.2.2. Modeling approach and assumptions

The proposed method is formulated under the following criteria (see introductory chapter): 1) it should be transparent, easy to implement, generic and replicable, 2) it should be inexpensive to adapt to constrained R&D budgets, 3) it should be built in well-known platforms and 4) it should include the maximum number of key elements of the ideal approach to estimating biomass energy potential (i.e. demographic data, market data, land use, macro-economic effects and environmental impacts). These criteria are then utilized to select the most appropriate approach among state-of-the-art methods. Complex methods, which are difficult to implement and reproduce, such as resource-focused spatially explicit analyses are excluded as they do not satisfy the first criterion. All remaining methods satisfy the second and third criterion. After considering the fourth criterion, it appears that resource-focused statistical analysis and demand-driven cost-supply analysis are the methods that offer the maximum number of key elements of an ideal approach (e.g. demographic data, market data, land use, macro-economic effects and environmental impacts, as described in Section D.1). It is therefore concluded that more advantages could be obtained by combining both methods than by selecting either, on the condition that individual drawbacks are mitigated. Consequently, the proposed method is an improved combination of a resource-focused statistical analysis with a demand-driven cost-supply analysis (see Figure 15, which is a representation adapted from (Berndes, Hoogwijk, & Van den Broek, 2003)) which includes demographic and market data, land use and macro-economic effects but excludes environmental impacts at this stage. Proposed improvements and modifications are explained as follows.

Improvement to the resource-focused statistical analysis

A bottom-up statistical analysis is applied to appraise the availability of the different biomass categories as well as to estimate the competition for residues and by-products among energy production and other uses (see more info in Chapter C and in (Gonzalez-Salazar, et al., 2014a)). In addition, the macro-economic influence of global biofuel use on agricultural prices, production and demand is considered through the use of global scenarios selected from literature.

Modifications to the demand-driven cost-supply analysis

Rather than evaluating the cost of supplying biomass for energy purposes, it is proposed to evaluate the cost competitiveness of biomass for different uses (food, wood, biofuels, others) through the use of a land use and trade model whose driver is the maximization of the profit. Competition is considered at three levels: food vs. biofuels, residues for energy vs. other uses and local production vs. imports, although an exhaustive representation of all economy sectors and international trade is beyond the scope of this investigation. For competition between local production vs. imports, goods are assumed to be heterogeneous, which means that imports are imperfect substitutes of local products. Heterogeneity of goods has been modeled under the simplified assumption that the market share of a local product is inversely proportional to its price relative to its competitors, as described in (Argonne National Laboratory, 2007).

For land competition, it has been assumed that land is perfectly substitutable between different uses. Concerning modeling dynamics a recursive dynamic method has been assumed in which previous land-use decisions may influence subsequent ones with time-dependent variables updated exogenously (e.g. population, available area, commodity prices, yields, etc.), as described by (Heistermann , Müller, & Ronneberger, 2006). It is important to mention that since commodity prices, yields and demand are exogenous inputs to the model, the proposed method is only applicable to countries with domestic markets which are unable to influence international markets.

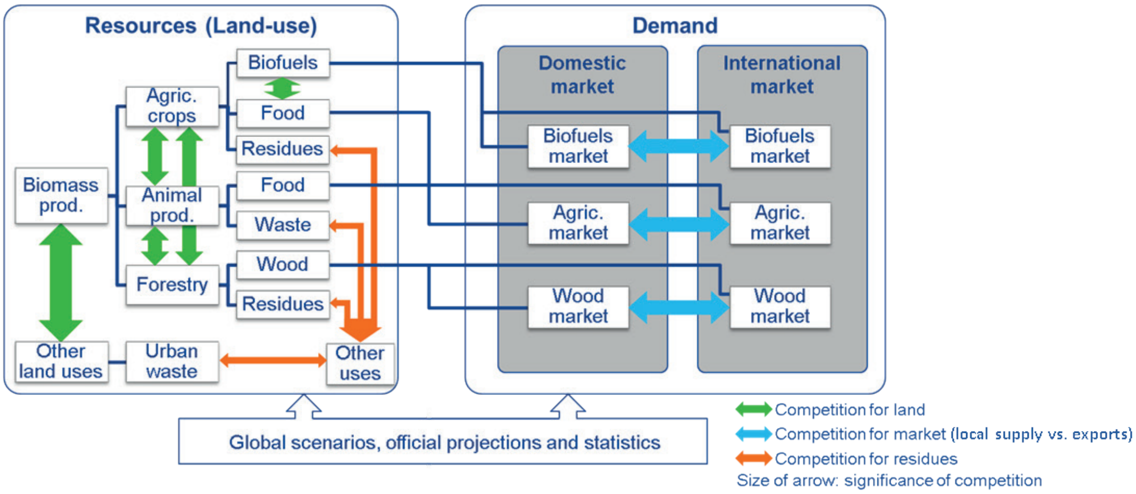


***Figure 15.*** *Method of estimating future biomass energy potential*

Other assumptions considered in this study include:

- The theoretical biomass energy potential, i.e. the amount of energy contained in biomass explicitly excluding biofuels, is calculated as described in detail in Chapter C. In addition, the bioenergy potential, i.e. the amount of energy associated with biofuels, is separately estimated following the guidelines presented in (Gonzalez-Salazar, et al., 2013).
- Local production and import of agricultural commodities are private activities. Therefore, no governmental activity is undertaken. It is assumed that both the local producer and importers are rational, which means that they always attempt to maximize their own profit.
- There are no maximum restrictions to selling commodities in the international market.
- There is enough labor force, fertilizers and capital to produce commodities each year.
- Taxes are not included as profit.

This framework favors a simple, quick but robust implementation over costly, complex and highly detailed approaches. Thus, it is expected that the proposed method is advantageous to countries at an early stage in the process of assessing the future biomass energy potential.

## D.2.3. Information processing

The strategy for processing the information according to the method described above is illustrated in Figure 16. Data is first collected from different sources and grouped into five main categories, i.e. global scenarios, local biofuel scenarios, market data, economic data, and finally technical data and projections. Collected data are exogenous inputs to the optimization model. The optimization model maximizes the yearly profit perceived by local actors according to the model inputs and is subject to certain constraints (more info in Section D.2.4). The optimization is conducted year by year with outputs of year *i* influencing decisions of year *i+1.* It uses a metaheuristic algorithm whose outputs include the production and import of commodities, the land use and the demand for labor and fertilizers. Subsequently, results of local production of commodities and land use are used as inputs to calculate the associated energy potential. The method and assumptions described in Chapter C are used to estimate the theoretical biomass energy potential, while the method presented in (Gonzalez-Salazar, et al., 2013) is employed to estimate the bioenergy potential associated with biofuels (e.g. bioethanol and biodiesel). Finally, a Monte-Carlo algorithm is utilized to compute the sensitivity of results to the input variables.

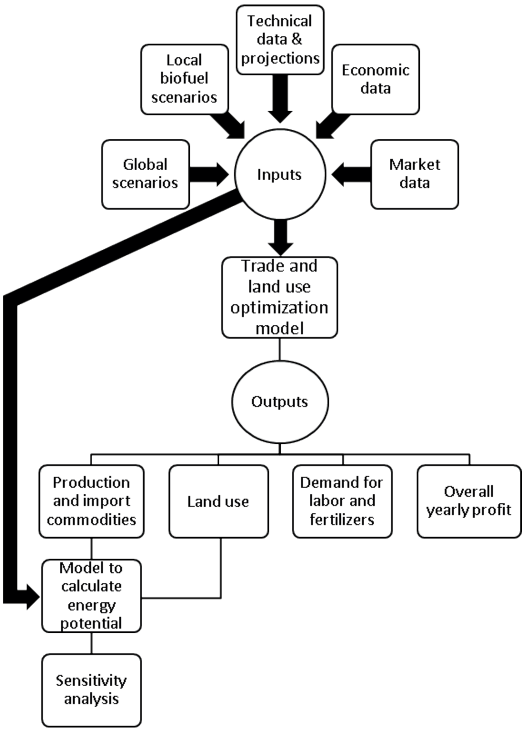


***Figure 16.*** *Proposed method*

## D.2.4. Mathematical formulation

In the proposed method the biomass energy potential is influenced by the demand and land use under different global scenarios selected from literature. The model is built on the assumption that the fundamental driver of land use and trade is the maximization of the profit perceived by local actors. Two local agents are taken into account, i.e. the local producer and the importer (see Figure 17). Thus, land use and trade are allocated through an optimization algorithm in which the objective function is to maximize the profit of the domestic producer and the importer.

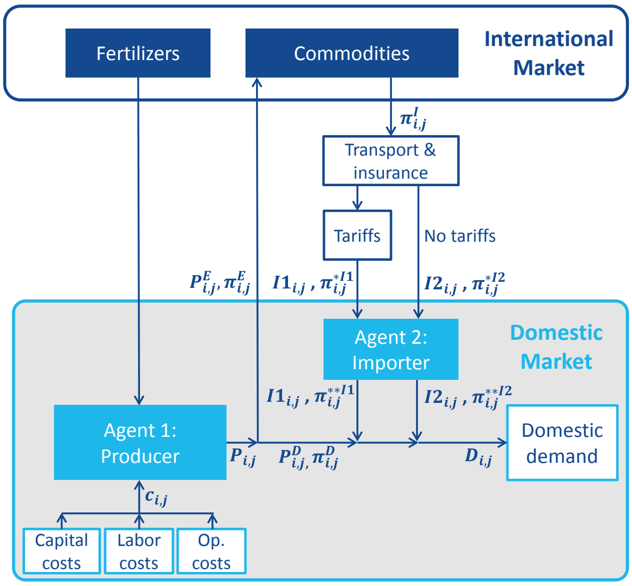


***Figure 17.*** *Representation of the market structure*

It is assumed that domestic production and imports can supply local demand (i.e. there is not an unsatisfied demand) and that local production can be destined to the domestic market or exports. This means that a country can simultaneously be an importer and exporter of a particular commodity.

It is assumed that only local agents, i.e. local producers and importers contribute to the creation of profit within the country, therefore the optimization function for year *i* is shown in Eq. 19.

Eq. 19 $Max\ M_i\colon M_i^D + M_i^I$ , subject to Eq. 26-Eq. 38

where the profit perceived by the local producer and importer of commodities in year *i* are described in Eq. 20 and Eq. 21, respectively.

Eq. 20 $M_i^D = \sum_j \left[P_{i,j}^D\left(\pi_{i,j}^D - c_{i,j}\right) + P_{i,j}^E\left(\pi_{i,j}^E - c_{i,j}\right)\right]$
Eq. 21 $M_i^I = \sum_j \left[I1_{i,j}\left(\pi_{i,j}^{**I1} - \pi_{i,j}^{*I1}\right) + I2_{i,j}\left(\pi_{i,j}^{**I2} - \pi_{i,j}^{*I2}\right)\right]$

In these equations, the variables that are optimized include the local production commodities to meet the internal demand ($P^D$) and for export ($P^E$) as well as the volumes of imported commodities *I1* and *I2.* In contrast, other variables are added exogenously to the model, and therefore are not optimized. Exogenously added variables include the price $\pi$ and the production cost *c* for the different commodities by year. These variables are taken from forecasts, estimations and official data available in literature. It is important to mention that these variables are expressed in present values, i.e. non-discounted values, for instance the price of commodity *j* in year 2020 is expressed in U.S. dollars. To transform non-discounted prices to discounted prices (e.g. US$2005), the following expression is used:

Eq. 22 $\pi_{i,j}\ [US\$\ year\ i+1] = \frac{(PI)_{i+1}}{(PI)_i} \cdot \pi_{i,j}\ [US\$\ year\ i]$

In the case where data is available in a local currency, it is necessary to transform it into U.S. dollars and for this reason the following expression is used:

Eq. 23 $\pi_i\ [US\$] = \pi_i\ [local\ currency] \cdot E_i[US\$/\ local\ currency]$

The price of commodity $\pi$ is here treated as "free on board" (FOB), which is the price of commodities placed on board a carrier at the point of shipment. The price $\pi^*$ includes transport, insurance and tariffs, but excludes the margin for importers. Finally, the price $\pi^{**}$ includes transport, insurance, tariffs and the margin for importers. It is assumed that importers will sell duty-free imported commodities and imported commodities subject to tariffs at the same price as the domestic market. In other words, $\pi_{i,j}^{**I1} = \pi_{i,j}^{**I2}$, and therefore the margin that importers will obtain for duty free imports is higher than for imports subject to tariffs.

The current production costs of commodities are taken from official data and are generally dependent on local and world price indexes, exchange rate, local minimum wage, GDP deflator growth and the fertilizer price index:

Eq. 24 $c_{i,j} = f(PI_i,\ LPI_i,\ FPI_i, E_i, GDG_i, W_i)$

Concerning the estimation of the future production cost of commodities, the process is to take the current production costs and then escalate them using the following expression:

Eq. 25 $c_{i+1,j} = c_{i,j} \cdot \frac{Y_{i+1,j}}{Y_{i,j}} \cdot \frac{(PI)_{i+1}}{(PI)_i}$

where *c* is the production cost, *Y* is the yield and *PI* is the price index. The price index and the yields for different commodities are also exogenous variables and are taken from forecasts, estimations and official data available in literature.

The optimization function is subject to various constraints, explained as follows:

1. The production of a commodity is a function of the area and yield. The yearly area required to produce each commodity $A_{i,j}$ is a variable indirectly optimized in the model and the yield $Y_{i,j}$ is a parameter entered exogenously:

Eq. 26 $P_{i,j} = A_{i,j} \cdot Y_{i,j}$

2. The overall use of the land should not exceed the maximal area available within the country (Eq. 27). The maximum area available $A^{Max}$ is a fixed parameter, while the area for different uses (e.g. agricultural $A_i^{Agric.}$, forestry $A_i^{Forestry}$, and other $A_i^{Other}$) is exogenously added year by year into the model.

Eq. 27 $A_i^{Agric.} + A_i^{Forestry} + A_i^{Other} \leq A^{Max}$

In addition, the overall area for produce agricultural and forestry commodities in year *i* should not exceed the maximal area for those uses:

Eq. 28 $\sum_j A_{i,j} \leq A_i^{Agric.}, j \in$ agricultural commodities
Eq. 29 $\sum_j A_{i,j} \leq A_i^{Forestry}$ , $j \in$ forestry commodities

Since the yields for the different commodities are exogenously added into the model, the area required to produce a commodity *j* in year *i*, is a variable indirectly optimized in the model.

3. There is a maximal yearly growth in area (or in production for non-land competing commodities) for each commodity based on statistics:

Eq. 30 $A_{i,j} \leq A_{i-1,j} + \Delta A_j^{Max}$

4. For permanent crops there is a maximum and a minimum (always positive) yearly growth in area based on statistics:

Eq. 31 $A_{i-1,j} - \Delta A_j^{Min} \leq A_{i,j} \leq A_{i-1,j} + \Delta A_j^{Max}$

5. The domestic demand should be fulfilled, see Eq. 32 and Eq. 33.

Eq. 32 $P_{i,j}^D + I1_{i,j} + I2_{i,j} = D_{i,j}$

Eq. 33 $P_{i,j} = P_{i,j}^D + P_{i,j}^E$

The domestic demand $D_{i,j}$ is an exogenous input to the model. It is estimated deterministically by multiplying the population by the demand per capita for the different commodities, see Eq. 34.

Eq. 34 $D_{i,j} = d_{i,j} \cdot N_i$

where $d_{i,j}$ is the demand per capita of commodity *j* in year I, and $N_i$ is the overall population in year *i*. The production to supply the domestic demand $P_{i,j}^D$ is estimated deterministically using Eq. 35, Eq. 36 and Eq. 37. The volume of duty free imports $I2_{i,j}$ is a variable optimized in the model and is subject to policies defining maximum duty free imports (see Eq. 38). Finally, by having optimized $I2_{i,j}$ and having deterministically estimated $D_{i,j}$ and $P_{i,j}^D$, it is possible to obtain the volume of imports subject to tariffs $I1_{i,j}$.

6. The theoretical market share of the local production is assumed to be inversely proportional to its price relative to its competitors, as shown in Eq. 35 and described in more detail for energy products in (Argonne National Laboratory, 2007). Prices for domestic and imported products are entered exogenously. The price sensitivity coefficient *k* is calculated empirically from statistics.

Eq. 35 $\left[\frac{P_{i,j}^D}{D_{i,j}}\right]_T = \frac{\left(\frac{1}{\pi_{i,j}^D}\right)^k}{\left(\frac{1}{\pi_{i,j}^D}\right)^k + \left(\frac{1}{\pi_{i,j}^{I1}}\right)^k}$

7. The theoretical production to supply the domestic demand $\left(P_{i,j}^D\right)_T$ is defined in Eq. 36. The actual production to supply the domestic demand is evaluated in Eq. 37 as a logical function. If the total yearly production of a commodity $P_{i,j}$ is higher than the theoretical production to supply the domestic demand, then the actual production to supply the domestic demand is the theoretical value calculated in Eq. 36. Otherwise, its value is equal to $P_{i,j}$.

Eq. 36 $\left(P_{i,j}^D\right)_T = D_{i,j} \cdot \left[\frac{P_{i,j}^D}{D_{i,j}}\right]_T$

Eq. 37 $If\ P_{i,j} \geq \left(P_{i,j}^D\right)_T \rightarrow\ then\ P_{i,j}^D = \left(P_{i,j}^D\right)_T,$
$otherwise\ P_{i,j}^D = P_{i,j},$

8. The yearly volume of duty free imports should be lower than a maximum volume defined in policies or regulations.

Eq. 38 $I2_{i,j} \leq I2_{i,j}^{Max}$

### D.2.5. Optimization algorithm

A metaheuristic algorithm is employed to conduct a deterministic optimization given its ability to solve problems with a large number of variables, to avoid local optima and to find a nearly optimal solution. These advantages result in improved outcomes and performance compared to classic optimization methods, although the best solution found is not guaranteed to be the global optima. This method treats the objective function as a black box and improves a candidate solution iteratively to reach an optimal solution. In this investigation, the optimization is performed in Oracle® Crystal Ball 11.1.2.1 with OptQuest as the optimization engine. OptQuest is based on scatter search and incorporates other complementing mechanisms including genetic algorithms, particle swarm optimization and cross entropy, among others (Laguna, 2011). Other characteristics of the optimization include 50,000 trials per case per year and a Latin Hypercube sampling method using 1,000 bins.

### D.2.6. Sensitivity analysis

A Monte-Carlo algorithm is used to perform a variance-based sensitivity analysis to probabilistically quantify the contribution of inputs to the results of the sub-model that calculates the biomass energy potential (see Figure 16). The Monte-Carlo algorithm is used to generate random sampling of input variables according to probability distributions. The algorithm performs then a deterministic calculation of each trial and quantifies the probability of the occurrence of the model outputs. In this study a triangular probability distribution is employed to assign a probability to all input variables. A default ±10% deviation from the mean has been used as maximum and minimum probability limits for all inputs. The sensitivity analysis in this investigation is conducted in Oracle® Crystal Ball 11.1.2.1 using 0.5 million trials and a Latin Hypercube sampling method using 1,000 bins.

### D.2.7. Selected global scenarios

In order to provide a modeling framework consistent with other state-of-the-art projections, global scenarios for analysis are selected from literature rather than formulated. Global scenarios are selected based on their ability to describe the influence of global biofuel use on agricultural price, production and demand. Bearing this in mind, four state-of-the-art scenarios published by IIASA and FAO are selected (Fischer, 2011).

These four scenarios evaluate the macroeconomic impacts of future demand for biofuels at different levels: a) no use of agricultural crops in the future for biofuel production (FAO-REF-00); b) future use of biofuels will follow the same trend as in the past (FAO-REF-01), c) biofuel production as predicted by the International Energy Agency in the World Energy Outlook (WEO-V2) and d) fast expansion of biofuel production to satisfy mandates and targets in different countries by 2020 (TAR-V1). In addition to these four scenarios and for comparative purposes, two additional datasets are incorporated, even though they do not evaluate the macroeconomic impacts of global biofuel use. These two datasets are the price forecast for commodities published by (World Bank, 2012) and data from the World Agricultural Outlook published by the Food and Agriculture Policy Research Institute (FAPRI) (FAPRI-ISU, 2011). More details about the characteristics, assumptions and design of the selected scenarios and datasets are given in Table 6.

## D.3. Study case: Colombia

The method of assessing the future trade, land use and biomass energy potential described earlier is applied to a case study of Colombia.

### D.3.1. Prior art

As for other developing countries, Colombia is characterized by a vast biomass energy potential contrasted with limited strategic planning and R&D activities. The assessment of future biomass energy potential has so far been explored solely by governmental agencies.

The Mining and Energy Planning Unit (UPME), an affiliate of the Ministry of Mines and Energy has issued two reports that evaluate the demand for bagasse, wood fuel, residues and biofuels during the period 2010-2030 (UPME, 2010a; UPME, 2010b). These studies report the use of econometric models and time series to assess the demand of biomass resources, though specific details of the method, assumptions and boundary conditions are not described. Results from UPME predict a steady increase in the demand for bagasse, bioethanol and biodiesel, driven by a biofuel blend mandate and the potential to export biofuels. On the other hand, UPME expects a decrease in the demand for wood fuel, as it will continue to be substituted by liquefied petroleum gas (LPG) in rural areas.

***Table 6.*** *Comparative overview of selected global scenarios and datasets*

| Scenario | Institution | Definition | Characteristics |
|---|---|---|---|
| **FAO-REF-00** | IIASA-FAO | Assumes a world with no agricultural crops used as feedstock for biofuel production | Modest increases in world market prices between 2000 and 2050 |
| **FAO-REF-01** | IIASA-FAO | Assumes historical biofuel development until 2008; biofuels feedstock kept constant after 2008 | Characterized by modest increase in prices. Used as reference to compare alternative biofuel scenarios |
| **WEO-V2** | IIASA-FAO | Assumes transport energy demand and regional biofuel use as projected by IEA in WEO 2008 reference scenario | It assumes that biofuels are produced with 1st Gen until 2030 and that 2nd Gen is available afterwards |
| **TAR-V1** | IIASA-FAO | Assumes transport energy demand as projected by IEA in WEO 2008 reference scenario. Assumes that biofuel targets worldwide will be implemented by 2020 | Scenario characterized by biofuel consumption two times larger than projected in WEO 2008. 2nd Gen biofuels become available after 2015 with gradual deployment |
| **WB** | World Bank | It is not a scenario but a dataset. World Bank publishes a price forecast every month for more than 30 agricultural commodities until 2025. No details are published about how the forecasts are created. | World Bank dataset foresees a reduction in price for the period 2010-2030 for all commodities except maize, chicken and wood |
| **FAPRI** | FAPRI | It is not a scenario but a dataset. FAPRI publishes the World Agricultural Outlook, which includes price projections of commodities, demand and macroeconomic data. It is the only institution that forecasts the price of biofuels | FAPRI prices are similar to WB, with the exception of sugar and palm oil which are the highest for all scenarios. FAPRI does not forecast the prices of some commodities (bananas, cotton, etc.), in those cases FAO-REF-01 data is used |

## D.3.2. Inputs

The period of analysis is set between 2010 and 2030. Inputs to the model are grouped into five categories, i.e. economic data, global scenarios, local biofuel scenarios, market data and lastly technical data and projections.

### D.3.2.1. Economic data

Economic inputs to the model include price indices, exchange rate, minimum wage and characteristics of commodities in Colombia. No projections from governmental sources on these parameters for the period 2010-2030 are publicly available. Therefore, projections from international agencies are used. The measure used to estimate the escalation of future prices in Colombia is the average Gross Domestic Product (GDP) deflator growth for Latin America predicted in (FAPRI-ISU, 2011). Similarly, the projection of the exchange rate between Colombian peso and U.S. dollar is taken from (FAPRI-ISU, 2011). On the other hand, the measure for estimating the escalation of global prices of commodities in the future is the Manufactures Unit Value (MUV) Index published by (World Bank, 2012). Regarding the minimum wage, the current value is taken from the Central Bank of Colombia (Banco de la República, 2012). A projection of the minimum wage is not found in public literature and therefore it is assumed to vary according to the GDP deflator growth in the future. A summary of the economic inputs to the model is presented in Table 7. Regarding the characteristics of commodities in Colombia, the land use and trade model considers 18 commodities classified into agricultural crops, forestry and livestock. Two main features characterize these commodities: firstly, the distinction between whether they compete for land or not, and secondly, the type of market, which might be a) production for domestic supply only, b) production for domestic supply and exports and c) production for domestic supply, imports and exports.

***Table 7.*** *Summary of economic inputs to the model*

| | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|
| GDP deflator growth (% previous year) [b] | 4.86 | 4.17 | 3.92 | 3.85 | 3.75 |
| Price index for Colombia, current prices (2005=1) [b] | 1.27 | 1.67 | 2.03 | 2.45 | 2.95 |
| Exchange rate growth (% previous year) [b] | -12.03 | 1.99 | 2.40 | 1.70 | 1.16 |
| Exchange rate (COL/US$) [b c] | 1899 | 2019 | 2334 | 2697 | 2930 |
| MUV index (2005=1) [a] | 1.13 | 1.20 | 1.19 | 1.23 | 1.27 |
| Minimum wage (COL/day) [b c] | 17167 | 21511 | 26146 | 31599 | 38040 |

**References:**
[a] (World Bank, 2012), [b] (FAPRI-ISU, 2011), [c] (Banco de la República, 2012)

Characteristics of the different commodities assumed in this study are shown in Table 37 in the Appendix.

### D.3.2.2. Global scenarios

The main inputs from the global scenarios are the predicted international price of commodities. The trade and land use model proposed in this study considers 18 main commodities for Colombia, of which 13 are assumed to be traded not only at the domestic market but also on the international market (see Section D.3.2.4). In general, while most global scenarios and datasets predict the price of at least 11 commodities (see Table 37 in the Appendix), none of them evaluate the price of all 13 internationally traded commodities relevant for Colombia. Therefore, data from global scenarios is adapted following the procedure explained as follows.

Scenarios projected by IIASA and FAO aggregate the commodities into five main categories, namely crops, cereals, other crops, livestock products and agriculture. Moreover, the projected price indices for commodities are also aggregated into these five categories. Authors of the scenarios informed through personal communication that a further disaggregation by commodity is not available. Therefore, some assumptions are made. First, relevant commodities for Colombia are grouped into the five categories: crops (coffee, sugar), cereals (maize and rice), other crops (cotton), livestock products (beef meat, chicken meat and pork meat) and agriculture (wood logs). It is also assumed that palm oil and bananas will have the same price indices as cereals, as the historical price growth of these commodities has increased in a similar way to cereals since the 1990s (see (World Bank, 2012) for more information). Second, the current international price of commodities is taken from the World Bank database (World Bank, 2012) and escalated according to the price indices projected by IIASA-FAO. Although the IIASA-FAO study is designed to describe the influence of global biofuel use on agricultural prices, it does not project the price of biofuels. Among the selected scenarios and datasets, only FAPRI predicted the future growth in the price of bioethanol and biodiesel. Results of a regression analysis show that the growth in price for biodiesel is somewhat correlated to the growth in price for palm oil in the following way (current prices, $R^2$=0.892):

$$\text{Eq. 39} \quad \Delta\pi_{biodiesel}\left[\frac{US\,\$}{gallon}\right] = \Delta\pi_{p.oil}\left[\frac{US\,\$}{ton}\right]\cdot 0.625 + 0.01$$

Similarly, the growth in price for bioethanol is correlated to the growth in price for sugar (current prices, $R^2$=0.825):

$$\text{Eq. 40} \quad \Delta\pi_{bioethanol}\left[\frac{US\,\$}{gallon}\right] = \Delta\pi_{sugar}\left[\frac{US\,\$}{ton}\right]\cdot 1.5 + 0.02$$

For the sake of comparison, these correlations are used to estimate the future price of bioethanol and biodiesel for the four IIASA-FAO scenarios and for the World Bank dataset. In a similar way, only FAPRI predicts the future price of pork meat, therefore this prediction is also used for all other scenarios and datasets. However, the FAPRI dataset does not predict the price of some commodities including bananas, cotton, coffee, rice and wood logs. In this case the corresponding prices of the FAO-REF-01 reference scenario are used in the FAPRI dataset. A comparative summary of the predicted Free on Board (FOB) prices (in US$2005) for all scenarios and datasets is presented in Table 38 in the Appendix.

### D.3.2.3. Technical data and projections

Inputs in this category include the availability of land, production yields, projections of population and domestic demand and finally the method for accounting cattle stocks. Availability of land for the different uses is an exogenous input to the model and is based on statistical information. Main sources of statistics for Colombia include the Ministry of Agriculture and Rural Development (MinAgricultura, 2012) and FAOSTAT (FAO, 2012b). Significant differences in statistics on land use are found between these two sources, though a dedicated comparison is beyond the scope of this study. Generally speaking, FAOSTAT offers a clear accounting method and a large amount of data, while MinAgricultura publishes only agricultural area based on information reported by producers. The FAOSTAT database is therefore selected to estimate the availability of land in this study, as it provides a more consistent method and a larger amount of data. According to FAOSTAT, the forest area in 2009 accounts for 60.6 mio ha. The deforested area is estimated to be 100 kha per year in the last 20 years, resulting in a continuously increasing area for permanent meadow, pastures and crops. It is assumed that this deforestation rate and the consequent transformation of forest land into agricultural land will continue over the next 20 years. The area for other uses (e.g. urban use, etc.) is estimated by FAOSTAT to be about 7.8 mio ha. This area has remained relatively constant since 2000 (0.1% increase in a decade) and it is assumed to remain constant at 8 mio ha until 2030. FAOSTAT estimates the total agricultural area in 42.54 mio ha in 2009, which includes area for permanent meadows and pastures (39.18 mio ha) and area for crops (3.35 mio ha) (MinAgricultura, 2012). The area required for the 18 commodities considered in this study accounts for 2.94 mio ha in 2009, while the remaining 0.41 mio ha correspond to other commodities not included in this study. The area required to produce these latter products has been reduced from 1.5 mio ha in 1990 to 0.41 mio ha in 2009. In this work it is assumed that this area will remain constant at 1 mio ha until 2030. The assumed overall availability of land in the period 2010-2030 is illustrated in Table 8. In the optimization model the area for agricultural crops and land-competing livestock commodities should not exceed the 'area for commodities not included in the model', whereas the area for the production of wood should not exceed the 'forest area' in Table 8.

***Table 8.*** *Availability of land in the period 2010-2030*

| **Availability of land (mio ha)** | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|
| Forest area | 60.50 | 60.00 | 59.50 | 59.00 | 58.50 |
| Other land | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Area for comm. not included in model | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Area for comm. included in model | 41.45 | 41.95 | 42.45 | 42.95 | 43.45 |

The maximum yearly growth in the area for commodities competing for land is estimated from statistics. For non-land competing commodities such as livestock products, the maximum yearly growth in stocks is estimated. Outlying observations are rejected according to the criterion proposed by (Thompson, 1935). A summary of collected data for minimum and maximum yearly bounds for the different commodities is shown in Table 39 in the Appendix. Production yields for the different commodities and their associated projected growth are collected from various sources (see Table 40 in the Appendix). Projections for growth in yields of commodities such as bananas, coffee, palm oil, plantain, sugar, cattle density (animal/ha) and jaggery are not found in literature. In these cases, time-series methods are used to estimate a mathematical fit for historical data whose trend is assumed to continue into the future. The tool employed for time-series analysis is Predictor in Oracle® Crystal Ball 11.1.2.1. The demand for commodities is estimated as the product of the demand per capita and the population. One notable exception is the projected demand for bioethanol and biodiesel under different local biofuel scenarios, which is explained in detail in Section D.3.2.5. The current population is taken from (World Bank, 2013), while projected growth is taken (DANE, 2005) for the period 2010-2020 and from (World Bank, 2013) for the period 2020-2030 (see Table 9).

***Table 9.*** *Assumed population*

| | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|
| Population (mio persons) | 46.19 | 48.93 | 51.68 | 54.11 | 56.17 |
| Yearly growth in pop. (%) | 1.18 | 1.14 | 1.07 | 0.92 | 0.75 |

On the other hand, historical and projected demand per capita for the different commodities are taken from various sources (See Table 41 in the Appendix). The scenarios developed by IIASA and FAO predict varying demand for cereals according to the level of global biofuel expansion, which is also included. Projections of demand for some commodities including cotton, horse meat and wood are not found in literature and are estimated using time-series methods. Regarding the method for accounting for cattle stocks, the Livestock Development Planning System v2 (LDPS2) sub-model developed by FAO (FAO, 2012a) is used. Some important assumptions made include a fertility rate of 80% for dairy cattle and 53% for beef cattle, a prolificacy rate of 100%; 5.5 years in breeding herd for beef cattle and 5 for dairy cattle; 2.5 years in replacement herd for beef cattle and 1 year for dairy cattle; 2.5 years from young to slaughter for beef cattle and 1 year for dairy cattle.

#### D.3.2.4. Market data

Inputs in this category include the market structure, production costs and domestic prices of commodities, price of imported commodities, free trade agreements and market shares. In addition, all other assumptions discussed in Sections D.2.2 and D.2.4 are applied. Regarding the market structure, two local agents are considered, i.e. the local producer and the importer as illustrated in Figure 17. For the case of Colombia, it is assumed that importing commodities is an activity undertaken only by local companies. On the contrary, it is assumed that transporting and insuring imported and exported commodities are activities undertaken by foreign companies. Concerning the estimation of the production cost of commodities, the process is to first evaluate the current production costs and then escalate them using adequate factors. While current production costs for different commodities are available in literature, detailed data on cost supply curves is not found. Given the lack of data, it has been assumed that current production costs are not dependent on supply size. Current production costs are gathered from various references in public literature, including Sistema de información de Precios del Sector Agropecuario (CCI, 2012), Ministry of Agriculture and Rural Development (MinAgricultura, 2012), UPME (UPME, 2005), DNP (DNP, 2008) and others. Production costs are broken down into cost groups depending on the commodity, as shown in Table 42 in the Appendix. The current costs of production are escalated in the future according to Eq. 25.

The method used to estimate the future price of commodities at the domestic level is a three step process:

First step
Data on the historical domestic price of commodities is collected. Main sources include the Ministry of Agriculture and Rural Development (MinAgricultura, 2012), Fedearroz (Fedearroz, 2012), Fedepalma (Fedepalma, 2012), the Colombian stock market (BVC, 2012) and others. The historical minimum margin for the local producer based on production costs and domestic price is estimated (See Table 43 in the Appendix). The future price ensuring a minimum margin to the local producer is then evaluated, $\left(\pi_{i,j}^{D}\right)_{Marginal}$.

Second step
The potential correlation between historical domestic prices (on a current basis) and either international prices or the price index for Colombia is investigated. Based on these correlations, the future price of commodities is calculated $\left(\pi_{i,j}^{D}\right)_{Correlated}$, assuming that historical correlations might continue in the future (see Table 43 in the Appendix).

Third step
The maximum between the two future prices calculated in steps 1 and 2 is taken as the future price of commodities. This price ensures a minimum margin to the producer and varies at an equal or higher pace than the price index (tied to the GDP deflator). This is mathematically expressed by the following equation:

$$\text{Eq. 41} \quad \left(\pi_{i,j}^{D}\right)_{Final} = MAX\left[\left(\pi_{i,j}^{D}\right)_{Marginal}, \left(\pi_{i,j}^{D}\right)_{Correlated}\right]$$

Regarding trade agreements (FTA), Colombia signed an FTA with the United States in 2012. This agreement eliminates tariffs and import quotas for all commodities (USDA, 2012). Under this agreement, Colombia will phase-out tariffs on agricultural products within a period of 19 years depending on the product. While the phase-out period for some products like corn and cotton is immediate, for others like rice and chicken meat this will take place in 2030. The latter imported products will however benefit from immediate duty-free market access through continuously increasing tariff-rate quotas (TRQ) (USDA, 2012). Although some daily commodities like milk powder can be imported with reduced tariffs and increasing TRQ, for simplicity in this study it is considered that milk will be supplied by local producers only. Assumptions related to the FTA are summarized in Table 45 in the Appendix. Other FTAs already signed or in the process of being approved are not considered in this study.

The future price of imported commodities is estimated by adding costs of transport, insurance and importing tariffs to FOB prices of commodities. It is assumed that importers will sell duty-free imported commodities and imported commodities subject to tariffs at the same price as the domestic market. In other words, $\pi_{i,j}^{**I1} = \pi_{i,j}^{**I2}$, and therefore the margin that importers will obtain for duty free imports is higher than for imports subject to tariffs. Current transport costs are taken from the OECD database (OECD, 2012), assuming that the only origin of imported commodities is the U.S. and that the transport type is maritime. The cost of insurance is assumed to be 3% of the FOB price for all commodities. Subsequently, the price of commodities including transport and insurance, commonly known as CIF price (here treated as $\pi^{*I}_{i,j}$), is estimated. Afterwards, a tariff (percentage of the CIF price) is imposed on certain commodities, according to the FTA conditions mentioned earlier. After custom clearance, the importers charge a margin to the commodities and afterwards commercialize them. It is assumed that the margin perceived by the importer for all commodities is 40%, of which 5% is for importing, 30% for distributing and 5% for brokerage. The estimated price of importing commodities is also shown in Table 45 in the Appendix.

Finally, the price sensitivity coefficient *k* employed in Eq. 35 is defined to estimate the market shares. Historical values of market shares and relative prices are collected and regression curves are investigated. Values of the price sensitivity coefficient *k* are estimated using the method of maximizing the coefficient of determination $R^2$ in regression curves. The results obtained for the price sensitivity coefficients are shown in Table 44 in the Appendix. In general, it is worth mentioning that although obtained results do follow the trend of historical market shares, they are unable to fully describe the behavior of such curves.

### D.3.2.5. Local biofuel scenarios

Various local biofuel scenarios are defined in order to investigate the influence of biofuel policies on land use and biomass energy potential. Local biofuel scenarios are possible storylines developing under a common global scenario and aim at assessing the demand for biofuels if the local blend mandate changes. The selected common global scenario is FAO-REF-01, which assumes that future global use of biofuels will follow the same trend as in the past. The reference local biofuel scenario assumes a conservative increase in blend mandate from 8% in 2010 to 10% (by volume) in 2030 for bioethanol and from 8% in 2010 to 12% (by volume) in 2030 for biodiesel. The reference local biofuel scenario is also used to estimate the demand for biofuels in the remaining parts of this study. Three alternative scenarios evaluate blend mandates at different levels over the period 2010-2030:

1. A hypothetical no blend mandate
2. A constant blend mandate
3. An aggressive increase in blend mandate

Assumptions of the different local biofuel scenarios are given in Table 10. For all scenarios, the overall demand for bioethanol and biodiesel is calculated using the percentage blend mandates and the forecasted demand for diesel fuel and gasoline taken from (UPME, 2010b).

***Table 10.*** *Assumptions of local biofuel scenarios*

| | | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| Biodiesel in blend (% vol.) | No mandate | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | Constant | 8.1% | 8.5% | 8.5% | 8.5% | 8.5% |
| | Reference | 8.1% | 9.1% | 10.1% | 11.0% | 12.0% |
| | Aggressive | 8.1% | 11.1% | 14.1% | 17.0% | 20.0% |
| Bioethanol in blend (% vol.) | No mandate | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| | Constant | 7.6% | 8.0% | 8.0% | 8.0% | 8.0% |
| | Reference | 7.6% | 8.3% | 8.9% | 9.4% | 10.0% |
| | Aggressive | 7.6% | 9.5% | 11.3% | 13.2% | 15.0% |
| Biodiesel demand (mio liters) | No mandate | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Constant | 383.5 | 484.9 | 565.7 | 640.2 | 710.3 |
| | Reference | 383.5 | 517.7 | 668.8 | 830.4 | 1002.8 |
| | Aggressive | 383.5 | 631.8 | 935.0 | 1282.3 | 1671.4 |
| Bioethanol demand (mio liters) | No mandate | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | Constant | 339.2 | 381.7 | 415.5 | 450.0 | 485.4 |
| | Reference | 339.2 | 397.6 | 461.6 | 531.3 | 606.8 |
| | Aggressive | 339.2 | 450.8 | 586.9 | 739.7 | 910.2 |

## D.3.3. Model validation

The model considering the inputs and assumptions described in Section D.3.2 is validated against historical data for the period from 1999 to 2009. Deviation between calculated production values and historical production values for the different commodities is presented in Figure 18. In general, predicted values for the majority of the commodities considered in the model deviate ±20% from the historical production values. A notable exception is the case of cotton, in which the predicted value is underestimated by values ranging from 20 to 70%. Another example of high deviation from the historical value occurs in the first year of biodiesel production (2008), although it reduces to less than 5% in the following year.

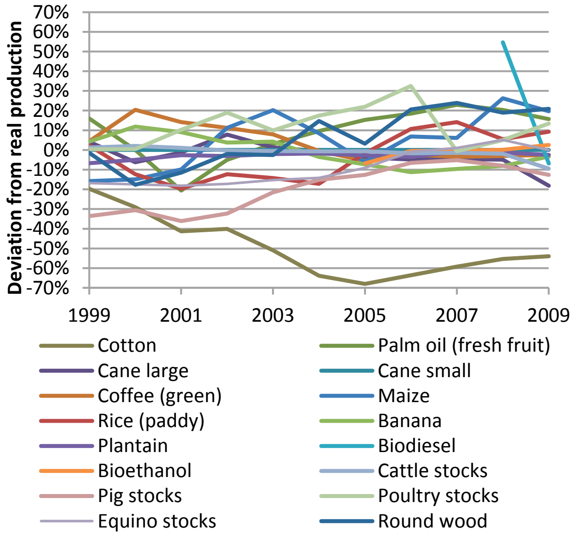


***Figure 18.*** *Deviation between calculated and historical values*

The theoretical biomass energy potential defined as the energy associated with biomass that can be used for energy purposes is calculated according to the method described in Chapter C and in (Gonzalez-Salazar, et al., 2014a). Potential for both the predicted and the historical values for the period between 1999 and 2009 are compared in Figure 19. Results show that the theoretical potential of predicted values lie within ±5% of the potential associated with historical values. This deviation is acceptable for the general purpose of this study and therefore the model is considered calibrated and validated. However, in cases where more precision is needed, it is recommended to refine the model by using more accurate methods to estimate market behavior. One example is the use of price elasticities of demand, supply and substitution, though they are currently not available in public literature for Colombia. Other acknowledged limitations of the model at this stage include the omission of climate and environmental effects as well as storage of commodities in predictions.

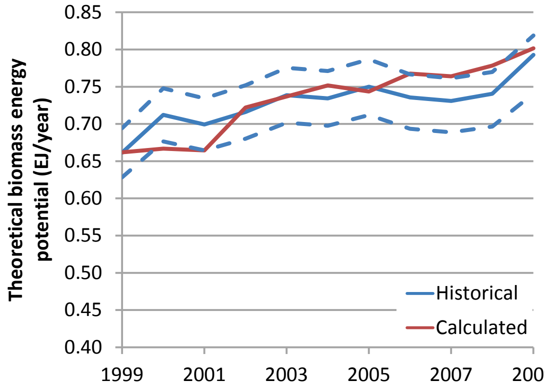


***Figure 19.** Theoretical biomass energy potential for calculated vs. historical production values*

### D.3.4. Results

Outcomes of the proposed model include the overall profit, the land use, the theoretical biomass energy potential and the bioenergy potential (associated with biofuels). Profit here relates to the difference between the price and production cost of a commodity divided by the production cost. Profit does not include general expenses like overhead, payroll, taxation, interest payments, local transport costs, etc. For this reason, results should be interpreted with caution. This profit should be regarded as a relative measure to compare the cost-effectiveness of the different commodities on a consistent basis rather than an accounting measure of the absolute profitability associated with trading commodities.

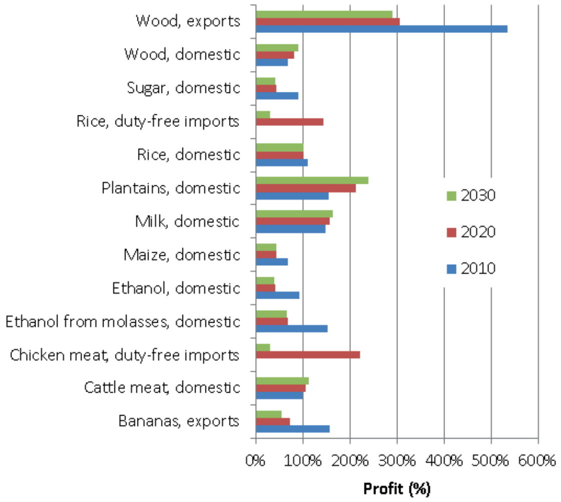


***Figure 20.** Profit by commodity for FAO-REF-00*

Results of the most cost-effective commodities for scenarios FAO-REF-00 and TAR-V1 in 2010, 2020 and 2030 are reported in Figure 20[6] and Figure 21 respectively. Nine of the thirteen most cost-effective commodities are products destined for the domestic market, e.g. cattle meat, ethanol, maize, milk, plantains, rice, sugar and wood. The most cost-effective products for export are bananas and wood, whereas the most cost-effective products for import (duty free) are rice and chicken meat. Higher profits are expected in scenario TAR-V1 compared to FAO-REF-01 for all commodities due to higher international and domestic prices. Remarkably, in both scenarios the profit perceived for cattle commodities is higher than for biofuels and other agricultural products.

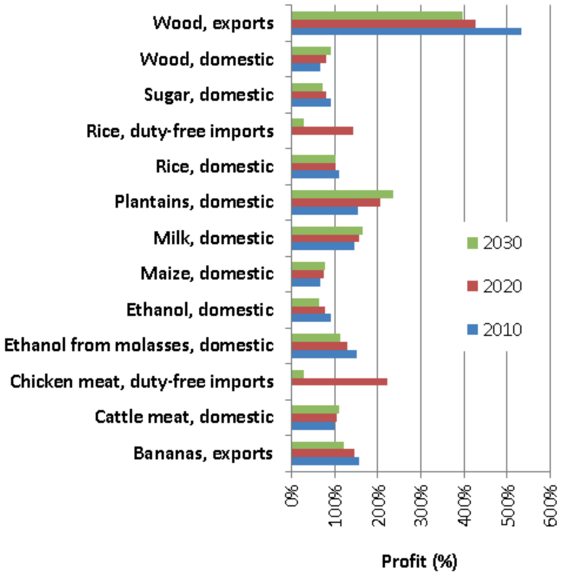


***Figure 21.** Profit by commodity for TAR-V1*

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[6] Note that profit should be regarded as a relative measure to compare the cost-effectiveness of the different commodities on a consistent basis rather than an accounting measure of the absolute profitability associated with trading commodities.

Estimated profits shown in Figure 20 and Figure 21 can go as high as 500%. These results must be interpreted with caution. As mentioned before, these profits do not represent the actual absolute net profits perceived by local producers or exporters. They do not include general expenses (i.e. overheads, payroll, taxation, interest payments, local transport costs, etc.) and thus represent a measure to compare the cost-effectiveness of the different commodities on a relative basis.

Results of the overall profit for all scenarios are reported in US$2005 in Figure 22. According to the assumptions made, an overall profit of nearly 12,000 mio US$2005 in 2010 is expected, which grows between 66% and 100% (20,000-24,000 mio US$2005) by 2030 depending on the scenario. A higher profit is expected for scenarios TAR-V1 and WEO-V2 compared to FAO-REF-00 and FAO-REF-01, as a consequence of higher international and domestic prices. The profit estimated for datasets of FAPRI and the World Bank lie between the extreme values predicted by the IIASA scenarios and near the WEO-V2 scenario. Results of the predicted agricultural land use are reported in Figure 23 to Figure 25.

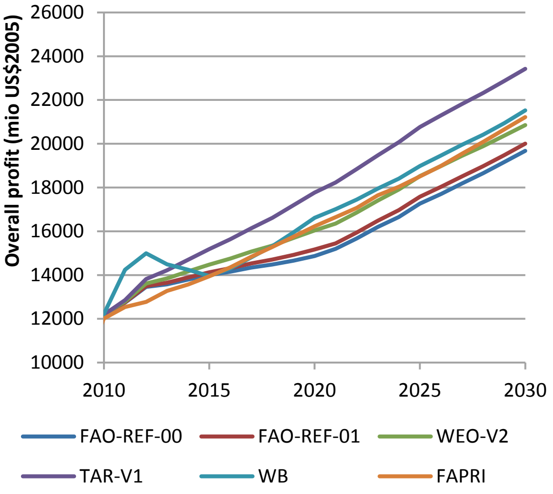

***Figure 22.*** *Overall profit for all scenarios*

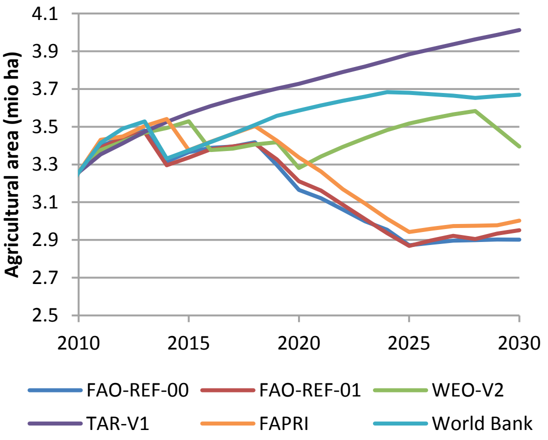

***Figure 23.*** *Agricultural area for all scenarios*

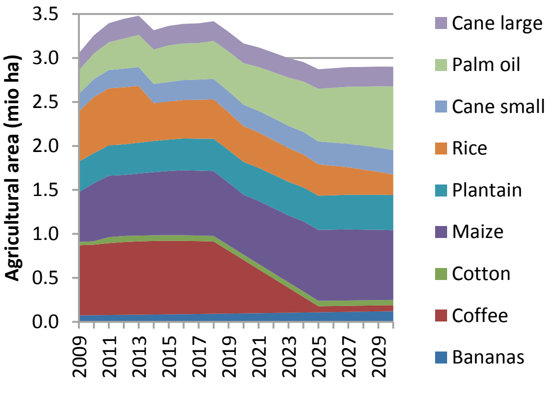

***Figure 24.*** *Agricultural area by commodity for FAO-REF-00*

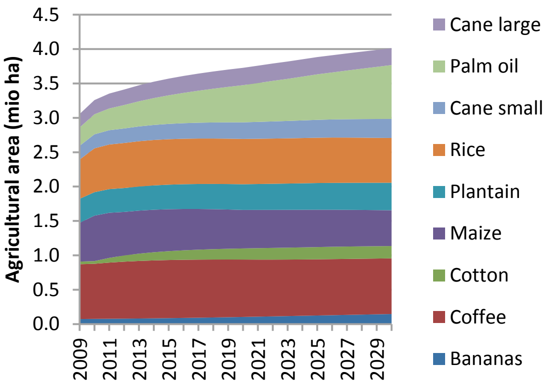

***Figure 25.*** *Agricultural area by commodity for TAR-V1*

Agricultural land is expected to reduce for scenarios FAO-REF-00, FAO-REF-01 and FAPRI as a consequence of various factors. Firstly, low international prices for coffee cause a significant reduction in harvested area accounting for 0.7 mio ha (see Figure 24). Secondly, a more cost-competitive rice imported from the U.S. has been available since 2012, causing a reduction in the area for rice production. After 2025, this reduction will be somewhat compensated by an increase in the area for cultivating other commodities such as palm oil (motivated by the local demand for biodiesel) and cane on a small scale. The combination of these two trends results in a slight increase in the agricultural land between 2025 and 2030. On the other hand, agricultural land is expected to increase by one mio ha between 2010 and 2030 for the scenario TAR-V1 (see Figure 25). In this scenario a steady increase is expected in areas for most commodities (Figure 25), but particularly for palm oil and cotton.

In contrast to the reference scenarios, in TAR-V1 the area for coffee and rice remains constant or even increases. Finally, agricultural land in scenarios WEO-V2 and the World Bank is expected to remain fairly constant and to lie between the extremes mentioned above. As described in Table 8, forest land in Colombia is expected to decrease by 2 mio ha between 2010 and 2030 as a consequence of deforestation. The area required for woodfuel production (see Figure 26) is expected to increase from 300 kha in 2010 to about 500 kha in 2030 for all scenarios, accounting for a small portion of the total forest land (58.5 mio ha in 2030).

The predicted use of land for cattle is shown in Figure 27. Contrary to agricultural land, the land for cattle is expected to increase for all considered scenarios. This increase ranges from 1.2 mio ha for TAR-V1 to 2.4 mio ha for FAO-REF-00. A change in land use is therefore required to justify this increase in all scenarios. Two types of changes in land use are foreseen, e.g. agricultural land and forest land transformed into land for cattle.

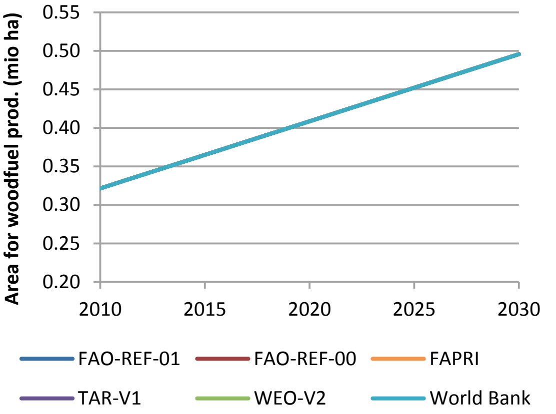

***Figure 26.*** *Area for woodfuel production by scenario*

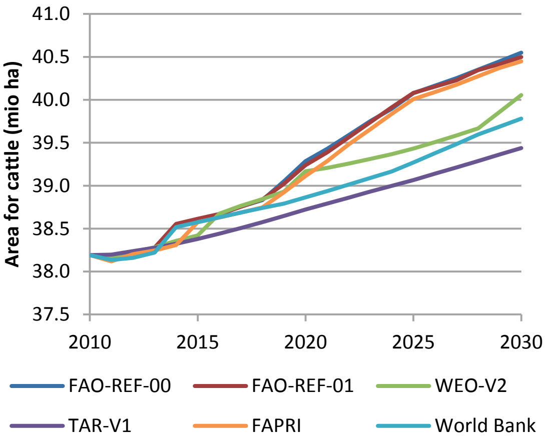

***Figure 27.*** *Area for cattle for all scenarios*

Transformation of agricultural land into land for cattle occurs for all scenarios except TAR-V1 and World Bank (in which agricultural land increases), accounting for up to 0.4 mio ha. The transformation of forest land into land for cattle via deforestation therefore occurs in all scenarios to cover the remaining gap, accounting for 0.8 to 2 mio ha. In general, it is found that the increase in land for cattle is more pronounced in scenarios forecasting low commodity prices, e.g. FAO-REF-00 and FAO-REF-01. The reason for this lies in the higher cost-effectiveness of cattle products (meat and milk) compared to other agricultural products (see Figure 20 and Figure 21). Therefore, cattle products are likely to win the land competition, particularly at lower commodity prices.

Results of the theoretical biomass energy potential for all scenarios during the period 2010-2030 are shown in Figure 28. An increase in the theoretical biomass energy potential is predicted from 0.74 EJ in 2010 to a value ranging from 1.08 to 1.18 EJ in 2030 depending on the scenario. It is found that the highest potential corresponds to scenarios with high global biofuel expansion, e.g. TAR-V1 and WEO-V2. However, the difference in prediction between scenarios describing the lowest and highest global biofuel expansion is relatively small (0.1 EJ). Therefore, the theoretical biomass energy potential in Colombia depends only to a small extent on international prices and on global biofuel expansion. Results for databases from FAPRI and the World Bank are consistent with results obtained for scenarios developed by FAO-IIASA.

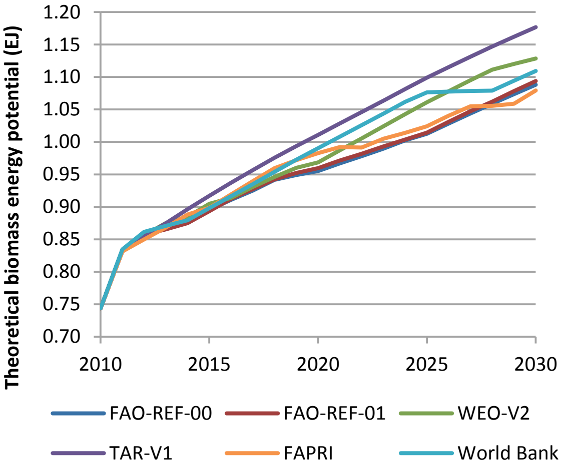

***Figure 28.*** *Theoretical biomass energy potential for all scenarios*

Results of the bioenergy potential (the potential associated with bioethanol and biodiesel production) are shown in Figure 29. The bioenergy potential is expected to grow almost identically for all scenarios from 20 PJ in 2010 to about 90 PJ in 2030. These results also show that bioenergy potential depends primarily on the internal demand for biofuels rather than on the degree of global biofuel expansion. While comparing the theoretical biomass energy potential and the bioenergy potential might not be absolutely consistent, it is possible to observe that the scale of bioenergy potential is much lower than that of the theoretical biomass energy potential. This finding agrees with conclusions presented in an earlier study (Gonzalez-Salazar, et al., 2013).

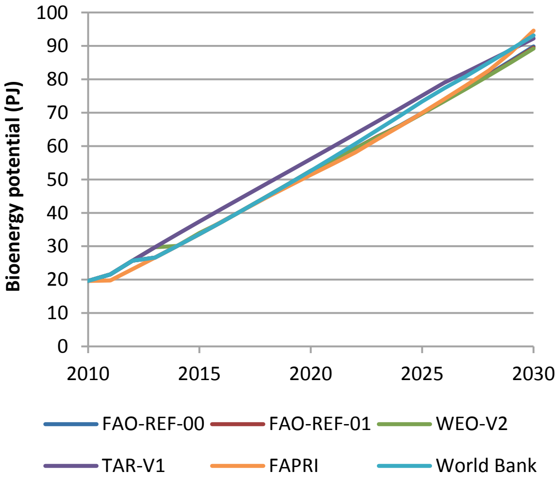

***Figure 29.*** *Bioenergy potential for all scenarios*

Results for local biofuel scenarios

The overall profit for alternative local biofuel scenarios relative to the reference is reported in Figure 30.

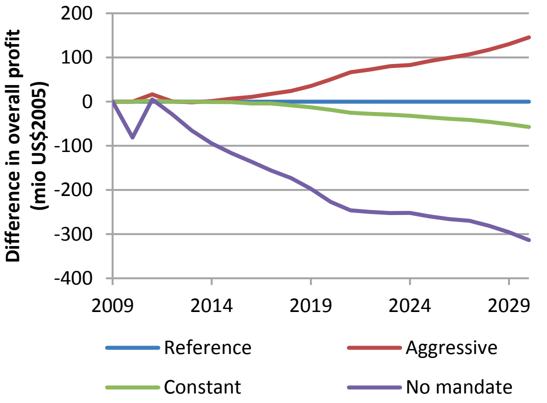

***Figure 30.*** *Difference in overall profit between reference and local biofuel scenarios*

The profit for the scenario with an aggressive blend mandate is expected to be higher than the reference throughout the entire investigated period; this difference in profit is predicted to increase to 146 mio US$2005 in 2030. According to the assumptions made, a negative difference in profit is expected between the reference and scenarios with a lower or no blend mandate relative; relative decreases of 57 and 314 mio US$2005 are respectively estimated for those scenarios in 2030. As the local demand for biofuels is bound by the blend mandate and not driven by the market, results show that higher blend percentages relative to the reference would translate into higher demand for biofuels and higher profits for local biofuel producers. While a higher profit for local biofuel producers is surely desirable, it also involves negative effects. A higher profit for local biofuel producers comes at the expense of higher costs to consumers, which are bound to the use of biofuels. These biofuels (e.g. bioethanol and biodiesel) are typically characterized by a lower energy content than the corresponding fossil fuels, which results in a higher price per energy content. Dedicated analysis of increasing blend mandates of biofuels should therefore consider both positive and negative impacts.

Result of the predicted agricultural land use for local biofuel scenarios is reported in Figure 31. Agricultural land is expected to reduce between 2010 and 2030 for the reference scenario (equivalent to scenario FAO-REF-01) in the same way as shown in Figure 23. As explained before, this reduction in agricultural land is a consequence of various factors including low international prices for coffee and a more cost-competitive rice imported from the U.S. Similarly, agricultural land for alternative local biofuel scenarios decreases throughout the entire period.

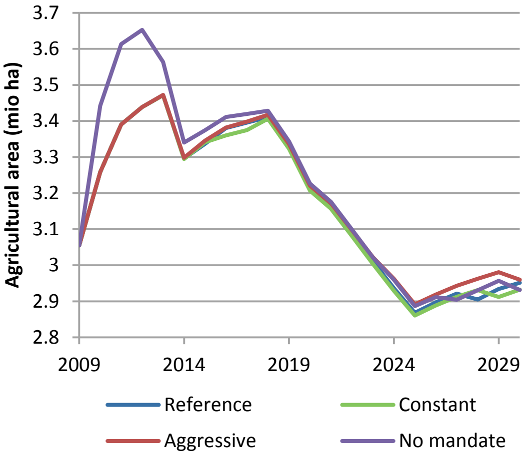

***Figure 31.*** *Agricultural area for local biofuel scenarios*

Agricultural land is expected to remain somewhat unchanged for scenarios with an aggressive blend mandate and a constant blend mandate relative to the reference. However, relative to the reference, the agricultural land for the scenario with no blend mandate would increase between 2010 and 2018 (i.e. a relative increase of up to 223 kha would have occurred in 2011). A closer look at the scenario with no blend mandate reveals that sugar cane would significantly contribute to the relative increase in agricultural land between 2010 and 2013 (see Figure 32). This brief growth in land for sugar cane is motivated by exports of bioethanol (not shown), as in this scenario there is no local demand for highly profitable biofuels. However, after 2013 exporting bioethanol would not be as lucrative as trading other commodities and land for sugar cane would drop to levels below the reference.

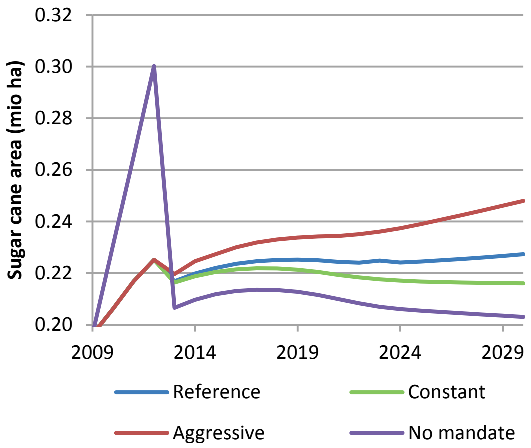

***Figure 32.*** *Sugar cane area for local biofuel scenarios*

The estimated use of land for sugar cane for the different local biofuel scenarios is shown in Figure 32. The land for sugar cane is predicted to vary according to the blend mandate. An increase from 196 kha in 2010 to 248 kha in 2030 is expected for the scenario with an aggressive blend mandate. Between 2015 and 2030, this area is expected to maintain relatively unchanged in scenarios with a constant blend mandate (~216 kha in 2030) and with no mandate (~203 kha in 2030). It is important to note that in this study the land for cultivating sugar cane is strictly limited to the Valley of the Cauca River and no expansion into the Llanos region in the east of the country is considered. Figure 33 shows the difference in the bioenergy potential (i.e. potential associated with biofuels only) of alternative local biofuel scenarios compared to the reference.

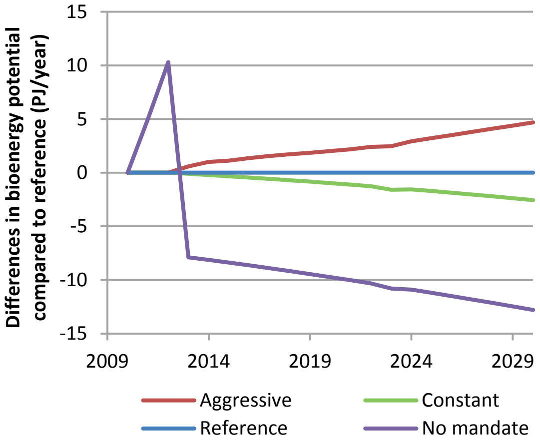

***Figure 33.*** *Differences in bioenergy potential between reference and local biofuel scenarios*

A relative increase in the bioenergy potential of 5 PJ is expected in 2030 for the aggressive blend mandate compared to the reference. This accounts for 5% of the bioenergy potential of the reference mandate in 2030. On the other hand, a relative decrease in the bioenergy potential is expected for scenarios with a constant blend mandate and with no blend mandate compared to the reference. The decrease ranges from 2.5 PJ for the scenario with a constant blend mandate to 13 PJ for the scenario with no blend mandate in 2030. This accounts for 2.8% and 14.3% of the bioenergy potential of the reference mandate in 2030, respectively. For the scenario with no blend mandate, there is an increase of 10 PJ in the bioenergy potential between 2010 and 2013; this short-term effect is a consequence of a transient rise in ethanol production for exports, as mentioned above.

### D.3.5. Sensitivity analysis

A variance-based sensitivity analysis is performed to probabilistically quantify the contribution of inputs to the results of the sub-model that calculates the biomass energy potential. As mentioned before, a triangular probability distribution with a default ±10% deviation from the mean is used for all inputs. Figure 34 shows the most relevant inputs contributing to the results of the theoretical biomass energy potential for reference scenario FAO-REF-01 in the years 2010, 2020 and 2030. It can be deduced from this figure that ten inputs contribute to 60% of the variance, while other inputs contribute to the remaining 40%.

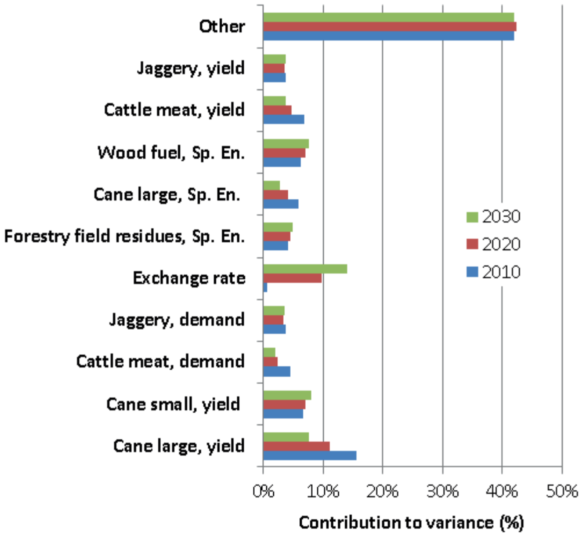

***Figure 34.*** *Sensitivity analysis of the theoretical biomass energy potential for FAO-REF-01*

From these ten inputs, four relate to yields of production (jaggery, cattle meat, cane on a large and small scale); three to specific energy associated with biomass resources (wood fuel, forestry field residues and cane on a large scale); two to demand of commodities (jaggery and cattle meat) and only one related to economic data, e.g. the exchange rate. It can therefore be concluded that agricultural yields, demand and specific energy associated with biomass resources have a stronger influence on biomass energy potential than macroeconomic effects or global biofuel use.

## D.4. Summary and discussion

This chapter presents a method of estimating the future biomass energy potential in countries with domestic markets unable to influence international markets. In the proposed method, the biomass energy potential is driven by demand and land use under different global scenarios selected from literature. The theoretical biomass energy potential in Colombia during 2010-2030 is estimated as a study case. Results show that the theoretical biomass energy potential is expected to increase from 0.74 EJ in 2010 to a value ranging from 1.08 to 1.18 EJ in 2030 depending on the scenario. The most relevant parameters contributing to the biomass energy potential include agricultural yields, demand for commodities, specific energy of biomass resources and, to a lesser extent, the global biofuel use. Agricultural land is expected to reduce for most scenarios as a consequence of low prices for key commodities and competition with imported products. On the other hand, land for cattle is expected to increase for all scenarios as a result of a higher cost-effectiveness of cattle products compared to many agricultural products. In general, it is found that the scale of the bioenergy potential associated with biofuels is much lower than that of the theoretical biomass energy potential.

The method shown in this chapter offers an inexpensive, easy to implement, and robust technique which is fully supported by official statistics and that might be advantageous for countries at an early stage in the process of assessing future biomass energy potential. Recommendations for future work include the development of methods for estimating market behavior more accurately, development of cost supply curves for all relevant commodities in Colombia, implementation of climate effects, environmental impacts and the storage of commodities. Additionally, implementation of methods to endogenously link demand and yield as well as to include the impact of land demand on land price would be highly beneficial for improving the current model.

# Chapter E. Development of a technology roadmap for bioenergy exploitation

## E.1. Overview

### E.1.1. Chapter structure

This chapter describes the process of developing a technology roadmap for deploying bioenergy technologies at a country level. Firstly, a literature review of energy technology roadmapping at a country level is presented and gaps in knowledge are identified (see Section E.2.1). Secondly, a method for energy technology roadmapping adapted to the conditions of developing countries is proposed. This method aims to be simple, affordable and supported by analytical modeling (see Section E.2.3). Thirdly, the proposed method is applied to Colombia for creating a plan to deploy sustainable bioenergy technologies until 2030 (see Section E.3). This plan consists of a set of long-term goals, milestones, barriers and action items identified by over 30 experts for different bioenergy technology areas. Finally, the relevance of the process of developing a technology roadmap for bioenergy exploitation in Colombia in other developing countries is discussed (see Section E.5).

### E.1.2. Technology roadmapping

A technology roadmap is a strategic plan that describes the steps required to achieve stated outcomes and goals (IEA, 2010). Roadmapping is the process of developing, implementing, monitoring and updating a technology roadmap (IEA, 2010). An effective technology roadmap must address three key questions: Where are we now? Where do we want to go? How can we get there? (Phaal & Muller, 2009). The process of developing a technology roadmap is as important as the roadmap itself, because of the associated communication and consensus generated between stakeholders (Phaal & Muller, 2009).

Technology roadmapping offers the key advantage of providing information to organizations or nations to make better technology investment decisions (Garcia & Bray, 1997; Phaal, Farrukh, & Probert, 2001; IEA, 2010). Technology roadmapping does this by: a) engaging diverse stakeholders in finding consensus on common goals (e.g. needs, solutions, etc.), b) identifying critical needs that drive technology selection and decisions, c) identifying technologies that satisfy critical needs and d) developing and implement a plan to deploy selected technology alternatives. Technology roadmapping is particularly important when the investment decision is not straight forward, because of uncertainty in which alternative to pursue, or because a need to a coordinated deployment of multiple technologies exists (Garcia & Bray, 1997). While technology roadmapping is a powerful tool, it is also very resource intensive. It requires substantial amount of information, it requires skilled participants, and since it is a collaborative and iterative process, it requires significant planning and coordination (Garcia & Bray, 1997; Phaal, Farrukh, & Probert, 2001; IEA, 2010). So far, technology roadmapping has mostly been applied in industrialized nations and large emerging economies, where the requirements described above for carrying out technology roadmapping have been fulfilled and where more R&D activities have taken place (Amer & Daim, 2010). In contrast, technology roadmapping has been rarely employed in developing countries, where available data, skilled labor and resources may be limited.

Technology roadmapping has been extensively used at product, technology, company, sector and national levels by companies, NGO's, universities and international organizations to address a wide variety of topics (Amer & Daim, 2010). Across topics, energy is the single topic with the highest number of public domain roadmaps (Amer & Daim, 2010). Across energy roadmaps, Amer & Daim report that sustainable energy is the most addressed topic.

In the particular context of bioenergy, various roadmaps have been proposed in industrialized countries and emerging economies. Examples include: global technology roadmaps on biofuels for transport (IEA, 2011b) and bioenergy for heat and power (IEA, 2012c), European Union roadmaps on biomass technology (RHC, 2014), biofuels for transport (E4tech, 2013) and biogas (AEBIOM, 2009), United States roadmaps on bioenergy and biobased products (Biomass Technical Advisory Committee, 2007) and algal biofuels technology (DOE, 2010a), a roadmap for sustainable aviation biofuels for Brazil (Boeing-Embraer-FAPESP-UNICAMP, 2014), China roadmaps on biomass energy technologies (ERI-NDRC, 2010) and rural biomass energy (Zhang, Watanabe, Lin, DeLaquil, Gehua, & Howell Alipalo, 2010), and a roadmap for biorefineries in Germany (Bundesregierung, 2012). However, despite vast potential and the significant demand for bioenergy, the deployment of technology roadmaps for exploiting bioenergy in developing countries has been scarce. In summary, in developing countries the use of technology roadmapping has been scarce in general and particularly rare in the context of bioenergy, despite having vast potential.

## E.2. Method

This section presents an overview of the state-of-the-art approaches for energy technology roadmapping at a country level and presents a proposed method adapted to the conditions of developing countries.

### E.2.1. State-of-the-art

There are many of methods and approaches in the literature for creating technology roadmaps, as documented by (Amer & Daim, 2010). An analysis of 80 different roadmapping approaches concluded that while it is not possible to declare a single best and definitive method, there are a number of good practices (de Laat, 2004; Kostoff, Boylan, & Simons, 2004). Good practices include identifying key stakeholders, organizing workshops, encouraging a multi-perspective approach, among others (de Laat, 2004; Kostoff, Boylan, & Simons, 2004; Amer & Daim, 2010).

Amer & Daim analyze the different techniques used in technology roadmapping at a national level in the particular context of renewable energy. Techniques frequently used in more than 50% of the roadmaps include scenario based planning and expert panels, while a technique used in approximately 50% of the roadmaps is SWOT analysis. On the other hand, techniques rarely used in roadmaps include Delphi method, risk assessments, PEST analysis, patent analysis, citation work analysis and quality function deployment (QFD) (Amer & Daim, 2010). Amer & Daim further recommend standardizing these renewable energy roadmaps by proposing a generic framework (Amer & Daim, 2010). The guide to develop and implement energy technology roadmaps by the International Energy Agency (IEA, 2010) is a step in this direction. This guide aims at providing countries and companies with a framework to design, manage and implement an effective energy roadmap process. The guide proposes a roadmap structure composed of five elements (IEA, 2010): 1) goals: set of targets that will result in the desired outcome, 2) milestones: interim performance targets for achieving the goals, 3) gaps and barriers: list of gaps in knowledge and barriers to achieve goals and milestones, 4) action items: actions to be taken to overcome gaps in knowledge or barriers for achieving the goals and 5) priorities and timelines: list of most important actions needed to achieve the goals and time frames.

Regarding the roadmapping process itself, the guide proposes a process consisting of two types of activities (expert judgment and consensus and data and analysis) and four phases (planning and preparation, visioning, roadmap development and roadmap implementation and revision). The first activity, expert judgment and consensus activities, is proposed to build consensus on goal and targets, verify assumptions, identify barriers and strategies. The second activity, data and analysis, is proposed to support and facilitate expert judgment with sound facts. These two activities are carried out in four phases. In the planning and preparation phase, the scope, boundaries and implementation approach are defined. In the visioning phase, workshops are conducted to identify long-term goals. In the development phase, further workshops are conducted to setup priorities and the actual document is created, reviewed and refined. Finally, in the implementation phase, the roadmap is implemented and monitored and further workshops are conducted to re-assess priorities as time progress. The IEA recommends involving 40-100 stakeholders in the development of a roadmap and estimates 6-14 months to develop it.

Advantages of this guide include: a) a very robust and systematic structure that allows its application to any sector and country, b) use of data and analysis to support expert judgment, c) detailed definition of activities, goals and responsibilities by the different stakeholders and d) recommendation of effective mechanisms to implement roadmaps. Disadvantages of this guide include: a) it can be challenging to implement the method in developing countries, as its structure might be too complex and the process too lengthy, b) while analytical modeling is considered, it is only optional, c) there is a lack of methods to address the challenge of not building consensus among experts (the IEA recommends to choose one position, to present the opposing views if one of those is the minority, or to attempt to create consensus between the two sides).

### E.2.2. Gaps in knowledge

In summary, in developing countries the use of technology roadmapping has been scarce in general and particularly rare in the context of bioenergy, despite having vast potential. Regarding methods, while the guide proposed by IEA is a very detailed and robust method that can be applied to any country, its structure is best adapted to OECD countries. For developing countries, it can be challenging to implement the full method, which requires various detailed and lengthy processes and involve multiple working groups. In addition, in the IEA guide there is a lack of methods to address the challenge of not building consensus among experts and analytical modeling is only optional. The method proposed here aims at filling this gap.

### E.2.3. Proposed method

A method for energy technology roadmapping adapted to the conditions of developing countries is proposed. The method consists of three components: 1) a simplified version of the IEA's guide structure, 2) a new strategy to build consensus and 3) a strong focus on analytical modeling for supporting expert judgment. This method recognizes the advantages of the guide to develop and implement energy technology roadmaps by the IEA and proposes various modifications to reduce its disadvantages when applied to developing countries.

Firstly, it is proposed to maintain the robust IEA's structure consisting of two types of activities (expert judgment and consensus and data and analysis) and four phases (planning and preparation, visioning, roadmap development and roadmap implementation and revision) but in a simplified version. The proposed method is shown in Figure 35, where feedback loops are avoided and workshops are reduced to a minimum. However, expert judgment as well as communication and consensus between stakeholders are needed for developing effective roadmaps. Hence, a new strategy to build consensus is proposed. This strategy combines surveys and a workshop following the Delphi method (see Figure 36). Rather than conducting three workshops at the visioning phase as in the IEA's guide, it is suggested to conduct two sequential surveys and a single workshop, following the Delphi method.

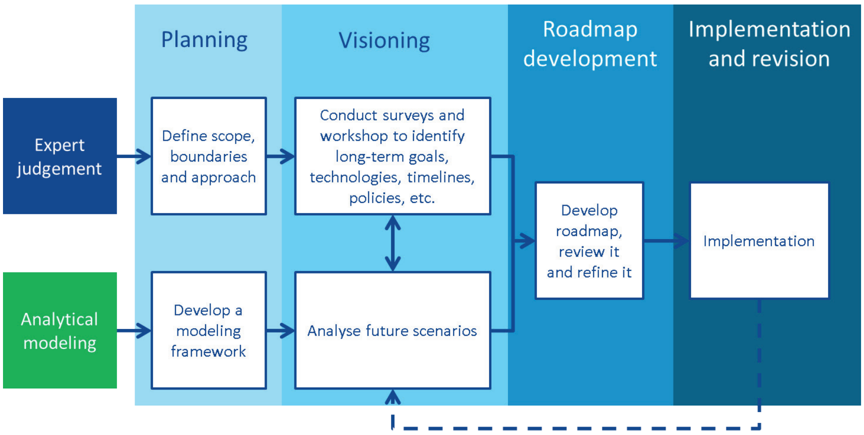

***Figure 35.*** *Proposed method for energy technology roadmapping, adapted from (IEA, 2010)*

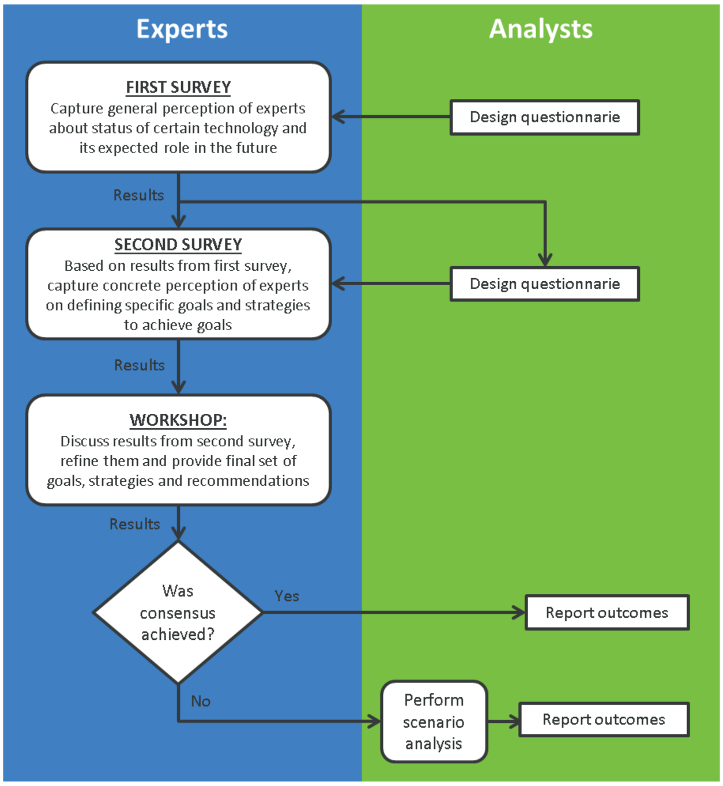

***Figure 36.*** *Proposed strategy to build consensus*

In the first survey, analysts design a questionnaire whose goal is to capture the general perception of experts about the status the technology of study and its expected role in the future. Results from the first survey (maintaining anonymity of the participants) are summarized and based upon the results a new questionnaire is designed by analysts. This second survey aims at capturing more concretely the perception of experts on the technology of study, and encourages them to define specific goals and strategies to achieve these goals. Results of the second survey (again maintaining anonymity of the participants) are summarized and presented in a workshop. In this workshop, experts discuss the results, refine them and define a final set of goals, strategies and recommendations. This sequential process follows the Delphi method, in which the opinion of individual experts at various stages is influenced by the opinion of the group. Opinion of experts tends to converge after various rounds, which encourages consensus building (Hsu & Sandford, 2007). If consensus was achieved during the process, analysts report outcomes. If consensus is not achieved, performing scenario analysis, i.e. considering various possible storylines, is proposed.

The third component of the proposed method is giving a stronger focus to analytical modeling for supporting expert judgment. The IEA's guide considers that analytical modeling adds value to the roadmapping process, but that it is not required. Moreover, the IEA's guide suggests that the extent to which analytical modeling should be applied depends on the amount and quality of available data, skilled labor and resources, which are limited in developing countries. While it is acknowledged that start applying analytical modeling is challenging, it is essential for assessing complex challenges like energy, economy, emissions and land use and their linkages. Hence, use of analytical modeling for supporting expert judgment and for adding value to technology roadmapping is here proposed.

## E.3. Application of the method to Colombia

### E.3.1. Motivation

Colombia is contemplating peace agreements after a 50-year armed conflict, which would open up the possibility of modernizing agriculture, improving living standards in rural areas and exploiting the vast bioenergy potential (i.e. Colombia is one of the seven countries in the world where more than half of the potentially available global arable land is concentrated (FAO, 2011)). However, Colombia does not yet seem prepared for such ambitious reforms. While today bioenergy is the second largest renewable energy resource (3.8 million tons of oil equivalent –Mtoe–) after hydro power (4.2 Mtoe) (UPME, 2011b), only a limited number of studies have previously explored its further deployment (MRI-UNC-NUMARK, 2010; Mora Alvarez, 2012) and the magnitude of its impact has not been investigated in detail. More importantly, no official plans exist today for exploiting it in the long-term at a national level. Recognizing the importance of biomass and the lack of long-term strategic planning to exploit it, a roadmap to support the deployment of bioenergy technologies until 2030 is proposed for Colombia.

### E.3.2. Scope

The proposed method is applied to create a plan (roadmap) to deploy sustainable biofuel and biomass technologies in Colombia for the period 2015-2030. Concretely, the roadmap aims at:

1. Defining long-term goals, strategies, plans and policies to continue deploying first generation biofuels (sugar cane-based bioethanol and palm-oil based biodiesel) and to start deploying second-generation biofuels[7] and biomass-based heat and power generation technologies (using non-food feedstock, e.g. wood, agricultural residues, biogas, landfill gas, etc.).
2. Identifying gaps in knowledge and barriers to accomplish the proposed goals.
3. Defining actions that should be taken by stakeholders to overcome barriers and accomplish the proposed goals.

### E.3.3. Positions towards residual biomass

The roadmap supports the ongoing deployment of first-generation biofuels, but strongly encourages an accelerated and sustainable exploitation of residual biomass and other non-food feedstocks for energy production. The main reason for encouraging the use of non-food biomass feedstocks over sugars and vegetable oils for energy production is to reduce the potential upward pressure on agricultural and forestry land, commodity prices and ultimately food security. Recent studies have shown that while the current use of bioenergy production in Colombia has not triggered significant impacts on supply and prices, this might change if more biofuel targets are put in place (FAO-GBEP, 2014; Gonzalez-Salazar, et al., 2014b). Increasing blend mandates of bioethanol and biodiesel might lead to an associated decrease in forestry land and land for cultivating other agricultural products (Gonzalez-Salazar, et al., 2014b), as well as negative repercussions on environmental and social sustainability (FAO-GBEP, 2014; FAO, 2014).

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[7] Solid, liquid and gas biofuels produced from feedstocks not used for human consumption (IEA, 2008).

### E.3.4. Process

The method proposed in Section E.2.3 for technology roadmapping was used to build consensus among a group of 30 experts from the government, academia, industry and NGO's upon long-term goals and strategies (Gonzalez-Salazar, Venturini, Poganietz, Finkenrath, Kirsten, & Acevedo, 2014c). Firstly, the opinions of experts on the future deployment of bioenergy in Colombia were gathered through two surveys. The first survey captured the general perception of experts about the current status of bioenergy in Colombia, its expected role in the future and the key barriers to further deploying bioenergy in the country. The questions included in the first survey and the responses received from experts are reported in Table 46 in the Appendix. The second survey collected the advice of experts about concrete long-term goals to deploy bioenergy and specific pathways to achieve these goals (questions are reported in Table 47 in the Appendix, while expert feedback is shown in Figure 105 to Figure 108 in the Appendix). Experts met in a workshop to discuss the results of surveys and to provide recommendations. Finally, independent researchers from academia reviewed the goals and milestones of the two long-term visions and provided complementary remarks and suggestions. It is hoped for that the long-term goals, milestones and action items identified here will be revised and adjusted by policy makers and local authorities and lead to an implementation program.

## E.4. Results of the roadmapping process for Colombia

### E.4.1. Overview of the vision

In order of importance, roadmap experts consider the three following reasons critical to supporting the deployment of bioenergy technologies in Colombia:

1. To promote rural development
2. To enhance energy security[8]
3. To reduce greenhouse gas emissions

In addition, experts consider that further deployment of bioenergy should be one of the top three national energy targets to be implemented by 2030, the other two targets being increased energy efficiency nationwide and increased power coverage in non-interconnected zones (NIZ). Five bioenergy technology areas are considered fundamental for future deployment in Colombia: a) bioethanol, b) biodiesel, c) renewable diesel, d) biomethane and e) biomass-based power generation and combined heat & power (CHP). Some of them have already been deployed to a certain extent in the country (e.g. bioethanol, biodiesel, biomass-based power generation and CHP), while others have not been commercially explored yet (e.g. renewable diesel[9] and biomethane).

Experts unanimously agreed on the long-term vision of some bioenergy technology areas but disagreed on others. While there was general consensus among experts on the long-term vision for biomethane and biomass-based power generation and CHP, there were opposing views with regard to the long-term vision of liquid transport biofuels (i.e. bioethanol, biodiesel and renewable diesel). In particular, experts consider that advanced liquid biofuels (e.g. cellulosic ethanol, biodiesel from microalgae and other advanced routes) are not expected to become commercially available in Colombia before 2030 and that first generation liquid biofuels (biofuels produced from feedstocks that are used for human consumption, e.g. cane-based bioethanol, palm-based biodiesel, palm-based renewable diesel, etc.) will continue being produced in the future. The opinions of experts particularly differed on the levels of blend mandates to be implemented in the future. On one hand, some experts advocate for a significant growth in the production of first generation liquid transport biofuels by increasing blend mandates. On the other hand, other experts consider that any further increase in the production of first generation biofuels might worsen the conflicts of land use and food vs. biofuels and are in favor of fixing the current blend mandates. As a consequence of the mentioned dilemma, two different visions are considered:

- **Vision focusing on new technologies**: this targets the deployment of new technologies for the production of biomethane, electricity and CHP and fixes the current blend mandate of first generation liquid biofuels.
- **Vision combining new and traditional technologies**: this targets a combination of new technologies for production of biomethane, electricity and CHP with further growth of first generation biofuels (i.e. bioethanol and biodiesel and renewable diesel).

A detailed set of long-term goals, milestones, technologies, policies and barriers are defined for each of the two visions and are described as follows.

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[8] While Colombia exports coal and crude oil, it also imports crude oil (1-3% of the local demand) as well as refined fuels such as diesel fuel (up to 35% of the local demand), fuel oil (up to 50% of the local demand) and gasoline (<1% of the local demand) for providing energy primarily to the transport sector, but also to power generation (UPME, 2011b). Thus, enhancing energy security has become a priority in recent years.

[9] The Colombian national oil company, Ecopetrol, has already started analyzing the production of renewable diesel in dedicated or co-processing plants in the country (Ecopetrol, 2013).

### E.4.2. Long-term goals

Long-term goals are quantifiable targets classified by bioenergy technology area for the two visions. Goals for the vision focusing on new technologies cover biomethane and power generation and CHP, while goals for the vision combining new and traditional technologies cover all bioenergy technology areas. Long-term goals for bioethanol, biodiesel and renewable diesel aim at significantly increasing the quota mandates relative to fossil fuels in the transport sector (see Figure 37 and Table 11). A second goal for bioethanol is the launch of a new E85 fuel program by 2030. These goals reflect an interest in decreasing fossil fuel dependency and reducing carbon emissions in the transport sector through the use of first generation biofuels already deployed in Colombia (with the exception of renewable diesel, which has not been commercially deployed yet). On the other hand, the goals for biomethane, power generation and CHP are considered novel in the Colombian context and aim at multiple directions, including: a) implementing advanced biofuels such as biomethane, b) implementing a renewable power target and deploying novel technologies such as biomass-based power plants, co-firing and gasification plants and c) increasing the exploitation of residual biomass (e.g. biogas from animal waste and wastewater treatment plants, landfill gas, etc.) for energy purposes. These goals show not only an interest in decreasing oil dependency and carbon emissions but also in using advanced biofuels and biomass technologies that offer lower life cycle GHG emissions and land use than first generation commercial biofuels.

### E.4.3. Milestones of the bioenergy technology roadmap

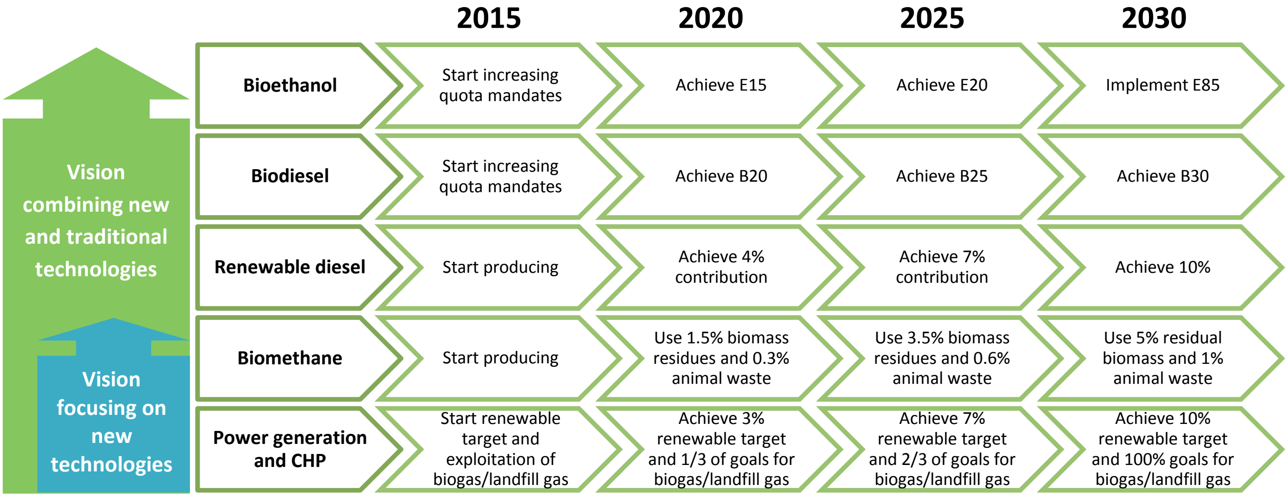
Milestones are intermediate steps required to accomplish the long-term goals. Details of the milestones classified by bioenergy area for the two visions are also shown in Table 11.

Most of the identified milestones are quantifiable measures. Examples include gradual increases in the biofuels quota mandate (i.e. achieve B20 in 2020 and B30 in 2030), in the renewable target in power generation (i.e. reach 10% renewables in 2025), in the contribution of renewable diesel to total diesel production (i.e. reach a 10% contribution in energy in 2030) and in the exploitation of residual biomass (i.e. exploit 5% of the biomass residues in 2030).

In order to realize the quantitative milestones different technical pre-conditions have to be achieved, which have to be settled in qualitative milestones. Two examples are given for the biodiesel and bioethanol areas. For bioethanol, a set of qualitative milestones is required to make sure that an increase in the quota mandate is feasible. These milestones include ensuring that non-flex-fuel aging vehicles with mid-level ethanol blends (>E10) can successfully operate and that all new gasoline-fuelled vehicles and motorcycles are flex-fuel. Similarly, for biodiesel, a set of qualitative milestones is required to ensure that aging and new diesel-fuelled vehicles can operate with blends higher than B10 as targeted in the long-term goals.

### E.4.4. Barriers to implement the bioenergy technology roadmap

There are various regulatory, market, technological and public acceptance barriers and gaps in knowledge that might thwart achieving the long-term goals and milestones. Next sections discuss in detail the barriers and gaps in knowledge identified by experts, as well as the recommended action items necessary to overcome them.



| | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|
| **Bioethanol** | Start increasing quota mandates | Achieve E15 | Achieve E20 | Implement E85 |
| **Biodiesel** | Start increasing quota mandates | Achieve B20 | Achieve B25 | Achieve B30 |
| **Renewable diesel** | Start producing | Achieve 4% contribution | Achieve 7% contribution | Achieve 10% |
| **Biomethane** | Start producing | Use 1.5% biomass residues and 0.3% animal waste | Use 3.5% biomass residues and 0.6% animal waste | Use 5% residual biomass and 1% animal waste |
| **Power generation and CHP** | Start renewable target and exploitation of biogas/landfill gas | Achieve 3% renewable target and 1/3 of goals for biogas/landfill gas | Achieve 7% renewable target and 2/3 of goals for biogas/landfill gas | Achieve 10% renewable target and 100% goals for biogas/landfill gas |

***Figure 37.*** *Timeline of long-term goals*

***Table 11.*** *Set of long-term goals and milestones*

| Vision | Bioenergy area | Long-term goals | Milestones |
|---|---|---|---|
| Vision combining new and traditional technologies | **Bioethanol** | • Increase the quota mandate from E10 to E20 (20%v anhydrous ethanol in gasohol) for gasoline-fuelled vehicles and motorcycles in 2025<br>• Implement an E85 (85%v anhydrous ethanol in gasohol) fuel program in 2030 | • Gradually increase the bioethanol quota mandate. Start in 2015 and reach E20 in 2025<br>• Ensure that all new gasoline-fuelled vehicles and motorcycles commercially available are flex-fuel vehicles (FFV) as of 2017<br>• Ensure satisfactory operation of non-flex-fuel aging vehicles with mid-level ethanol blends (>E10) by 2017-2020 |
| | **Biodiesel** | • Increase the quota mandate from B10 to B20 in 2020 and to B30 (30%v biodiesel in blend) in 2030 for all diesel-fuelled vehicles | • Gradually increase the biodiesel quota mandate. Start in 2015 and reach B20 in 2020 and B30 in 2030<br>• Ensure that all new diesel-fuelled vehicles commercially available can operate with blends higher than B10 by 2017<br>• Ensure satisfactory operation of aging diesel-fuelled vehicles with blends higher than B10 by 2017-2020 |
| | **Renewable diesel** | • Achieve a 10% contribution (on an energy basis) of renewable diesel in the total diesel fuel production in 2030 | • Gradually increase the contribution of renewable diesel in the total diesel fuel production. Start in 2015 and reach 10% in 2030 |
| Vision focusing on new technologies | **Biomethane** | • Use 5% of biomass residues and 1% of biogas from animal waste nationwide to produce biomethane to be injected into the natural gas network by 2030 | • Gradually increase the exploitation of residues and animal waste for biomethane production. Start in 2015 and reach goals in 2030 |
| | **Power generation and CHP** | • Supply 10% of the national electricity demand from renewable energy sources (excluding hydro > 10 MWe) by 2025. This target includes the following sub-targets:<br>○ Use 5% of the biogas from animal waste and municipal wastewater treatment plants nationwide for energy purposes (electricity, heat or CHP) by 2030<br>○ Use 100% of the biogas produced in the wastewater treatment process of biodiesel production plants for energy purposes by 2030<br>○ Use 10% of the municipal landfill gas produced nationwide for energy purposes by 2030 | • Increase the renewable target from 0% in 2015 to 10% in 2025<br>○ Increase the exploitation of biogas from animal waste and municipal wastewater treatment plants. Start in 2015 and reach 5% in 2030<br>○ Increase the exploitation of biogas in biodiesel production plants. Start in 2015 and reach 100% in 2030<br>○ Increase the exploitation of landfill gas. Start in 2015 and reach 10% in 2030 |

### E.4.4.1. Regulatory barriers

The regulatory barriers to accomplish the goals of the two visions are classified by bioenergy area and shown in Table 12. For biofuels already deployed in the country (i.e. biodiesel and bioethanol), most of the regulatory barriers relate to the lack of a centralized and consolidated authority issuing regulations, defining non-political mechanisms and long-term policies that allow further growth.

For the particular case of biodiesel, the lack of regulations and mechanisms for monitoring and controlling the quality of biodiesel at all stages of the supply chain represents another critical barrier. For power generation and CHP, the lack of an effective regulatory framework and pricing scheme that supports the deployment of renewable energy, distributed and small-scale power generation and CHP represents the largest barrier. To the date of writing this study, a new legislation on power generation and CHP has been approved (Law 1715 of 2014). As this law has not been regulated yet, the scope and potential impacts of it are not covered in this study.

Hence, it is acknowledged that some of the barriers and actions identified in this study might be already addressed by Law 1715. For other biofuels such as renewable diesel and biomethane, there are currently no regulations or incentives to encourage deployment.

### E.4.4.2. Market barriers

Market barriers are summarized by bioenergy area in Table 13. The principal market barrier for the two long-term visions is the economics of various biomass conversion processes, which are currently not competitive with fossil-based alternatives without subsidies (IEA, 2012d). This barrier is more severe for advanced biofuels and technologies such as biomethane, biogas and renewable diesel than for mature technologies (e.g. first generation biofuels, biogas, etc.). Other market barriers include: a) unfavorable pricing schemes and market conditions, b) linking to the international price of oil and commodities and c) market restrictions to deploy certain technologies.

Small-scale power plants are for example unable to sell power surplus and benefit from incentives, which prevents them from competing with large-scale hydro power plants. Currently, the governmental regulation sees a linking of local biodiesel and bioethanol prices to the international price of oil, commodities (e.g. palm oil and sugar) and the exchange rate. By this, macroeconomic trends influences directly local prices without taking into account the local market conditions. Presently, for economic and technical reasons, car manufacturers are not willing to produce or import vehicles able to operate the proposed biofuel blends.

### E.4.4.3. Technological barriers

Various technological barriers were identified for the different bioenergy areas and can be divided into four categories: a) barriers due to appropriate feedstocks, b) barriers due to incompatibility and operability problems of biofuels in aging engines, c) barriers due to limited technology transfer and d) barriers due to unsound technological practices. These barriers are described for the different bioenergy areas as follows.

Bioethanol

Firstly, a conflict of crops for food vs. biofuel exist because the feedstock used for producing bioethanol (e.g. sugar cane) is also used for producing sugar for human consumption. In addition, alternative feedstocks are not expected to be cost-competitive before 2030 with cane-based bioethanol. Lignocellulosic bioethanol is not expected to become commercially available, although it is a topic of joint research between Ecopetrol and the National Renewable Energy Laboratory (NREL) (Ecopetrol, 2013a). Other alternative feedstocks to produce bioethanol are neither expected to be competitive in the short term: a) Jaggery cane is a non-concentrated, artisanal industry with limited opportunities to profit from economies of scale; thus, production costs are high and logistics are difficult, b) cassava-based ethanol has been tested in Colombia by the national oil company, Ecopetrol (Ecopetrol, 2013a) and it was not found economically viable; a disadvantage of cassava compared to sugar cane is that it does not provide a by-product that can be used as an energy source and c) red beet-based ethanol by Maquilagro S.A. has also been tested in Colombia with poor results (El Tiempo, 2014); the reasons in this case were low productivity and non-economic performance. Secondly, barriers due to incompatibility and operability problems of bioethanol in aging engines are expected. While mid-level ethanol blends (> 10 v%) have been tested in aging vehicles in Colombia, claimed positive results are not fully acknowledged by all stakeholders. In 2009, the Universidad Tecnológica de Pereira jointly with the Ministry of Mines and Energy and Ecopetrol started testing E12, E15 and E20 in four vehicles. After five years of testing, it was claimed that mid-level ethanol blends did not present serious threats to the operability of gasoline-fuelled vehicles in Colombia (Asocaña, 2010; Asocaña, 2013; Portafolio, 2012b). However, these claims have been questioned by the car industry and some sectors of academia. One of the main reasons for this skepticism is that previous international experiences using or testing such blends in non-flex-fuel aging vehicles are not conclusive[10].

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[10] An example of the use of mid-level ethanol blends in an aging fleet occurred in the late 1970s at the beginning of the Proalcool program in Brazil. In-use vehicles operated ethanol blends of 15% in 1979 and 20% in 1981 without modifications. This was possible because in-use vehicles were manufactured with no emissions or fuel economy requirements (ORNL, 2007). This trend changed in the 1980s, when Proalcool promoted the modification or development of vehicles to run with higher ethanol blends. Other countries have started testing the impacts of mid-level ethanol blends on an aging fleet with contrasting results. In 2003, Australia commissioned a test program by the Orbital Engine Company, which found that materials used in vehicles (similar to Tier 1 vehicles in the U.S.) were not sufficiently compatible with E20 to satisfactorily operate over the lifetime. The U.S. Department of Energy (DOE) initiated in 2007 a test program to assess the impacts of E15 and E20 on tailpipe, evaporative emissions, catalyst and engine durability, vehicle drivability and operability, vehicle and engine materials, as well as on infrastructure material compatibility. Test results indicate that the use of mid-level ethanol blends in 86 Tier 2 vehicles (produced after 2004): a) did not present signs of corrosion or wear in the power train (DOE, 2010b), b) did not produce higher exhaust emissions (NOx, CO and NMVOC) compared to aging vehicles on ethanol-free fuels (NREL, 2012a) and c) presented a lower fuel economy, lower in proportion to the lower energy density (NREL, 2012a). These results have, however, been challenged by the Coordinating Research Council (CRC), an organization founded by automobile and oil companies in the U.S., which also conducted durability tests in 28 aging vehicles running with E15 and E20 (CRC, 2012; CRC, 2013). CRC results claim that E15 could damage valves and valve seals in 2001-2009 vehicles and have been criticized for using a questionable methodology (Bevill, 2012).

*Table 12.* *Regulatory barriers*

| Vision | Bioenergy area | Regulatory barriers |
|---|---|---|
| Vision combining new and traditional technologies | **Biodiesel and bioethanol** | • Currently biofuel regulations are separately defined by different authorities including the Ministry of Mines and Energy, the Ministry of Agriculture and the Ministry of Environment<br>• There is a lack of national long-term targets for biodiesel and bioethanol. Additionally, current biofuel policies are strongly influenced by the political agenda of the government and pressure from third parties (e.g. industry, foreign countries, trading partners, etc.)<br>• There is a lack of regulations and mechanisms for monitoring and controlling the quality of biofuels (particularly of diesel) at all stages of the supply chain<br>• Policies regulating flex-fuel vehicles and vehicles operating high biodiesel blends in Colombia are contradicting and not supportive of further growth in biofuels[11] |
|  | **Renewable diesel** | • While some regulations have been recently issued (e.g. (MME, 2014)), there are no current incentives to encourage the deployment of renewable diesel |
| Vision focusing on new technologies | **Biomethane** | • There is a lack of an effective regulatory framework, technical standards and an attractive pricing scheme that supports the transformation of residues or waste into alternative biofuels (e.g. biomethane) for energy purposes<br>• There is lack of regulations or incentives to avoid emission of methane (e.g. biogas) to the atmosphere or use it for energy purposes<br>• A barrier for alternative biofuels to substitute and compete with coal (actually the cheapest fuel for industrial use available in the market) is the lack of environmental regulations to penalize coal combustion (source of particulate matter, SOx, NOx, short-lived climate pollutants, etc.)[12]<br>• While in theory the National Fund for Royalties[13] can fund projects associated with biogas/biomethane, in practice it is very difficult. The main reason is that projects proposing only technology transfer are rejected and are required to prove local innovation for support. As Colombia is in an early stage of R&D, fulfilling the requirements of technology transfer and local innovation for alternative biofuel projects might be challenging. Nonetheless, there are successful examples where technology transfer stimulated innovation, such as the biodiesel industry that started importing equipment and currently develops some processes locally. |
|  | **Power generation and CHP** | • There is the perception among utilities, investors, regulators and policy makers that hydro power is the best solution (i.e. available, cheap and clean), even though it is very climate-dependent and it might compromise grid reliability and vulnerability<br>• There is lack of an effective regulatory framework and an attractive pricing scheme that supports distributed generation beyond bagasse large-scale cogeneration in sugar mills<br>• According to the existing regulation, cogeneration power plants cannot apply for the “reliability charge” incentive[14], which is a stimulus for power generation units able to guarantee the reliability of the system. Therefore, there is a competitive disadvantage compared to the large-scale power generation units (e.g. hydro and thermal power plants), which can effectively apply for this incentive<br>• Despite the fact that cogeneration power plants can currently sell power surplus to the grid, so-called “self-generators”[15] (<10 MWe) are not allowed. However, it is difficult to estimate the real potential and impact of “self-generators”, as the installed capacity is unknown<br>• The government is not willing to promote or subsidize technologies that are more expensive than hydro power plants, arguing that the overall emissions related to power generation are low compared to other sectors[16]. |

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[11] Despite decrees 2629 (Alcaldía de Bogotá, 2007) and 1135 (Alcaldía de Bogotá, 2009) defining the mandatory use of flex-fuel vehicles in Colombia as of 2012, decree 4892 (MME, 2011) overruled them and defined a voluntary use of flex-fuel vehicles.

[12] One example of lack of regulations and incentives for promoting alternative biofuels occurs in brick factories, which are allowed to burn any type of fuel (mainly coal, but also diesel fuel, wood and even tires) to produce heat with no regulation on emissions. In this case, alternative biofuels are the least used option because they are less polluting but commonly more expensive.

[13] Fondo Nacional de Regalías; see details in (DNP, 2014).

[14] Cargo por confiabilidad; see details in (CREG, 2014).

[15] Auto-generadores; see details in (UPME, 2004).

[16] In fact, GHG emissions associated with power generation in 2004 were 15 mio ton of $CO_2$ -eq., which accounted for 8.5% of the total emissions in the country (IDEAM-UNDP, 2009).

***Table 13.*** *Market barriers*

| Vision | Bioenergy area | Market barriers |
|---|---|---|
| Vision combining new and traditional technologies | **Biodiesel** | • The cost of producing biodiesel is currently too high to compete with diesel fuel without governmental support<br>• Car manufacturers are currently not willing to produce or to import vehicles able to operate blends with more than 7% biodiesel (by volume). The position of car original equipment manufacturers (OEMs) regarding biodiesel blends is mixed. While many car OEMs support up to B5 (mainly European), others support up to B20 (National Biodiesel Board, 2014). Most of the OEMs supporting up to B5 do not extend the warranty if equipment is damaged by higher blends, unless models are tested on biodiesel blends. In addition, engine manufacturers will not test the impact of biodiesel blends on legacy models.<br>• Market conditions to exploit by-products or sub-products of the palm oil or the biodiesel industry (e.g. biomass-based chemicals, biogas, etc.) are suboptimal<br>• The competitiveness of biodiesel is affected by high volatility in price, which in turn is driven by the price of oil and commodities and the exchange rate |
| | **Bioethanol** | • Car manufacturers are currently not willing to produce or to import flex-fuel vehicles to Colombia, arguing that it is a niche market<br>• The cost of producing ethanol is currently too high to compete with gasoline without governmental support<br>• The competitiveness of ethanol is affected by the volatility of international prices of oil and sugar and the exchange rate |
| | **Renewable diesel** | • Long-term goals for biodiesel might create competition for feedstock, in particular for palm oil |
| Vision focusing on new technologies | **Biomethane** | • The cost of producing biomethane either from biogas or syngas might be too high and noncompetitive with the cheapest fuels available in the market (coal for industrial use and natural gas for residential use) |
| | **Power generation and CHP** | • The current market for cogeneration power plants (particularly at capacities below 20 MWe) is almost inexistent. There are two potential causes for this: i) small and medium enterprises (SMEs) demanding heat and power are not willing to make significant investments and ii) current process economics are not favorable to self-producing heat and power and selling power surplus to the grid.<br>• While some experts consider that the low price of electricity is a market barrier, the fact is that the electricity price in Colombia is relatively high compared to that of neighboring countries and only behind Brazil and Chile in South America (EIA, 2010) |

Finally, three main barriers associated with limited technology transfer or to unsound technological practices exist and hinder a further deployment of bioethanol. The first one relates to the lower yields (~70-80 ton-cane/ha) that can be expected from cultivating cane in regions other than the Valley of the Cauca River. This is not only due to the sub-optimal soil and climate conditions but also to the limited infrastructure and skilled labor. The second one relates to the fact that today 70% of the cane fields in Colombia are burned before harvesting to facilitate the collection of stalks (BID-MME, Consorcio CUE, 2012). Thus, tops and leaves that could potentially be used in a power plant are wasted causing several environmental problems. These include air pollution, increased difficulty of using biological pest control, possibility of losing control of the fire in the fields and occasional interruptions in high voltage lines in the vicinity of the fields (Cannavam Rípoli, Molina Jr., & Cunali Rípoli, 2000). The third one relates to the transport of cane-based bioethanol from processing plants in the Valley of the Cauca River to end users throughout the country by diesel-fuelled trucks rather than by pipeline. This increases the lifecycle GHG emissions associated with bioethanol and reduce its environmental benefits.

Biodiesel

A conflict of crops for food vs. biofuel also exists for biodiesel because the feedstock used for producing it (e.g. palm oil) is also for human consumption. Alternative feedstocks like Jatropha curcas, soy, sunflower, algae, etc. are not expected to become cost-competitive in the short term.

Various operability and incompatibility problems of using biodiesel in aging engines remain unsolved and might become a significant barrier to expansion. Unsolved issues include: a) increase in tailpipe $NO_x$ emissions (Demirbas, 2009), b) a potential reduction in particulate matter from using biodiesel blends (Demirbas, 2009; Kousoulidou, Fontaras, Mellios, & Ntziachristos, 2008) remains to be proved in the field[17], c) biodiesel's oxidative degradation over time

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[17] Various studies have experimentally tested the influence of palm-based biodiesel blends on particulate matter by diesel engines in Colombia. However, results are non-conclusive. While Salamanca et

as a consequence of high concentration of fatty acids with double bonds negatively affect the emissions and engine performance (Kalam & Masjuki, 2002; Gan & Ng, 2010; Rizwanul Fattah, Masjuki, Kalam, Mofijur, & Abedin, 2014; Pullen & Saeed, 2014), d) emission of ultrafine particles in reciprocating engines using biodiesel remains to be tested, e) best practices on wastewater treatment (e.g. biogas capture and use of residues for energy purposes) are not commonly employed, f) the majority of methanol used for biodiesel transesterification is produced via petrochemistry, which adversely affects the life cycle emissions of biodiesel (Verhé, Echim, De Greyt, & Stevens, 2011), g) glycerol obtained as a by-product of the transesterification process presents a limited quality, which requires additional processing to be commercialized (Macario, Giordano, Bautista, Luna, Luque, & Romero, 2011) and h) biodiesel crystallization might occur, causing fuel filter clogging and impeding the flow of fuel in cold weather (NREL, 2012b).

On top of these technical issues, there is concern among various stakeholders that car manufacturers won't be willing to offer vehicles able to operate with blends containing more than 10% biodiesel by volume. Various references state that diesel fuel can be substituted by maximum 20% biodiesel with no or minor engine modifications (NREL, 2009; Minnesota Department of Agriculture, 2009; Verhé, Echim, De Greyt, & Stevens, 2011). However, certain manufacturers do not extend the warranty if equipment is damaged by such blends. Biodiesel can also be used pure, but in this case it does require engine modifications (NREL, 2009). International experiences on the extent to which biodiesel should be blended with diesel fuel is non-conclusive. While in the European Union the majority of blending is in the range 4-7%, in some U.S. states (e.g. Illinois, Minnesota) up to B20 has been successfully used, fulfilling the ASTM D6751 standards and with limited operability issues (NREL, 2009; Verhé, Echim, De Greyt, & Stevens, 2011).

Other barriers associated with limited technology transfer or to unsound technological practices exist and hinder a further deployment of biodiesel. Firstly, there is uncertainty regarding the environmental benefits of using biodiesel as a transport fuel in the Colombian context. Results from a number of studies show that GHG emissions of biodiesel blends strongly depend on land use change, fertilization schemes as well as waste and wastewater treatment practices (BID-MME, Consorcio CUE, 2012; Castanheira, Acevedo, & Freire, 2014). The influence of land use change is particularly large and significant differences in GHG emissions are expected for biodiesel from palm oil produced in different land types (e.g. cropland, savanna, scrublands, tropical rainforest, etc.). These differences might translate into uncertain environmental benefits if additional land for cultivating palm oil occurs in high carbon stock land (e.g. primary forest, tropical rain forest, etc.) and if waste and wastewater treatment processes are not sustainable. Secondly, some current practices are detrimental to the environmental benefits of biodiesel. Examples include: a) coal and diesel fuel are used to supply heat in biodiesel production plants, b) feedstocks to biodiesel processing plants and biodiesel to demand users are transported in diesel-fuelled trucks over long distances rather than by pipeline and c) methane and $CO_2$ are commonly released from water treatment plants in biodiesel processing plants.

Renewable diesel

The first barrier that hinders the production of renewable diesel relates to the use of appropriate feedstocks. Production of renewable diesel might compete with biodiesel production plants for feedstocks, particularly palm oil. Alternative feedstocks are not expected to be competitive with palm oil in the short term. Thus, additional land for cultivating palm oil is required and concerns about crops for food vs. biofuels and single crop farming remain unsolved.

The second barrier relates to a limited technology transfer and operability issues. Firstly, large-scale processing plants producing renewable diesel (hydrotreated vegetable oil) should demonstrate robust and reliable operation in the Colombian context to support expansion (IEA, 2011b). Secondly, a careful blending is required, given that the final fuel delivered to end-users of reciprocating diesel engines would contain diesel fuel, biodiesel and renewable diesel (Neste Oil, 2014). Thirdly, hydrogen required in the process is produced via petrochemistry, which negatively affects the life cycle emissions of renewable diesel (IEA, 2011b).

Biomethane

Although biomass gasification is a mature technology (IEA, 2012c), it still needs to prove operability, reliability and quality standards in the Colombian context. The combination of gasification, syngas clean-up, methanation and upgrade processes increases its complexity. In addition, the production and further use of tars derived from the gasification process is a problem that remains unsolved. Another important challenge to ensure the operation of biomethane process plants is to fulfill the quality standards of pipeline natural gas (e.g. pressure, water content,

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al. (Salamanca, Mondragón, Agudelo, & Santamaría, 2012) found a reduction in particulate matter as a function of the biodiesel added to diesel fuel, Rojas et al. (Rojas, Milquez Sanabria, & Sarmiento, 2011) found no significant difference in particulate matter between diesel- and B15-fuelled engines.

contaminants, etc.). In particular, careful attention should be paid to removing $CO_2$, water, hydrogen sulfide and its oxidation products (Stamatelatou, Antonopoulou, & Lyberatos, 2011).

Power generation and CHP

While renewable power generation (excluding large hydro) is not new in Colombia[18], considerable technological challenges are expected from increasing the renewable target to 10% in 2025. Firstly, a significant increase in installed capacity of renewable power is necessary. This additional capacity needs to be carefully planned to ensure a safe planning reserve margin. It should account for a typically lower capacity factor of renewable power technologies, caused by their intermittent operation, compared to base load power plants. In addition, renewable power must ensure robust performance, reliability and economic feasibility in the Colombian context. Secondly, sustainable operation of biomass-based power generation must be ensured. This means that the volumes of feedstock to run the power plant need to be assured. Thirdly, there is a lack of local companies developing renewable power generation and CHP technologies. However, both technology transfer and local manufacturing and R&D are necessary to ensure continuity of projects. In the particular case of power generation using biogas and landfill gas, additional barriers are identified. While to a certain extent biogas has been produced via biodigestion and used for in situ heating in the porcine industry (CNPML, 2009), experience on biogas use for power generation and CHP is limited in Colombia. Similarly, the landfill gas collected in various landfill sites is commonly flared or vented and, to a very limited extent, used for power generation (due to the high cost of electricity). On the other hand, there is a lack of studies estimating the energy potential associated with biogas production in water treatment plants nationwide, even though the potential from livestock and agro-industrial waste has recently been estimated (CNPML, 2009). Finally, economics of power biogas and landfill gas for power generation and CHP strongly depends on size and are unfavorable for applications below 200 kWe (Bachmann, 2012).

Other important barriers relate to unsound technological practices and limited technology transfer. Some past experiences using biomass-based energy technologies in the country were not successful. For example a small-scale CHP system installed in 1969 in Capote Field burning wood residues ceased operation as a consequence of non-sustainable wood management and the subsequent depletion of resources (AENE, 2003). Also, an incinerator of municipal residues installed on the island of San Andrés ceased operation because of an insufficient volume of residues. Additionally, a wood gasifier in Necoclí (Antioquia, Colombia), a non-interconnected zone (NIZ), ceased operation because the town eventually gained connection to the national grid (Cuevas, 2013). On the other hand, various facilities using biomass for energy purposes currently employ obsolete technology, which, in many cases, aim at disposing of biomass residues rather than producing energy efficiently. Moreover, many companies producing large amounts of residues (e.g. agriculture, forestry and wood industry, livestock, etc.) have limited knowledge of technologies for power generation and CHP. This gap in knowledge contributes to undermining the trust in implementing these technologies.

#### E.4.4.4. Public acceptance barriers

Public acceptance barriers can be divided into three categories: a) lack of acceptance of the current regulatory framework, b) overlooking benefits associated with bioenergy and c) lack of acceptance of new technologies (see Table 14). Various stakeholders including end-users, smallholders, farmers and sectors of academia consider the current regulatory framework and commercialization scheme of biofuels (viz. bioethanol and biodiesel) to be inappropriate. On the other hand, the benefits of distributed generation and CHP are not perceived by sectors of the government, utilities and investors mainly because large hydro is considered the best option. Regarding new technologies, such as biomethane and renewable diesel, there is a perception that there is lack of collaborative projects between OEMs, utilities, SMEs and universities.

### E.4.5. Action items to implement the bioenergy technology roadmap

In order to overcome barriers and achieve the envisioned long-term goals and milestones for the two visions, various action items are required. These action items are divided into: a) sustainability, b) regulatory, c) financing mechanisms and business development and d) technological. Sustainability is an overarching concept that requires consideration of regulatory, financing and technological items. Therefore, cannot be considered at the same level of these items. For this reason, sustainability action items prevail over other action items.

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[18] Up until 2009 the installed capacity of renewable power generation excluding large hydro was 852.5 MWe, of which 519 MWe corresponds to small hydro, 205 MWe to bagasse CHP, 18.4 MWe to wind and 110 MWe to waste. In total, the renewably generated electricity amounted to 1.2 TWh (UPME, 2011b).

*Table 14. Public acceptance barriers*

| Vision | Bioenergy area | Public acceptance barriers |
|---|---|---|
| Vision combining new and traditional technologies | **Biodiesel and bioethanol** | • While the current regulatory framework is designed to ensure a minimum profitability to local biofuel producers by controlling the biofuel price and the blend mandate quota, it does it at the expense of higher costs to consumers.<br>• Biofuels used in Colombia are typically characterized by having lower energy content than corresponding fossil fuels. However, the current biofuel pricing system does not acknowledge this effect, which results in higher costs per unit of energy for end-users compared to fossil fuels.<br>• The current regulatory framework does not include mechanisms to protect the interests of consumers.<br>• Subsidies and other benefits are granted even though local biofuel producers are not subject to a verifiable increase in rural jobs, increase in rural development in areas producing bioenergy, or reduction in life cycle GHG emissions.<br>• Subsidies to biofuels do not have a deadline or a gradual phase-out, which does not encourage local biofuel producers to become price-competitive over time.<br>• There is a serious concern with land use competition, the dilemma of crops for food vs. biofuels and the dependence on single crop farming (e.g. cane for producing bioethanol and palm oil to produce biodiesel). In the particular case of palm oil, there is concern that crop expansion in the last decade involved the forced migration of farmers, indigenous communities and ethnic minorities, deforestation and loss of biodiversity.<br>• There is concern over the existing business model, in which farmers cultivating palm oil on a small scale sell their production to large commercialized companies. While the farmers must take financial risks for cultivating the plant, only the commercialized companies have access to governmental aid (El Espectador, 2013).<br>• There is concern among end-users about the malfunction and failure of legacy or new vehicles caused by the increasing biofuel quota mandate. In the particular case of biodiesel, there is concern about the poor quality of the blend distributed in some regions.<br>• Some stakeholders consider electric mobility a more effective way to reduce GHG emissions in the transport sector than biofuels.<br>• There is a lack of communication and divulgation of results related to biofuels among universities and research institutions. |
| | **Renewable diesel** | Renewable diesel presents several advantages compared to biodiesel, e.g. higher energy content, higher cetane number, no detrimental effect on final boiling area, possibility to use current infrastructure. However, if palm oil is used as feedstock, the concerns about land competition, crops for food vs. biofuels and single crop farming remain unsolved. |
| Vision focusing on new technologies | **Biomethane** | • There is a lack of collaborative projects on biomethane production among OEMs, experienced companies, local utilities, SMEs and universities.<br>• There is the perception among some stakeholders that collecting 5% of the residues and animal waste resources for biomethane production is not feasible, the reasons being difficult logistics and unfavorable process economics. |
| | **Power generation and CHP** | • The benefits of distributed generation (e.g. reduction in distribution losses) and cogeneration (e.g. energy savings, reduced consumption of fossil fuels) are not known, perceived or acknowledged by sectors of the government, utilities and investors.<br>• There is concern about the risk of deforesting and clearing tropical forests to supply wood for biomass-based power plants.<br>• There is the perception that the power market is dominated by large utilities, which do not easily allow small producers to sell their power surplus and compete in the market. Additionally, there is a lack of collaborative projects among OEMs, experienced companies on renewable power generation, local utilities, small and medium power producers and universities.<br>• There is the perception that using biogas from water treatment plants is less impactful than other options, e.g. reducing GHG emissions from raising cattle. |

### E.4.5.1. Sustainability action items

Bioenergy is considered an alternative energy to reduce greenhouse gas emissions, decrease oil dependence, enhance rural development and diversify the energy matrix. However, significant concerns need to be addressed to make use of bioenergy. Hurdles include the presumed negative environmental impact, land use competition, crops for food vs. biofuels, direct and indirect land use change, deforestation, pressure on water resources, etc. In the Colombian context, additional concerns need to be considered. A 50-year armed conflict resulted in massive internal displacement of civilians, farmers and indigenous communities by illegal armed groups. Abandoned land was usurped, illegally traded and used for agriculture, mining and other purposes (UNDP, 2011).

In addition, public policies ruling rural areas have historically privileged large landholders over small farmers and have supported low productivity activities (e.g. extensive cattle farms) with limited capacity to create jobs (UNDP, 2011). Therefore, a more balanced and democratic land distribution that allows a more productive and environmentally friendly use of rural land should be a priority. The deployment of bioenergy technologies should be bound to ensure not only environmental and economic benefits, but also rural and social development. The inclusion of all stakeholders, particularly small- and medium-scale farmers, in the decision-making process of deploying bioenergy technologies is therefore essential. In this context, the victims and land restitution land law (Law 148) issued in 2011 in Colombia (MIJ, 2011) is certainly a step in the right direction.

There is scientific consensus that sustainability requirements and certification schemes are necessary to monitor environmental and social sustainability of bioenergy policies (GBEP, 2011a). Certification schemes also offer several advantages to biomass growers and bioenergy producers. On one hand, certification schemes ensure a credible standard to demonstrate benefits to tax payers and authorities. On the other hand, stakeholders can be recognized for the environmental, social and economic sustainable production of bioenergy. Strategic planning of land use should be emphasized to avoid deforestation, loss of biodiversity, displacement of communities, water and soil pollution, increasing gap between rich and poor and overall negative impacts. Various national and international initiatives and approaches for the sustainability certification of bioenergy have been recently proposed and developed worldwide.

More than 15 different certification schemes were identified in (Scarlat & Dallemand, 2011), which can be classified into the following categories: a) approaches with mandatory sustainability requirements, b) certifications for crops used as feedstock, c) national biofuel certifications and d) international biofuel certifications. Despite the rapid development of certification schemes globally, there is a lack of harmonized methodologies across approaches (Scarlat & Dallemand, 2011). Nevertheless, a general consensus on bioenergy sustainability criteria and a globally accepted GHG calculation framework is found in the Global Bioenergy Partnership (GBEP) (GBEP, 2011a). GBEP has developed a set of 24 sustainable indicators for the assessment and monitoring of bioenergy sustainability at a national level. This set of indicators has recently been tested in various countries, including Colombia (FAO-GBEP, 2014). Lessons learnt from testing the GBEP indicators in Colombia include: a) testing confirmed the usefulness of GBEP indicators to inform policymakers about the sustainability of bioenergy in the country and b) GBEP indicators are data and skills intensive; therefore, stakeholder engagement is necessary to get access to key data, process and interpret results. Although a dedicated effort to select and define bioenergy sustainability criteria for Colombia is certainly beyond the scope of this study, an exploratory scheme on the sustainability of bioenergy is suggested. This sustainability scheme also aims at mitigating the multiple public acceptance barriers identified in Section E.4.4.4. It is strongly recommended, however, that a commission representing all stakeholders (environmental authorities, industry, academia, local communities, etc.) take a leading role in defining a more detailed framework for bioenergy certification schemes in Colombia and consider lessons learnt from pilot testing the GBEP indicators in the country. The deployment of bioenergy technologies and particularly the long-term goals defined in Section E.4.2 should be bound to the bioenergy sustainability scheme to ensure not only environmental and economic benefits, but also rural and social development. The proposed scheme comprises four main categories of requirements explained as follows:

Requirements related to climate policy

Use of biofuels and conversion of biomass into energy should reach a minimum of GHG savings. Biofuels should reach a reduction in GHG of for example 40% relative to fossil fuels in 2015, 50% in 2020 and 60% in 2025. Biomass conversion to electricity, heating or cooling should reach a reduction in GHG of for example of 40% relative to fossil fuels in 2015, 50% in 2020 and 60% in 2025. Monitoring and reporting of GHG emissions is mandatory and should be rigorously supervised by environmental authorities. GHG savings should include emissions from cultivation, processing, transport, distribution and direct land use changes. Indirect land use changes (ILUC) must be included, but only after the scientific community reaches consensus on a sound accounting method. The method to calculate GHG savings should be widely recognized by the scientific community; examples include the Renewable Energy Directive 2009/28/EC of the European Union (EC, 2009a; EC, 2009b), the GBEP framework for GHG life cycle analysis of bioenergy (GBEP, 2011b), the Roundtable on Sustainable Biofuels GHG Calculation Method (RSB, 2011), among others.

Requirements related to environmental policy

Some land categories should be excluded of use for bioenergy production. These land categories include: a) natural parks and protected forests, b) tropical forests, native rain forest and wooded land, c) highly biodiverse ecosystems (wetlands, swamps, páramos, biodiverse savannah, etc.) and d) land with high carbon stock. Additionally, forests used to supply wood to energy projects (e.g. power generation, biofuels, biomethane, etc.) should comply with the certification of the Forest Stewardship Council (FSC), which is the best certification currently available (Leonard, 2010). Tropical forests or forests with indigenous vegetation must not be replaced by tree plantations. Tree plantations are monocultural fields of imported species, which provide relatively few jobs, increase the use of pesticides and negatively impact water cycles (Meadows, 1997). It might be advisable to use tree plantation only in eroded or degraded land. Regarding protection of water resources, biomass conversion and biofuels production must ensure that the quality of groundwater and surface water remains at high standards (a 5-day carbonaceous BOD below 2 mg/L) for human consumption, small-scale farming and fishing. Furthermore, it is advisable that these processes must regularly report their associated water footprint, which is the total volume of fresh water used.

Requirements related to rural development measures

The participation of local indigenous communities (natives, Afro-Colombians and members of other minorities) in the decision-making and the environmental planning process of projects affecting their land, resources and communities must be secured and protected. This in accordance with the United Nations Declaration on the Rights of Indigenous People adopted in 2007 (UN, 2007). Thus, permits to use land for bioenergy purposes fulfilling environmental requirements must be jointly evaluated by indigenous communities, and regulatory and environmental authorities.

Requirements related to incentives

Four main requirements related to incentives and financial mechanisms are recommended. Firstly, additional economic and tributary incentives should be given to conversion of waste, residues, non-food cellulosic and lignocellulosic biomass into energy. Secondly, as it is expected that biofuels and bioenergy will become more price-competitive over time, subsidies and economic incentives should not be indefinite and should start declining by 2015. Thirdly, access to subsidies and tributary incentives should be subject to a verifiable increase in rural jobs, and rural development (e.g. increase in rural GDP, infrastructure, etc.) in areas producing bioenergy, reduction in life cycle GHG emissions, protection of water sources and biodiversity and non-use of land categories excluded from bioenergy production. In the particular case of CHP, access to incentives should be subject to an appropriate use of the heat released in power plants to supply industrial, commercial, agricultural or energy processes. Finally, it is advisable to jointly revise and re-design the current biofuel regulatory framework with representatives from consumers, smallholders, farmers and academia. Topics to address include: a) appropriateness of subsidies, b) pricing system, c) mechanisms to protect the end-users, d) responsibilities of local biofuel producers to ensure sustainable operation, reduce GHG emissions, increase rural jobs, etc.

#### E.4.5.2. Regulatory action items

Regulatory action items classified by bioenergy area for the two visions are summarized in Table 15.

For bioethanol and biodiesel, it is firstly advisable to unify and centralize the definition of policies, regulations and long-term goals. It is also necessary to modify the existing policy framework (viz. to enable E20 in 2025, B30 and E85 in 2030, to implement a flex-fuel framework, to regulate the compliance of a sustainability scheme) to achieve the proposed long-term goals. For power generation and CHP, it is recommended to implement a renewable energy auction scheme, modify the existing policy framework to enable a renewable target of 10% in 2025 and stimulate the deployment of distributed generation, CHP, biogas, and landfill gas. For biomethane, it is appropriate to stimulate an efficient use of residues and encourage the substitution of highly pollutant coal in order to achieve the targets by 2030. For renewable diesel, a new policy is required to enable the implementation of a 10% energy contribution by 2030.

#### E.4.5.3. Action items on financing mechanisms and business development

Action items on financing mechanisms and business development are summarized in Table 16. In general, it is recommended that incentive programs to encourage the use of bioenergy through tax incentives and the local development of technologies are implemented. These incentive programs aim at reducing the production costs of bioenergy technologies, improving the efficiency of supply chains and conversion processes, improving the national competitiveness and supporting the local development of machinery, equipment and R&D.

***Table 15.** Regulatory action items*

| Vision | Bioenergy area | Regulatory action items |
|---|---|---|
| Vision combining new and traditional technologies | **Biodiesel and bioethanol** | • It is advisable that policies and regulations for biofuels are jointly created by the Ministry of Mines and Energy, the Ministry of Agriculture, the Ministry of Transport and the Ministry of Environment, or alternatively by a new institution, with members from these ministries, that centralizes actions and policies. This offers various benefits:<br>a. It would unify the official position of the government towards biofuels.<br>b. It would define a clear and unambiguous set of national long-term goals for biofuels, aiming at improving the sustainable development of the country.<br>c. It would centralize the definition of standards and rules (e.g. the bioenergy sustainability scheme), aiming at reducing the political influence of third parties on biofuel policies.<br>d. It would encourage a multidisciplinary discussion within the government to address biofuels from an energetic, agricultural and environmental perspective.<br>• It is required to implement a regulatory framework enabling: a) a gradual increase in quota mandate to B20 in 2020, E20 in 2025 and B30 in 2030 and b) the implementation of an E85 fuel program in 2030.<br>• It is required to implement a clear and definitive regulatory framework to force the introduction of flex-fuel vehicles (FFV) as of 2017. It would ensure that all new vehicles and motorcycles commercialized in the country are FFV and can satisfactorily operate with any blend of ethanol and gasoline. This regulatory framework should also force the introduction of diesel-fuelled vehicles able to operate blends higher than B10. Additionally, it would be advisable to design this framework in such a way that it does not block introduction of other vehicle alternatives, such as electric and hybrid vehicles.<br>• It is advisable to implement a regulatory framework to supervise and verify that local biofuel producers comply with the requirements of the sustainability scheme. It is also necessary, particularly in the biodiesel case, to control the quality of the biofuel at all stages of the supply chain. |
| | **Renewable diesel** | It is required to implement a new regulatory framework to enable the target of achieving a 10% contribution of renewable diesel in fuel diesel production by 2030. This framework should also regulate the quality of the renewable diesel and the blending conditions with diesel fuel and biodiesel. |
| Vision focusing on new technologies | **Biomethane** | It is required to modify existing regulations and legislation to:<br>a. Enable the implementation of biomethane targets by 2030.<br>b. Stimulate the substitution of highly-pollutant coal by biogas/biomethane in various sectors either by penalizing emissions, by offering incentives (tariff exemption for importing/developing equipment, tax reduction, support for demonstration projects, etc.) or by combinations thereof.<br>c. Create a mechanism to stimulate an efficient use of biomass residues and animal waste (urban and non-urban) for energy purposes. Potential solutions include price bonuses for effective waste management solutions, tariff exemption for developing equipment, tax reduction for imports, support for demos, etc.<br>d. Control and monitor the disposal of organic waste in landfills. |
| | **Power generation and CHP** | • The most appropriate framework to support a new power generation and CHP policy is the national renewable energy auction. It is considered the most appropriate because it respects the principle of equal opportunity and competitiveness among different technologies (a characteristic of the Colombian electricity framework), it limits the risk for investors and it increases the predictability of the renewable energy supply (Lucas, Ferroukhi, & Hawila, 2013). However, it should be carefully designed and acknowledge the experiences of other countries in order to avoid failures (e.g. favoring large players, discontinuous market development and risk of underbidding (Lucas, Ferroukhi, & Hawila, 2013)).<br>• It is required to modify existing regulations and legislation to:<br>a. Enable the implementation of a 10% renewable target by 2025, biogas and landfill gas targets by 2030.<br>b. Allow “self-generators” to sell power surplus to the grid. Additionally, it is advisable to estimate the actual installed capacity to evaluate the real impact of “self-generators”.<br>c. Allow cogeneration power plants to apply for the reliability charge incentive.<br>d. Allow the implementation of clusters of hybrid power plants (combination of different technologies, e.g. wind, small-hydro and biomass) to increase availability, reliability and risk mitigation not by power plant but by cluster.<br>e. Stimulate the capture and use of municipal landfill gas and biogas from animal waste, municipal wastewater treatment plants and biodiesel plants either by penalizing emissions or offering incentives. |

*Table 16. Action items on financing mechanisms and business development*

| Vision | Bioenergy area | Action items on financing mechanisms and business development |
|---|---|---|
| Vision combining new and traditional technologies | **Biodiesel and bioethanol** | • Implement a program to reduce the cost of producing bioethanol and biodiesel by improving the efficiency in harvesting, collection and exploitation of residues (e.g. cane leaves and tops and palm oil rachis), wastewater treatment practices (e.g. methane capture) and conversion processes (e.g. boilers and CHP systems). This program might be accompanied by benefits for developing or importing appropriate machinery and equipment<br>• Implement an incentive program primarily aimed at encouraging the local development or assembly of vehicles able to operate with high biofuel blends (e.g. flex-fuel vehicles for bioethanol) or secondly at reducing the import tariffs. Seek partnerships with OEMs willing to locally develop, assemble or import such vehicles<br>• Implement an incentive program aimed at reducing import tariffs or the value added tax (VAT) for importing agricultural supplies used by local producers of biomass and biofuels |
| | **Renewable diesel** | • Implement a careful plan for managing palm oil production and distribution to biodiesel and renewable diesel processing plants in order to reduce the impacts of competition for feedstocks. Additionally, implement a mitigation plant to identify and manage alternative feedstocks |
| Vision focusing on new technologies | **Biomethane** | • Implement an incentive program aimed at encouraging the substitution of cheap fossil fuels (e.g. coal, diesel fuel, etc.) by biomethane (pure or blended with natural gas) either by penalizing the consumption of fossil fuels or by reducing taxes on biomethane |
| | **Power generation and CHP** | • Implement an incentive program aimed at encouraging the operation of small scale and distributed power plants and CHP (e.g. (Gonzalez-Salazar & Willinger, 2007) through tax benefits and technical support. Additionally, encourage the local development or assembly of distributed and renewable energy technologies. It is crucial to seek partnerships with OEMs, utilities, SMEs & universities to build demos and pilot projects.<br>• New initiatives for providing services and energy solutions are required to support the incipient industry of distributed power generation and CHP. It would be advantageous to promote the creation of Energy Service Companies (ESCOs), able to provide energy savings projects, energy efficiency solutions, implementation of renewable energy sources, risk management, etc. However, a program for the promotion of ESCOs should be carefully designed in order to avoid the most common failures, e.g. lack of trust among investors, perceived high technical and business risk, lack of policy mechanisms to support ESCOs, high transaction costs, etc. (Bertoldi, 2007; Kostka, 2011) |

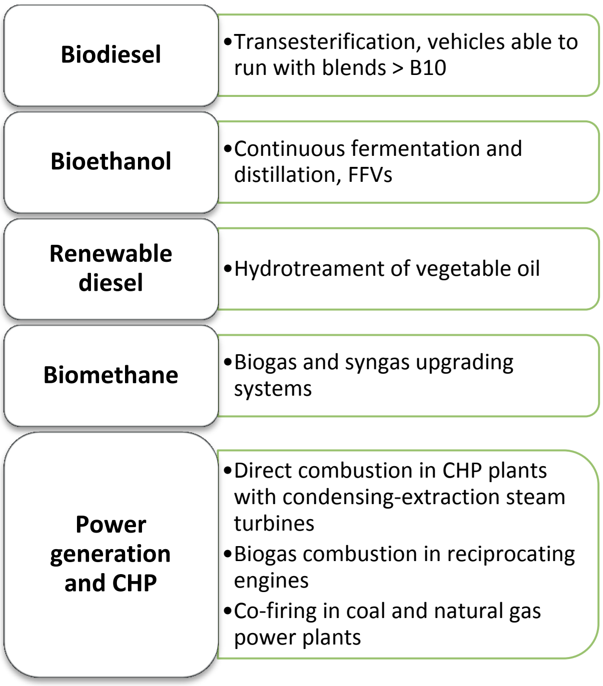

***Figure 38.*** *Technologies to deploy by bioenergy technology area*

For this purpose it is crucial to seek partnerships with OEMs, utilities, SMEs and universities to build demonstration and pilot projects, etc. Additionally, new initiatives for providing services and energy solutions (e.g. Energy Service Companies –ESCOs–) are required to support the incipient industry of distributed power generation.

### E.4.5.4. Technological action items

Technological action items by bioenergy technology area are described as follows. Technologies recommended for deployment by bioenergy technology area are summarized in Figure 38.

<u>Bioethanol</u>

It is recommended to further deploy cane-based bioethanol with continuous fermentation and vinasse recirculation, subject to compliance with the sustainability scheme. The main benefit of vinasse recirculation with yeast and organic matter separation is a lower vinasse production (0.8-3 l-vinasse/l-ethanol) than the ferti-irrigation approach used in Brazil (8-12 l-vinasse/l-ethanol) (BID-MME, Consorcio

CUE, 2012). It is also recommended to continue deploying water treatment plants for effluents to ensure high quality standards for ground- and surface water. Additionally, a satisfactory operation of non-flex-fuel aging vehicles and motorcycles with mid-level ethanol blends (> E10) must be ensured. Thus, it is recommended to start a well-coordinated test campaign involving all stakeholders (i.e. government, car and oil industry, biofuel producers, universities, standards organizations and end-users) and able to: a) test a statistically representative sample of the existing vehicle fleet (e.g. 86 and 28 vehicles were respectively tested by DOE (DOE, 2010b) and CRC (CRC, 2012; CRC, 2013) using a method that can be reproduced and verified by the scientific community, b) acknowledge results from previous international experiences, c) assess the effects of aging vehicles with mid-level ethanol blends and identify potential operability issues under real operating conditions in Colombia and d) define a mitigation plan to avoid operability issues, for example include the possibility to maintain E10 in fuel stations to allow consumers to choose their blend.

In order to improve the environmental performance of bioethanol, rigorous environmental studies subject to verification must be undertaken by independent institutions, including analyses of the impact of expanding cane cultivation on direct land use change (include ILUC only once scientific consensus on a sound method has been reached), water demand and wastewater produced, impact on biodiversity, impact of vinasse disposal on soil, groundwater and surface water, and finally life cycle emissions. Moreover, various improvements are recommended to enhance productivity and environmental performance, including: a) avoid cane burning before harvesting, b) deploy mechanical harvesting and recovery and exploitation of cane residues (e.g. leaves and tops) in CHP systems and c) transport of bioethanol from production sites to demand sites via pipeline. Even though various topics are not part of the present roadmap, it is recommended to start monitoring them and perform feasibility studies in the short term. These topics include biorefineries, lignocellulosic ethanol, bio-butane, drop-in biofuels and bioethanol direct cylinder injection in gasoline and diesel engines.

### Biodiesel

It is recommended to further deploy palm-based biodiesel via transesterification equipped with water treatment plants and subject to compliance with the sustainability scheme. In addition, a satisfactory operation of legacy vehicles operating with blends > B10 must be ensured. Similarly to the case of bioethanol, a well-coordinated test campaign involving all stakeholders and including the abovementioned guidance is recommended. A mitigation plan might include, for instance, the possibility of maintaining B10 in fuel stations to allow consumers to choose their blend. Further research is required to reduce the negative impacts associated with biodiesel blends. Topics include reduction of tailpipe NOx, particulate matter and ozone, reduction of negative impacts of antioxidant additives and minimization of the impact of biodiesel crystallization on engine operability, etc. Other recommended improvements to enhance productivity and environmental performance include: a) minimize the use of fossil fuels and encourage their substitution for palm oil residues, b) deploy technologies to capture methane from wastewater plants and c) motivate the transport of biodiesel from production sites to demand sites via pipeline. Finally, it is recommended to start monitoring various topics not covered in this study, such as biorefineries, glycerol-free processes (e.g. Ecodiesel®, DMC-Biod®, Gliperol®), second and third generation biodiesel (using jatropha, brassica, algae, etc.).

### Renewable diesel

Long-term goals for renewable diesel can be reached using hydrocracking or hydrogenation of vegetable oil, which are in an early commercial phase and are expected to become available in Colombia by 2015. It would be advantageous to deploy these plants as stand-alone as well as integrated into a standard oil refinery. Rigorous environmental studies subject to verification must be undertaken for the Colombian scenario. Additionally, further research is required to find ways to economically produce hydrogen from renewable sources and to carefully blend diesel fuel, biodiesel and renewable diesel.

### Biomethane

It is recommended that two technologies are deployed, depending on the feedstock: a) the purification of landfill gas and biogas from animal waste and b) syngas via gasification followed by methanation to convert biomass residues. While landfill gas/biogas purification is a mature technology, gasification and methanation are in an early commercial stage. Additionally, further research is required to increase the ability to process different types of feedstocks, to improve syngas cleaning and upgrade, and to reduce operability issues (particularly for biomass gasification). In addition, it is crucial to seek partnerships with OEMs, utilities, SMEs and universities to ensure that technology transfer encourages local innovation on this topic.

### Power generation and CHP

To achieve the renewable target of 10% in 2025, it is recommended to deploy onshore wind, small-hydro and biomass power plants. Other renewable energy technologies (e.g. solar, geothermal, offshore wind, etc.) are not included in the present roadmap, but it is recommendable to monitor their development and start feasibility analyses in the short-term. Recommended biomass-based power generation technologies include: a) direct combustion in CHP power plants using condensing-extraction steam turbines (feedstocks include wood residues, bagasse, cane tops and leaves, bagasse from jaggery cane, rice husk, and palm oil residues), b) co-firing in coal power plants using biomass pellets and co-firing in natural gas power plants using syngas from gasified biomass, c) combustion of landfill gas and biogas in reciprocating engines. It is also recommended that clusters of hybrid power plants (a combination of different technologies, e.g. wind, small-hydro and biomass) are implemented, thereby increasing availability and reliability not by power plant but by cluster. Best practices of the sugar cane and paper industry engaged in cogeneration should be replicated to other crops producing large amounts of residues and consuming energy, such as palm oil, jaggery cane, rice, coffee, coconut, etc. In addition, further research is required to evaluate the impact of replacing hydro power by biomass-based power. For instance, a complementing effect might be expected in dry seasons when the availability of bagasse-fired CHP tends to increase, while the availability of hydro power tends to reduce. Potential advantages include a higher availability and grid reliability and a reduced consumption of fossil fuels to replace hydro.

It is recommended to seek partnerships between OEMs, utilities, local companies and universities, to start demos and pilots in the short term that might lead to commercial projects in the medium term. It is crucial to acknowledge past experiences and design strategies to ensure sustainable operation by involving local communities. It is also necessary to encourage technology transfer combined with local manufacturing to ensure the continuity of projects and know-how creation. It is also important to educate the industrial sector on the benefits of distributed generation (e.g. electrification of remote areas, enhanced energy security, fast implementation, higher flexibility, reduced GHG emissions, wider acceptance, etc.), renewable power generation and cogeneration and exploitation of biomass residues, animal waste and by-products. Finally, it is recommended to start monitoring various topics not covered in this study, including: biomass pretreatment processes (i.e. torrefaction), biomass combustion with organic Rankine cycles (ORC), gasification in gas turbines, etc.

## E.5. Guidelines and recommendations

Considering the vast potential and the significant demand for bioenergy in developing countries, it is useful to ask how the process of developing a roadmap for deploying bioenergy technologies in Colombia can bring lessons and provide guidelines to other countries.

Firstly, it is fundamental to start a technology roadmapping process. In many countries, bioenergy resources have been used informally and inefficiently, which has led to severe environmental and health problems. Thus, initiating the process of technology roadmapping offers various benefits: a) it enables a nation to prepare for the future in an orderly and systematic way, b) it provides a basis for building consensus on needs and for measuring progress and impact and c) it turns consensus and analytical work into systematic actions. While technology roadmapping is very advantageous, it is also demanding. It involves many uncertainties in a rapidly changing external environment that demands significant more time and resources than short-term planning.

Secondly, it is fundamental to employ the right roadmapping method. In this study, a new method for technology roadmapping is proposed. This method is largely based on the guide to development and implementation of energy technology roadmaps developed by IEA (IEA, 2010). While the IEA's guide is a very detailed and robust method that can be applied to any country, its structure is best adapted to OECD countries. For developing countries, it can be challenging to implement the full method, which requires various detailed and lengthy processes and involve multiple working groups. Thus, the original IEA method has been here simplified. The number of process steps and feedback loops has been reduced, a new strategy for building consensus has been proposed and a more prominent role to analytical modeling has been given (optional in the IEA's guide).

Thirdly, it is critical to involve decision-makers and a significant number of experts representing all stakeholders. Involvement of decision-makers from the government would certainly facilitate not only the access to data and analyses, but also the process of implementing the roadmap and updating or continuing the roadmapping process. Moreover, decision-makers should drive the roadmapping process. The involvement of all stakeholders encourages inclusiveness in the definition of long-term strategies and adds credibility to the roadmap and its implementation. However, an extensive number of participants can be counterproductive, as reaching consensus might be difficult.

Fourthly, sometimes consensus cannot be reached among experts. In this case, the IEA recommends choosing one position, to present the opposing views if one of those is the minority, or to attempt to create consensus between the two sides. In this study, experts strongly disagreed on the long-term goals for deploying transport biofuels (i.e. bioethanol, biodiesel and renewable diesel) and no consensus could be reached. A scenario analysis to analyze both views separately is here proposed.

Finally, it is crucial to define the right mechanism to put the roadmap into place. The present study, which is an academic initiative, does not have forcing mechanisms to put it into place. Conclusions and recommendations presented here can be regarded as an attempt to initiate the technology roadmapping process and can be used as an input to policy-makers. Thus, to ensure the success of a technology roadmap, it is necessary that governmental agencies drive the process and ensure its implementation.

## E.6. Summary and discussion

In this chapter, the process of developing a roadmap for deploying bioenergy technologies at a country level is described. Firstly, a method for energy technology roadmapping adapted to the conditions of developing countries is proposed. The method consists of three components: 1) a simplified version of the structure proposed in the guide to develop and implement energy technology roadmaps by the IEA, 2) a new strategy to build consensus and 3) a strong focus on analytical modeling for supporting expert judgment. Advantages of the proposed method include: simplicity, adaptability to developing countries, a more systematic strategy to achieve consensus and to handle divergence and a stronger focus on analytical modeling compared to prior art.

Secondly, the proposed method is applied for creating a plan to deploy sustainable bioenergy technologies in Colombia until 2030. The plan consists of a set of long-term goals, milestones, barriers and action items identified by 30 experts for different bioenergy technology areas. Experts considered five key bioenergy technology areas: a) bioethanol, b) biodiesel, c) renewable diesel, d) biomethane and e) biomass-based power generation and CHP. Unanimous agreement was achieved on the long-term vision for biomethane and biomass-based power generation. However, there were opposing views on the long-term vision of liquid transport biofuels (i.e. bioethanol, biodiesel and renewable diesel) produced from feedstocks that are used for human consumption. Consequently, two different long-term visions are considered. The first vision targets the deployment of new technologies for the production of biomethane, electricity & CHP, while fixing the current blend mandate of 1st gen biofuels. The second vision targets the deployment of new technologies for the production of biomethane, electricity & CHP, while further growing 1st gen biofuels. Various actions are required to accomplish the long-term goals in both visions. Firstly, it is necessary to define and implement a bioenergy sustainability scheme to be bound to the deployment of bioenergy technologies. Secondly, new regulations and policies are required to enable the implementation of long-term targets for the different bioenergy areas. Thirdly, incentive programs and financial mechanisms need to be implemented to encourage technology transfer combined with local development. Fourthly, technical risks must be mitigated by engaging all stakeholders and local communities, acknowledging past international experiences and following best practices.

# Chapter F. Framework for evaluating the energy, emissions and land-use nexus

## F.1. Overview

This chapter is divided into four main sections. Section F.2 describes a proposed modeling framework to address the energy, economy, emissions and land use nexus focusing on the bioenergy exploitation in developing countries. Section F.3 describes in detail the Energy System Model (ESM) to replicate the behavior of the energy system at a country level. In Section F.4, the modeling framework is applied to the case study of Colombia. Finally, Section F.5 presents a summary and discussion of the chapter.

## F.2. Method

This section presents an overview of the state-of-the-art approaches for modeling the energy, economy, emissions and land use nexus. In addition, it presents a proposed modeling framework to address this challenge with a particular focus on bioenergy exploitation in developing countries.

### F.2.1. State-of-the-art

In the coming decades, energy, environment and sustainable development goals are expected to face serious challenges at national, regional and global levels (Rodriguez, Delgado, DeLaquil, & Sohns, 2013; UN, 2014b; Hoff, 2011; WEF, 2011; Hanlon, Madel, Olson-Sawyer, Rabin, & Rose, 2013; IPCC, 2014; UN, 2014a; Bizikova, Roy, Swanson, Venema, & McCandless, 2013; Halstead, Kober, & van der Zwaan, 2014; IEA, 2012d). Many of these challenges are fundamentally interrelated. For example, energy, water and land are required to cultivate food crops, which are needed to support the world's growing population. Water is needed for generating any form of energy, and energy is required for securing water supply. Population, water and energy infrastructure are needed for ensuring economic development. Land is not only required for food production but also for energy purposes and contributes significantly to greenhouse gas emissions. Energy, land use and economic development affect in many ways climate change, but are also affected by it. Various terminologies exist to refer to these relationships depending on the extent and number of linkages among the different sectors, e.g. water-energy nexus (WE), the water-energy-food (WEF), water-energy-land (WEL), the climate-land-energy-water nexus (CLEW) and the climate-land-energy-water-development nexus (CLEWD) (UN, 2014a), among others.

The depth and intensity of linkages between climate, energy, water, land and development vary enormously among countries and regions (Arent, et al., 2014; IPCC, 2014; Hanlon, Madel, Olson-Sawyer, Rabin, & Rose, 2013). Some of these linkages pose significant problems at the national or regional level, but can be solvable as are relatively short-lived (Halstead, Kober, & van der Zwaan, 2014). Examples of such linkages include: the energy-water nexus (Halstead, Kober, & van der Zwaan, 2014), the energy-sustainable development nexus (WEF, 2011) and the energy- and water-land nexuses (UN, 2014a). In contrast, some other linkages are global and worsen the impact of national or regional linkages in many parts of the world (IPCC, 2014; UN, 2014a). These linkages are long lived and are not easily solvable, typically requiring global solutions (Halstead, Kober, & van der Zwaan, 2014). Examples of such linkages include the influence in both directions of climate change with energy, water, land and economic development (Halstead, Kober, & van der Zwaan, 2014; UN, 2014a).

While challenges associated with these sectors have been mostly addressed and studied independently, a multidisciplinary approach to investigate the nexus can lead to a more efficient resource use as well as cross-sectorial consistence (Halstead, Kober, & van der Zwaan, 2014). In the last few decades, integrated approaches to investigate the above-mentioned interrelations have been promoted with moderate success. Today, multidisciplinary integrated approaches addressing these nexuses are uncommon, although certain exceptions exist (UN, 2014a).

Interrelations between sectors at a global or regional scale (e.g. focusing on climate change and its linkages) have been addressed by a limited number of multi-sectorial integrated assessed models (IAM) (UN, 2014a). IAMs are commonly used to investigate climate change and related global environmental problems by describing relevant parts of the energy-economy-climate system (UNEP, 2013; IPCC, 2014). IAMs describe in a simplified manner the interaction between multiple components of the overall system, for instance energy supply and demand, land use, the carbon cycle, atmospheric chemistry and climate system (UNEP, 2013). Examples of IAMs addressing three or more linkages at global or regional scale include: IMAGE, ASF, ICLIPS, IGSM, MERGE, GCAM, GEM E-3, and Second Generation Model (Pollitt, et al., 2010).

At the national level, a moderate number of approaches have addressed the mentioned nexus. Methods and characteristics vary largely across different approaches. Approaches can be classified according to various criteria: 1) type of analysis, 2) level of comprehensiveness, 3) extent of analysis, 4) type of entry point, 5) type of country targeted, 6) level of accessibility and 7) flexibility to be applied to different contexts and countries. Regarding the type of analysis, most of the tools are purely quantitative, while a few ones incorporate qualitative elements (Ferroukhi, et al., 2015). Regarding the level of comprehensiveness, most of the tools have complex frameworks, while there is a lack for relatively simple tools that can provide preliminary assessments (Ferroukhi, et al., 2015). Various approaches are “entry point” (i.e. one sector influences others), while a reduced number are “fully integrated” (i.e. relations between sectors exist in all directions) (Ferroukhi, et al., 2015). Regarding the extent of analysis, most studies investigate less than three sectorial linkages (e.g. (Masson, et al., 2014; Suttles, Tyner, Shively, Sands, & Sohngen, 2014; Di Leo, Pietrapertosa, Loperte, Salvia, & Cosmi, 2015; Viebahn, Vallentin, & Höller, 2014; Senger & Spataru, 2015; Bryan, Crossman, King, & Meyer, 2011; Edmonds, Clarke, Dooley, Kim, & Smith, 2004)), while only a few studies have investigated more than three (details in (UN, 2014a; Ferroukhi, et al., 2015)). Regarding the type of entry point, approaches have used either food or energy as entry point. Ferroukhi et al. point out that while various simple tools using food as entry point exist, there is a lack for simple tools using energy as the entry point. Regarding the type of country targeted, most approaches focus on industrialized countries and a few emerging economies, while only a few studies have addressed non-OECD developing countries, notable examples include (Hermann, et al., 2012; Morrison, 2012; Welsch, et al., 2014; Wattana, 2013; Omar, Almoustafa, & Al-Din, 2013; Daher & Mohtar, 2013; Swierinski, 2012). From studies in non-OECD countries, only five have addressed the topic of biomass and bioenergy and its interrelations with other sectors. Regarding the level of accessibility, most of the tools appear accessible to a large number of users and allow for policy making. Finally, Ferroukhi et al. conclude that most tools can be adapted to different contexts and geographies.

### F.2.2. Gaps in knowledge

There is a gap for relatively simple nexus tools with energy as the entry point that satisfy the following criteria: 1) provide preliminary assessment, 2) use energy as the entry point, 3) combine quantitative and qualitative methodologies, 4) address the topic of biomass and bioenergy and its interrelations with other sectors and 5) be applicable to developing countries. A proposed modeling framework aims at filling this gap.

### F.2.3. Proposed modeling framework

While the approach of most nexus tools found in literature is purely quantitative, the method proposed in this study combines a quantitative and a qualitative element (see Figure 39). There is a key advantage associated with this combination. While quantitative approaches (i.e. analytical modeling) are essential for assessing (separately and jointly) energy, economy, emissions and land use, they alone might be insufficient to identify potential solutions on the long-term.

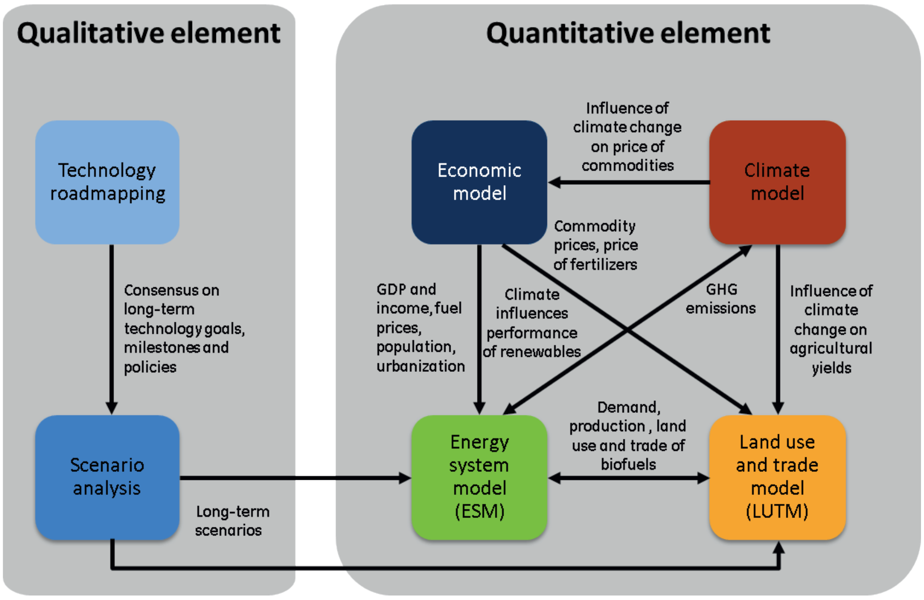

***Figure 39.** Modeling framework*

On the other hand, qualitative approaches are well-accepted methods to identify long-term solutions and to describe how and why they should be used (IEA, 2010). However, qualitative methods alone might also be insufficient to evaluate the impact of long-term solutions on different sectors. Thus, combining qualitative and quantitative elements offers the possibility of identifying potential long-term solutions and quantifying associated impacts. In the proposed modeling framework, the qualitative element combines two components: technology roadmapping (see Chapter E) and scenario analysis.

### F.2.3.1. Qualitative element

A qualitative element combining technology roadmapping (already described in Chapter E) with scenario analysis to address the challenge of identifying long term technology targets is proposed.

#### F.2.3.1.1 Technology roadmapping

A method for performing technology roadmapping under the conditions of developing countries has already been presented in Chapter E and for the sake of brevity is not shown here.

#### F.2.3.1.2 Scenario analysis

Sometimes, consensus cannot be built among experts in technology roadmapping exercises. In this case, the IEA's guide to development and implementation of energy technology roadmaps recommends either: 1) choosing one position, 2) presenting the opposing views if one of those is the minority, or 3) attempting to create consensus between the two sides. In this study, it is rather proposed to analyze multiple differing views through scenario analysis. Key advantages of scenario analysis include: a) it offers the possibility to address the uncertainty caused by unpredictability of future events, b) it allows considering various future storylines when consensus cannot be built and c) it allows policy analysis. By identifying the most effective policy measures, scenario analysis might contribute to increase the chances of implementing a technology roadmap.

### F.2.3.2. Quantitative element

The quantitative element is formulated under the criteria defined in the introductory chapter: 1) it should be transparent, easy to implement, generic and replicable, 2) it should be inexpensive to adapt to constrained R&D budgets, 3) it should be built in well-known and generic platforms in order to increase the level of accessibility and 4) it should follow robust and state-of-the-art approaches (preferably bottom-up) to address the gaps in knowledge described above. Thus, a combination of four integrated tools is proposed, namely the energy system model (ESM), the land use and trade model (LUTM), an external climate model and an economic model (see Figure 40). These tools are employed to evaluate the impacts of implementing the long-term technology targets on the energy system, the land use and the GHG emissions.

While in this framework relations exist between the four individual tools, these relations do not always occur in all directions. Thus, this framework can be described as one using energy as the entry point. Given that energy is the entry point, it is proposed to develop an energy model as comprehensive as possible. The ESM model is a scenario-based, demand-driven model that combines various modeling techniques to replicate the behavior of the country's energy system and the associated emissions. The ESM model is built on the Long-range Energy Alternatives Planning System (LEAP), a platform widely used to report energy policy analysis and greenhouse gas (GHG) mitigation assessments that is free for users in developing countries (Connolly, Lund, Mathiesen, & Leahy, 2010). Given the extension of the EMS model, a full separated section is dedicated to explain this model (see Section F.3). In contrast, relatively simple models for analyzing land use, trade, economy and climate are proposed. For the land use and trade it is proposed to use a simple resource-focused statistical model (LUTM), which is non-spatially explicit analysis and thus easy to implement and inexpensive. It estimates land use as well as production and trade of 18 agricultural and forestry commodities and is built in Microsoft Excel. The ESM and the LUTM models employ various state-of-the-art modeling techniques designed or adapted from prior art (see Sections F.2.3.3 and F.3, respectively), which satisfy the premises of being transparent and replicable. In addition, the two models are built on well-known and generic platforms, such as LEAP and Microsoft Excel, which makes them relatively inexpensive and easy to replicate.

#### F.2.3.2.1 Linkages between tools

The four tools of the quantitative element are interrelated, as shown in Figure 39 and Figure 40. Firstly, the scenarios defined in the qualitative element influence the ESM and the LUTM models. Long-term goals, policies and assumptions of the different scenarios are used as inputs for these two models. The ESM model is influenced by the LUTM model as well as by the economic and climate models. The demand for energy resources by the different sectors of the economy is influenced by multiple economic drivers including the GDP & household expenditure, population, energy prices and access to energy services (i.e. electricity, natural gas and biofuels).

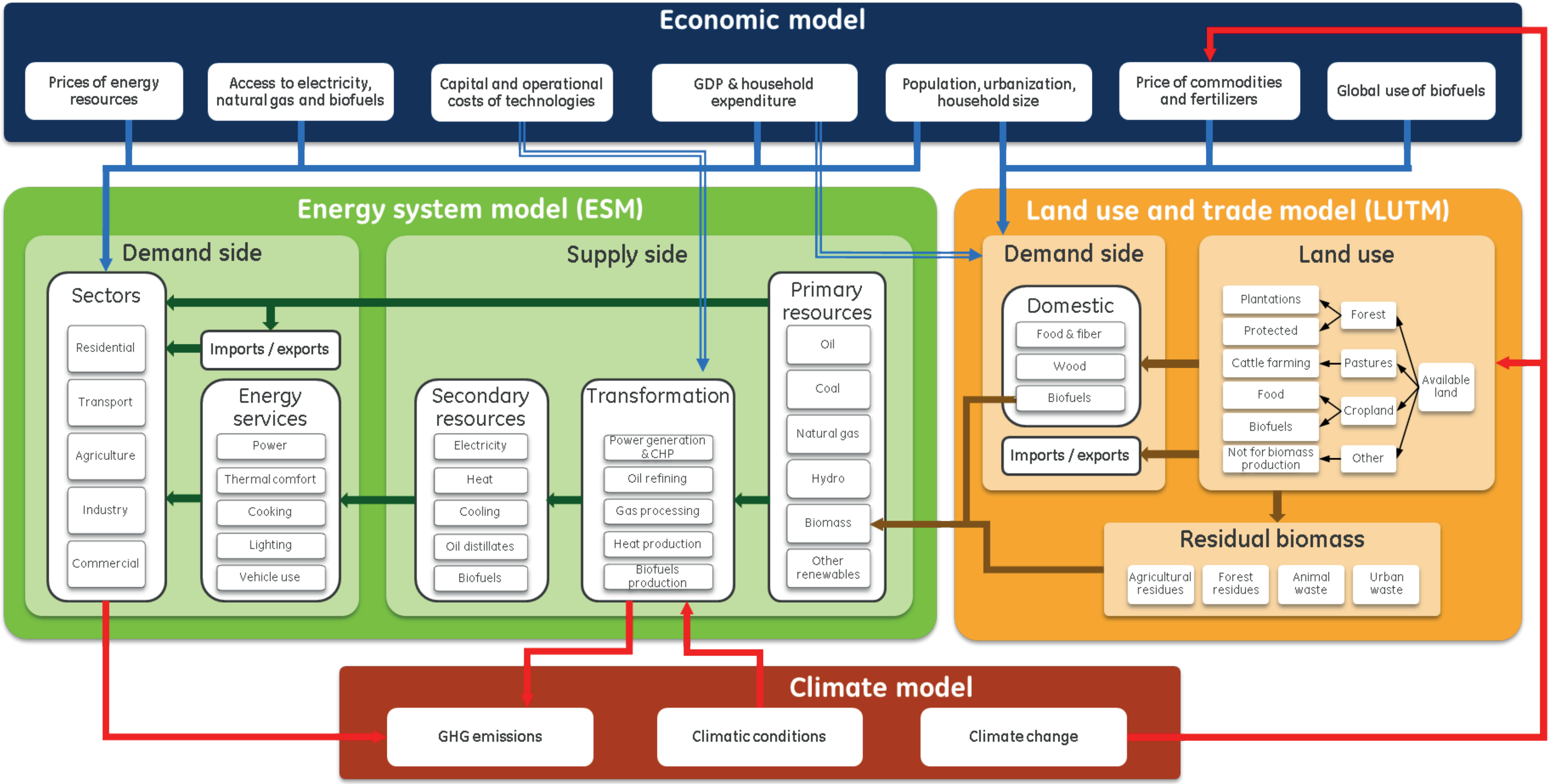

***Figure 40.*** *Quantitative element of the modeling framework*

The deployment and performance of technologies for transforming primary energy resources into secondary energy carriers is influenced by capital and operational costs and in some cases by climate conditions (e.g. hydro power, wind power, etc.). The demand for biomass resources estimated in the ESM model is then exported to the LUTM model. The LUTM model optimizes the production and trade of biofuels, woodfuel and other commodities and estimate feedstocks and required land. Outputs of the LUTM model are then used as inputs in the ESM model to estimate the conversion of residual biomass into energy.

In addition to the link with the ESM model, the LUTM model is also linked with the economic and climate models. GDP, population, price of commodities and global use of biofuels are the main economic drivers to estimate the demand for agricultural and forestry commodities in the LUTM model. The LUTM optimizes the land use and allocates production for supplying local demand and exports. Climate change influences this optimization, as agricultural yields and price of commodities depend to certain extent on climate change conditions.

Finally, GHG emissions produced on the demand and supply sides of the ESM model influence the climate change model. While in theory emissions associated with the land use in the LUTM model also influence the climate change model, this link is not covered in the present study.

#### F.2.3.2.2 Climate model

Rather than formulating a new climate model, the use of projections of external climate models is here proposed. It is proposed to use the projections of the general circulation model (GCM) developed by Fischer et al. at IIASA (Fischer, 2011). Relevant projections of this model to the present study include: a) influence of climate change on agricultural yields and b) influence of climate change on price of commodities. Details of the mentioned projections can be found in (Fischer, 2011). Additionally, climate conditions influence the performance (i.e. efficiency and capacity factor) of some renewable energy technologies, such as hydro power, wind, solar, biomass, etc. Thus, the use of external climate models to link the performance of some renewable energy technologies to climate data is proposed. For this purpose, projections of the GCM model developed by IIASA can be used (Fischer, 2011).

#### F.2.3.2.3 Economic model

Similarly to the climate model, the economic model also relies on projections or approaches by external models. Projections taken from external models are divided into seven categories: 1) GDP and household expenditure, 2) Population, urbanization and income distribution, 3) capital and operational cost of technologies, 4) access to electricity, natural gas and biofuels, 5) prices of energy resources, 6) price of commodities (agricultural and forest) and 7) global use of biofuels.

*GDP and household expenditure*

Projections of GDP for individual countries can be taken either from the World Bank (World Bank, 2013), FAPRI-ISU (FAPRI-ISU, 2011), or from official projects by governments. Household expenditure (*HH*) is the final expenditure per household in PPP (US$2005) and is taken from (World Bank, 2013). It varies widely across the different segments of the income distribution. Therefore, the future household expenditure is further disaggregated into income quintiles and expressed as household expenditure per person (expenditure by quintile divided by the quintile population, i.e. 20% of the total population), following the method suggested by (Daioglou, 2010):

Eq. 42 $HHp = HH/P$
Eq. 43 $HHp_{r,Q} = IS_r \cdot IS_Q \cdot HH/(P_r/5)$

Where $HHp_{r,Q}$ is the household expenditure per person by region and quintile (US$2005/person), $HH$ is the household expenditure (mio US$2005), $P_r$ is the population by region, $IS_Q$ is the income share by quintile and $IS_r$ is the income share by region. Subscripts *r* and *Q* represent region and quintile, respectively.

*Population, urbanization and household size*

Projections of population (*P*) and urbanization (*U*) are taken from the World Bank (World Bank, 2013). The number of households in a country (*H*) is typically quantified in national census. The household size (*S)* is then estimated as:

Eq. 44 $S = H/P$

The household size represents the number of inhabitants per household, which varies significantly by region (rural vs. urban) and by household income. Therefore, household size is estimated by region and by income quintile following the method suggested by (Daioglou, 2010). Allocation of household size by region (i.e. rural and urban) is estimated using the correlation proposed by (Daioglou, 2010):

Eq. 45 $S_u/S = 0.174078 \cdot U + 0.82592$
Eq. 46 $U = P_u/P$

Where $U$ is the urban fraction of the total population. Next, the allocation of household sizes across quintiles is defined using the approach defined in (Daioglou, 2010):

Eq. 47 $S_{u,Q} = S_u \cdot [1 + (-0.0383 \cdot S_u + 0.0766) \cdot (3 - Q)]$

Eq. 48 $S_{r,Q} = S_r \cdot [1 + (-0.0383 \cdot S_r + 0.0766) \cdot (3 - Q)]$

Where $Q$ are the different quintiles (i.e. 1, 2, 3, 4, 5), and $S_u$ and $S_r$ are the urban and rural household sizes. The floor space per person is determined using a Gompertz curve defined by the following equations proposed by (Daioglou, 2010):

Eq. 49 $FS = \varphi \cdot e^{-1.341 \cdot e^{(\frac{-0.125}{1000}) \cdot HHp}}$

Eq. 50 $FS_u = (0.2892 \cdot U + 0.7170) \cdot FS$

Eq. 51 $FSQ_{r,Q} = 1 + \left(0.131 \cdot (Q - 3)\right)$

Eq. 52 $FS_{u,Q} = (0.2892 \cdot U + 0.7170) \cdot FS \cdot FSQ_{r,Q}$

Eq. 53 $FS_{ru,Q} = \left[\frac{FS-(U \cdot FS_u)}{1-U}\right] \cdot FSQ_{r,Q}$

Eq. 54 $\varphi = (-2.964 \cdot ln(D) + 60.577) \cdot \left(1 + \frac{0.125 * HHp}{35000}\right)$

Where $FS$ is the average floor space ($m^2$/person), $FS_u$ is the average floor space in urban regions, $FS_{u,Q}$ and $FS_{Rural,Q}$ are the urban and rural floor spaces by quintile, $D$ is the population density, $FSQ_{r,Q}$ is the floor space quintile factor, $Q$ is the quintile number (i.e. 1, 2, 3, 4 and 5) and $\varphi$ is a parameter of the Gompertz curve. Note that when quintile is 3, the floor space quintile factor $FSQ_{r,Q}$ is 1. For quintiles with higher expenditure than Q3 (i.e. Q>3), the floor space quintile factor is higher than 1. Likewise, for quintiles with lower expenditure than Q3 (i.e. Q<3), the floor space quintile factor is lower than 1.

*Access to electricity, natural gas and biofuels*

The access to electricity, natural gas and biofuels follows an evolutionary trend over the years that might be described by a Gompertz curve. A general Gompertz curve defined by the following equation is used:

Eq. 55 $E_{E,r,t} = \kappa_1 \cdot e^{-\kappa_2 \cdot e^{-\kappa_3 \cdot (t-1973)}}$

Where $E_{E,r,t}$ is the access to energy services $E$ (i.e. electricity, natural gas, biofuels) by region $r$ in year $t$ and $\kappa_1, \kappa_2, \kappa_3$ are parameters of the Gompertz function. The parameters of the Gompertz function are positive numbers estimated through a regression analysis for electricity, natural gas and biofuels by region (i.e. rural and urban).

Disaggregation of the regional access to energy services (i.e. electricity, natural, and biofuels) by quintile in year $t$ ($E_{E,r,t,Q}$) is estimated using the following equations, as suggested by (Daioglou, 2010):

Eq. 56 $E_{E,r,t,Q} = E_{E,r,t} \cdot \left[1 + \nabla_{E,r,t} \cdot (Q - 3)\right]$

Eq. 57 $\nabla_{E,r,t} = 0.307 \cdot \left(\frac{E_{E,r,t}}{100} - 1\right)$

Where $Q$ are the different quintiles (i.e. 1, 2, 3, 4, 5), and $\nabla_{E,r,t}$ is a gradient to model the differences in access to energy services across quintiles. Note that when quintile is 3, the access to energy services $E_{E,r,t,3}$ is equal to the value $E_{E,r,t}$. For quintiles with higher expenditure than Q3 (i.e. Q>3), the expected access to energy services is $E_{E,r,t,Q} \geq E_{E,r,t}$. Likewise, for quintiles with lower expenditure than Q3 (i.e. Q<3), the expected access to energy services is $E_{E,r,t,Q} \leq E_{E,r,t}$.

*Capital and operational cost of technologies*

Current and projected capital and operational cost of technologies are taken from various sources including among others: the U.S. Energy Information Administration –EIA– (EIA, 2014), the International Energy Agency –IEA– (IEA, 2012a), the Nuclear Energy Agency –NEA– (IEA-NEA, 2010) as well as process simulation tools (Thermoflow, 2011).

*Prices of energy resources*

Projections of prices of energy resources are also taken from a variety of sources including: EIA (EIA, 2011), IEA (IEA, 2012d) and the UK Department of Energy & Climate Change (DECC, 2011).

*Price of commodities (agricultural and forest)*

Price of commodities are taken from FAO/IIASA (Fischer, 2011), the World Bank (World Bank, 2012) and FAPRI-ISU (FAPRI-ISU, 2011).

*Global use of biofuels*

Finally, projections on global use of biofuels and their influence on agricultural prices, production and demand are taken from FAO/IIASA (Fischer, 2011).

#### F.2.3.3. Land Use and Trade Model (LUTM)

A land use and trade model (LUTM) was developed to estimate the land requirements necessary to accomplish the roadmap targets. This model estimates land allocation as well as production, imports and exports of 18 agricultural and forestry commodities during the period 2010-2030. The model is built on the assumption that the fundamental driver of land use and trade is the maximization of the profit perceived by local actors (i.e. local producers and importers). Main inputs of the model include the demand, local biofuel policies, yields, local and international prices and macroeconomic variables. An optimization algorithm is employed to maximize the profit perceived by local actors and to allocate land and trade. Competition is considered at three levels: food vs. biofuels, residues for energy vs. other uses and local production vs. imports. Figure 15 in Section D.2.2 shows a representation of the method used in the land use and trade model (LUTM).

General boundary conditions of the LUTM model include:

- Land use is estimated under the premise that the main driver is maximizing the profit of local producers and importers of agricultural commodities. It is assumed that both producers and importers are rational, which means that they always attempt to maximize their own profit
- It is assumed that the domestic market for agricultural commodities is unable to influence international markets
- For competition between local production vs. imports, commodities are assumed to be heterogeneous, which means that imports are imperfect substitutes of local products.
- For land competition, it is assumed that arable land is perfectly substitutable between different uses.
- Local production and imports of commodities are private activities.

The energy system model (ESM) and the land use and trade model (LUTM) work in parallel in a process of 3 steps (see Figure 41).

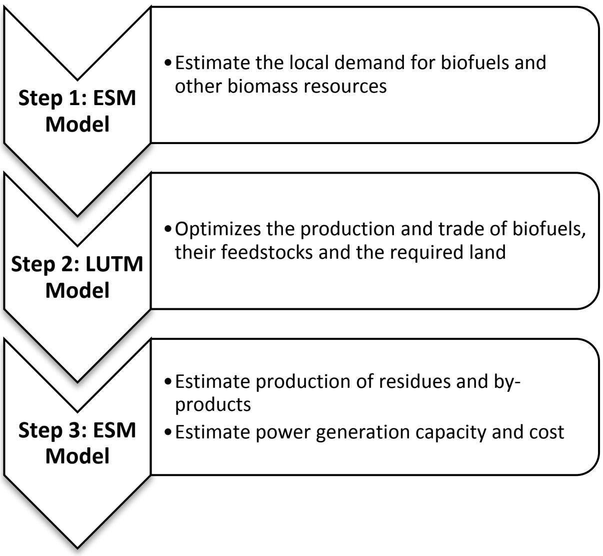

***Figure 41.** Linkages between the ESM and LUTM models*

In the first step, the local demand for biofuels (e.g. bioethanol, biodiesel, renewable diesel) and other biomass resources (biogas, biomethane, wood, etc.) is estimated in the ESM model and then exported to the LUTM model. In the second step, the LUTM model optimizes the production and trade of biofuels, woodfuel and other commodities and estimate feedstocks (e.g. sugar cane and palm oil) and required land. Finally, in the third step, the outputs of the LUTM model are used as a feedback loop in the ESM model to estimate the overall production of sugar cane and palm oil, as well as the power generation capacity and production of by-products and residues. Land use calculations generated by the LUTM model are used to estimate the land area required to achieve the long-term goals of different scenarios. Generally speaking, the method for building the LUTM model is the same as the one described in detail in Chapter D and in (Gonzalez-Salazar, et al., 2014b) with minor modifications.

While a Monte Carlo optimization algorithm was used to estimate the land use and trade in Chapter D and in (Gonzalez-Salazar, et al., 2014b), in the present LUTM model the optimization was performed using the Generalized Reduced Gradient (GRG) Nonlinear algorithm incorporated in Microsoft Excel. This change improved the efficiency and calculation time of the optimization. Moreover, in Chapter D and in (Gonzalez-Salazar, et al., 2014b), there were two main routes to processing sugar cane juice: one to co-produce bioethanol and sugar in a sugar factory and another to produce only bioethanol in an annexed distillery. In the present LUTM model there are three routes: one to produce only sugar, a second to co-produce sugar and bioethanol and a third to produce only ethanol. More details of these routes are explained in Section F.3.4.2.

#### F.2.3.4. Limitations

The proposed framework presents some limitations that are acknowledged. It focuses only on the quantification and analysis of the impacts that implementing various bioenergy policies might cause on the energy supply and demand, energy-related GHG emissions and land use at a country level. As discussed in the introduction chapter, a complete analysis of the social (i.e. job creation, improvement of the Human Development Index, etc.), environmental (i.e. life cycle GHG emissions, water footprint, impact on biodiversity, etc.) and economic impacts of implementing such policies is not covered and is considered beyond the scope of this study.

## F.3. Energy System Model (ESM)

The energy system model (ESM) is a data-intensive, scenario-based, demand-driven model that combines various methods to comprehensively replicate the behavior of the energy system at a country level. Since one of the premises to build the model was to have the highest possible accuracy in estimations, bottom-up approaches are employed as much as possible, accordingly to guidelines from earlier references (Connolly, Lund, Mathiesen, & Leahy, 2010; Bhattacharyya, 2011). The model has been built on the Long-range Energy Alternatives Planning System (LEAP) (Heaps, 2012), a platform widely used to report energy policy analysis and GHG mitigation assessments and free for users in developing countries (Connolly, Lund, Mathiesen, & Leahy, 2010). Two main sides represent the energy system in the model: 1) the demand side, in which the country's economy is divided into sectors (e.g. residential, industrial, transport, etc.) and 2) the supply side, in which conversion technologies and losses are considered (see Figure 42). For each side, the model calculates energy requirements, energy flows, required capacities, emissions and costs.

### F.3.1. General assumptions

For all scenarios, assumptions about future population, growth in domestic product (GDP), energy prices, climate conditions and availability of land, do not change and are exogenously added. GHG emissions associated with the direct combustion of fuels in each branch of the demand and the supply sides of the model are accounted using IPCC guidelines included in LEAP. Indirect emissions associated with transport, exposure, dose/response effects, but also land-use change, cultivation, irrigation, etc. are not considered. According to IPCC guidelines, biogenic $CO_2$ emissions (produced by burning biomass resources) are estimated but not counted as emissions of the 'energy sector', because they are considered emissions of the 'land use, land-use change and forestry' (LULUCF) sector.

### F.3.2. Modeling techniques

The ESM model is demand-driven, which means that the demand for energy is firstly calculated on the demand side and then on the supply side. Thus, a stronger focus has been given in this study to describe how the energy demand is estimated. In this regard, bottom-up techniques are considered for the residential, road transport and agricultural sectors, where typically bioenergy is mostly used (see Figure 43). Bottom-up techniques combine the use of economic variables (e.g. GDP, population, energy prices, income, etc.) and engineering variables (e.g. technologies, efficiencies, specific energy consumption, etc.) to estimate final energy demand. Bottom-up techniques used on the demand side include a comprehensive dynamic engineering-economy module of the residential sector, a stock-turnover-economic analysis of the road transport sector and an engineering module of the agriculture sector. In contrast, a less sophisticated top-down technique is used for other sectors not strongly linked to bioenergy such as commercial, industrial, non-road transport, etc. This top-down approach relies on econometrics to estimate the aggregate final demand by fuel and by sector as a function of key economic drivers (e.g. GDP, energy prices, etc.). The main advantage of using bottom-up techniques for sectors strongly linked to bioenergy and top-down techniques for other sectors is its simplicity. However, it is important to note that this approach reduces the degree of accuracy in estimation for sectors not strongly linked to bioenergy. There are two main reasons for this (Bhattacharyya, 2011): a) econometrics are not able to link the demand to the technology, policy or consumer habits and b) econometrics rely heavily on past trends to determine future demand, which might lead to poor forecasts.

On the supply side, a techno-economic approach was used to calculate energy production, capacity requirements by technology, losses and demand for resources. Efficiencies and cost of conversion technologies were collected from several sources available in literature and incorporated into the model. The competition between multiple technologies is simulated with an optimization approach.

### F.3.3. Model of the demand side

The model of the demand side is divided into the following main sub-models: 1) road transport, 2) cane and palm industries, 3) residential sector and 4) non-road transport, industrial and commercial sectors. A more detailed description of these sub-models is presented as follows.

#### F.3.3.1. Road transport

The energy demand of road transport and its associated emissions are estimated using a stock-turnover economic analysis consisting of four steps, as shown in Figure 44.

F.3.3.1.1 First step: estimate vehicle ownership

Models representing the future vehicle ownership as a function of economic and social data are defined. For vehicles with at least four wheels, the model proposed by (Dargay, Gately, & Sommer, 2007), which relates the future vehicle ownership to historical data, GDP per capita, density and urbanization is used. This model is a long-term dynamic S-shaped curve (Gompertz function), in which vehicle ownership growth is slow at the lowest income, then it rapidly increases as income rises and then it reaches a saturation level. The model is defined by next equation:

Eq. 58
$$V_t = (\psi_{MAX} + \lambda D_t + \varphi U_t) \cdot (\theta_R R_t + \theta_F A_t) \cdot e^{\alpha e^{\beta GDPp_t}} + (1 - \theta_R R_t + \theta_F A_t) \cdot V_{t-1} + \varepsilon_t$$

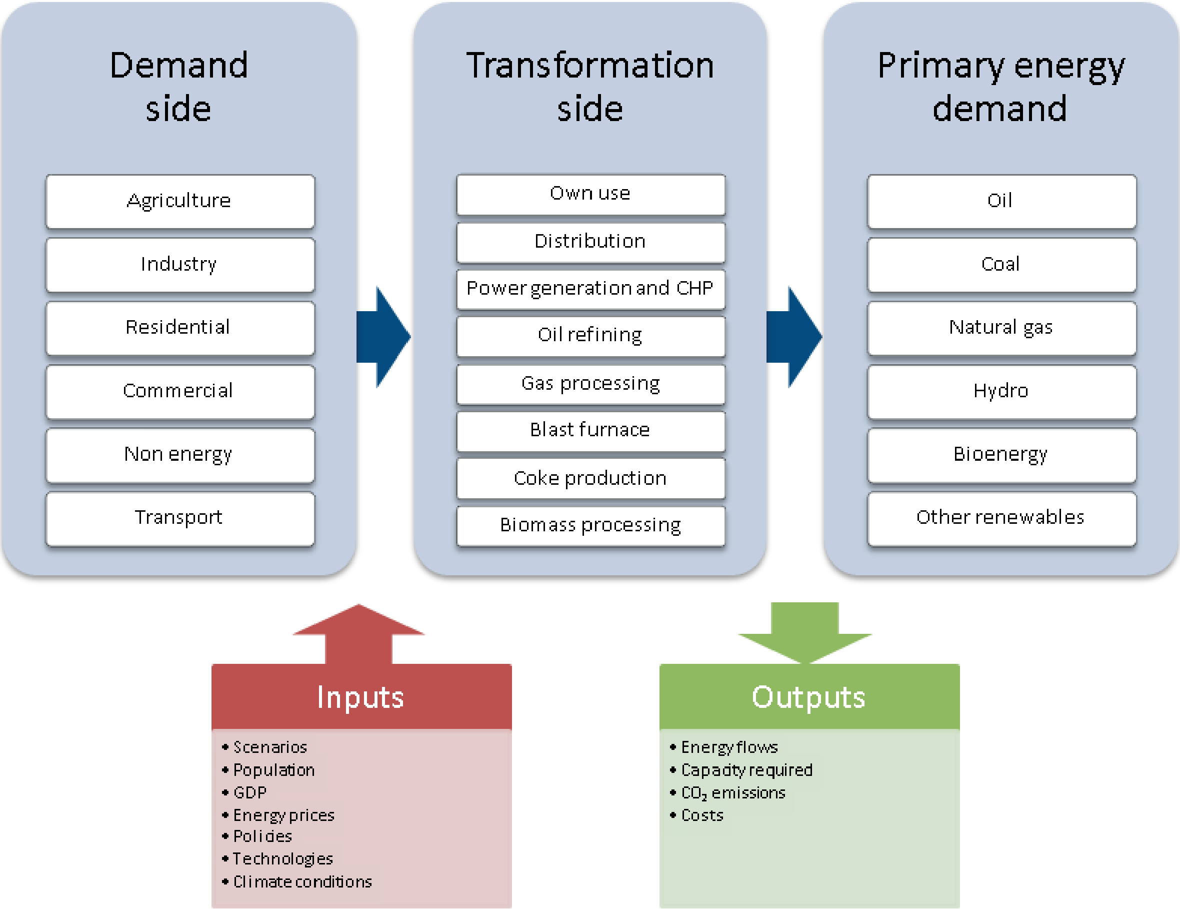

***Figure 42.*** *Outlook of the energy system model (ESM)*

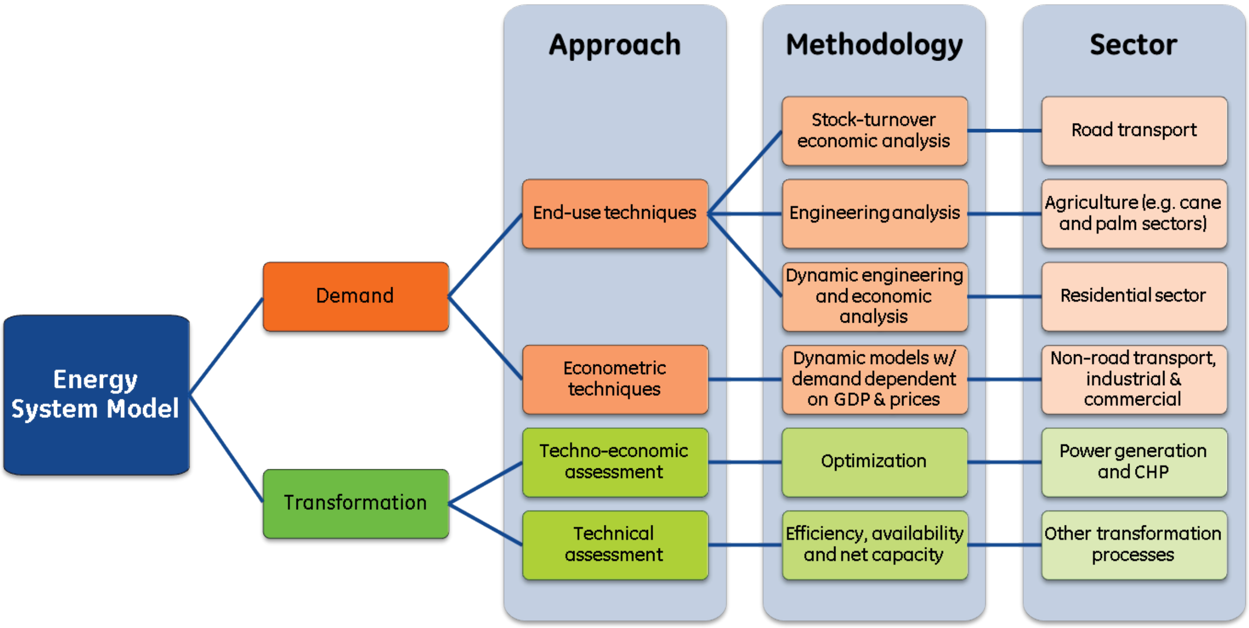

***Figure 43.*** *Summary of the employed modeling techniques by branch*

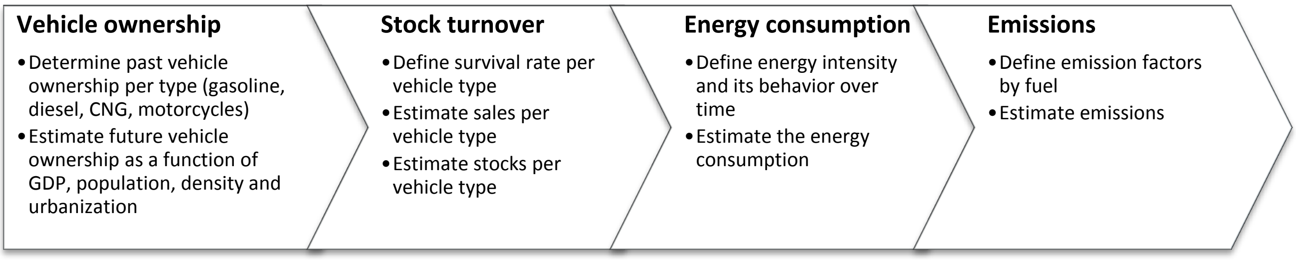

***Figure 44.*** *Process to estimate energy demand of road transport*

Where $V_t$ is the actual vehicle ownership (vehicles per 1000 people), $GDPp_t$ is the gross domestic product per capita (in purchasing power parity), $\psi_{MAX}$ is the saturation level, $D_t$ is the population density, $U_t$ is the urban franction of population, $\lambda$ and $\varphi$ are negative constants, $R_t$ and $A_t$ are dummy variables, $\theta_R$ and $\theta_F$ are speeds of adjustment for periods of rising and falling income ($0 \leq \theta \leq 1$), $\alpha$ and $\beta$ are parameters of the Gompertz function, subscript *t* represents the year and $\varepsilon_t$ its random error term. The dummy variables $R_t$ and $A_t$ are defined as:

Eq. 59 $R_t = 1\ if\ \ GDPp_t - GDPp_{t-1} > 0\ and\ 0\ otherwise$
Eq. 60 $A_t = 1\ if\ \ GDPp_t - GDPp_{t-1} < 0\ and\ 0\ otherwise$

While this model describes ownership for four-wheeled vehicles, it does not further disaggregate data by vehicle. Therefore, a logit function is used to estimate the share of each vehicle type per year as shown in the following equation:

Eq. 61 $SH_{c,t} = \frac{\left[{}^{1}/_{k_cF_{c,t}}\right]^{\gamma}}{\sum_c\left[{}^{1}/_{k_cF_{c,t}}\right]^{\gamma}} \cdot \theta + (1-\theta) \cdot SH_{c,t-1}$
Eq. 62 $\sum_c SH_{c,t} = 1$

In this equation, $SH_{c,t}$ is the share of each vehicle type per year ($0 \leq SH_{c,t} \leq 1$), $F_{c,t}$ is the fuel cost required for each vehicle type to drive 100 km (US$2005/100 km), $k_c$ is a cost exponent, $\gamma$ is the cost sensitivity coefficient, $\theta$ is the speed of adjustment ($0 \leq \theta \leq 1$), and subscripts *c* and *t* are respectively vehicle type and year.

The actual ownership per vehicle type and per year $V_{c,t}$ is given by Eq. 63. In addition, the sum of the actual ownership per vehicle results into the total vehicle ownership $V_t$, as shown in Eq. 64.

Eq. 63 $V_{c,t} = V_t \cdot SH_{c,t}$
Eq. 64 $V_t = \sum_c V_{c,t}$

Moreover, the actual number of vehicles in year *t* is estimated by multiplying the actual vehicle ownership $V_t$ (vehicles per 1000 people) by the population (thousand people) $P_t$:

Eq. 65 $Stock_t = V_t \cdot P_t$

For motorcycles, a simplified version of the model proposed by (Dargay, Gately, & Sommer, 2007) is used. This model is a long-term dynamic S-shaped curve, in which future motorcycle ownership $M_t$ is a function of historical ownership and GDP per capita:

Eq. 66 $M_t = \psi_{MAX} \cdot \theta e^{\alpha e^{\beta GDPp_t}} + (1-\theta) \cdot M_{t-1}$

Where $M_t$ is the actual motorcycle ownership (motorcycles per 1000 people) in year *t* and the other parameters have been defined above. These parameters are estimated using a regression analysis to best fit the historical data.

#### F.3.3.1.2 Second step: estimate stock turnover

In a second step, a detailed stock turnover analysis is performed. The stock analysis from LEAP is employed to estimate the retired, legacy and new vehicles for the different types of vehicle (gasoline, diesel, CNG and motorcycles) per year. The stock analysis is estimated using the following equations (Heaps, 2012):

Eq. 67 $Stock_t = V_t \cdot P_t = \sum_c Stock_{c,t}$
Eq. 68 $Stock_{c,t} = Sales_{c,t} + \sum_v Stock_{c,t,v}$
Eq. 69 $Stock_{c,t,v} = Sales_{c,v} \cdot Sur_{c,t-v}$

In these equations, $Stock_t$ is the actual number of vehicles in year *t*, which is estimated in Eq. 65 by multiplying the actual vehicle ownership $V_t$ by the population $P_t$. $Stock_t$ is also equivalent to the sum of vehicles of the different types *c* in year *t* ($Stock_{c,t}$). $Stock_{c,t}$ is then estimated as the sum of the sales of vehicles of type *c* in year *t* ($Sales_{c,t}$) and the summation of the number of legacy vehicles of the same type *c* produced in different years *v* and surviving in year *t* ($Stock_{c,t,v}$). In turn, $Stock_{c,t,v}$ is estimated as the multiplication of the sales of vehicles of type *c* produced in year *v* by the rate of these vehicles still surviving in year *t* ($Sur_{c,t-v}$).

### F.3.3.1.3 Third step: estimate energy consumption

In a third step the fuel economy and overall energy consumption per vehicle type are estimated using the following equations:

Eq. 70 $FE_{c,t,v} = FE_{c,v} \cdot Deg_{c,t-v}$

Eq. 71 $ECV_{c,t} = \sum_{v} \left( Stock_{c,t,v} \cdot FE_{c,t,v} \cdot Mil_{c,t,v} \right)$

Eq. 72 $ECV_{c,t,f} = \mu_{c,t,f} \cdot ECV_{c,t}$

Eq. 73 $ECV_{t,f} = \sum_{c} ECV_{c,t,f}$

Where $FE_{c,v}$ (MJ/100 km) is the fuel economy per vehicle type for a new vehicle, $FE_{c,t,v}$ (MJ/100 km) is the fuel economy per vehicle type per vintage and per year, $Deg_{c,t-v}$ is a factor representing the change in fuel economy as a vehicle ages, $Mil_{c,t,v}$ is the mileage (km/vehicle); $ECV_{c,t}$ (MJ) is the overall energy consumption per vehicle type per year, $ECV_{c,t,f}$ (MJ) is the energy consumption per vehicle type per year disaggregated by type of fuel and $\mu_{c,t,f}$ is the share of the energy consumption by fuel type. The overall energy consumption by fuel per year $ECV_{t,f}$ is thus the sum of the energy consumption by fuel per vehicle type per year $ECV_{c,t,f}$.

It is assumed that the fuel economy is proportional to the fuel's lower heating value *LHV* (MJ/l) and that biofuels do not affect it. While biofuels might offer certain advantages than counterparts (e.g. higher octane rating for bioethanol and higher lubricity and cetane number for biodiesel), significant modifications of the engine are required to exploit these advantages. For instance, to take advantage of the high octane number of bioethanol it is necessary to increase the compression ratio of the engine (Goettemoeller & Goettemoeller, 2007). A similar approach is needed for biodiesel (Muralidharan & Vasudevan, 2011). As technologies for modifying the engine are not considered in this study, it is assumed that biofuels do not impact fuel economy. Finally, the share of the energy consumption by fuel type $\mu_{c,t,f}$ is calculated. The fuel shares associated with the two types of fuels that can be used in vehicles, e.g. biofuels and fossil fuels, are here treated as $\mu_{c,t,bio}$ and $\mu_{c,t,fossil}$ respectively. The fuel share of biofuel in a type of vehicle *c* in year *t* ($\mu_{c,t,bio}$) is calculated as a function of the blend mandate ($BMV_{c,t,bio}$), the lower heating value of the biofuel in MJ/liter ($LHV_{bio}$), the lower heating value of the counterpart fossil fuel in MJ/liter ($LHV_{fossil}$) and the supply coverage of biofuel at a national level ($Cov_{t,bio}$).

Eq. 74 $\mu_{c,t,bio} = \left( BMV_{c,t,bio} \cdot \frac{LHV_{bio}}{LHV_{t,blend}} \right) \cdot Cov_{t,bio}$

Eq. 75 $LHV_{t,blend} = \left( BMV_{c,t,bio} \cdot LHV_{bio} \right) + \left( 1 - BMV_{c,t,bio} \right) \cdot LHV_{fossil}$

Eq. 76 $\mu_{c,t,fossil} = 1 - \mu_{c,t,bio}$

### F.3.3.1.4 Fourth step: estimate emissions

The fourth step is estimating the greenhouse gas emissions through the following equation:

Eq. 77 $GHG_{c,t,v,p} = ECV_{c,t,v} \cdot EF_{c,t,p} \cdot Deg_{c,t-v,p}$

Eq. 78 $GHG_{c,t,p} = \sum_{v} GHG_{c,t,v,p}$

Eq. 79 $GHG_{t,p} = \sum_{c} GHG_{c,t,p}$

Eq. 80 $GHG_{t} = \sum_{p} GHG_{t,p}$

Where $GHG_{c,t,v,p}$ (ton $CO_2$-eq.) are the emissions by pollutant for the different vehicle types, vintage and year, $EF_{c,t,p}$ is the emission factor by pollutant (kg/TJ) and $Deg_{c,t-v,p}$ is a factor representing the change in emissions as a vehicle ages. Pollutants analyzed in this study include carbon dioxide ($CO_2$, both biogenic and non-biogenic), carbon monoxide (CO), methane ($CH_4$), non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), Nitrous Oxide ($N_2O$) and sulfur dioxide ($SO_2$). For combustion of biofuels, it is used the method suggested in (TNO, 2009). This study suggests that emission factors for biofuels can be estimated using the following equation:

Eq. 81 $EF_{bio,p} = EF_{fossil,p} \cdot MEF_{bio,p}$

Where $EF_{bio,p}$ is the emission factor for biofuels by pollutant, $EF_{fossil,p}$ is the emission factor for counterpart fossil fuel and $MEF_{bio,p}$ is a multiplying emission factor for biofuels. $MEF_{bio,p}$ for gasoline vehicles and motorcycles using 100% bioethanol and diesel vehicles using 100% biodiesel is shown in Table 17.

For biofuel blends, the emissions are then proportional to the biofuel energy content in the blend. Further, it is assumed that the $CO_2$ emissions produced during combustion of bioethanol, biodiesel, renewable diesel and biomethane (present in CNG) are biogenic (EPA, 2008).

***Table 17.*** *Multiplying emission factors for biofuels (TNO, 2009)*

| Multiplying emission factor by pollutant | Gasoline vehicles and motorcycles using 100% bioethanol | Diesel vehicles using 100% biodiesel |
|---|---|---|
| Nitrogen oxides (NOx) | 1.28 | 1.3 |
| Particulate matter (PM) | 1.35 | 0.43 |
| Hydrocarbons (HC) | 1 | 0.46 |
| Carbon monoxide (CO) | 1 | 0.81 |

### F.3.3.2. Residential sector

The energy demand of the residential sector and its associated emissions are estimated using a bottom-up dynamic model consisting of four steps (see Figure 45). This approach is partly based on the method proposed in (Daioglou, 2010), which uses five exogenous primary drivers to determine five energy demand uses (see Figure 46). The primary drivers include population, household expenditure, population density, household size and ambient temperature. The energy demand uses include cooking, appliances, water heating, space heating/cooling and lighting.

#### F.3.3.2.1 First step: define primary drivers

Primary drivers include: population (*P*), population density (*PD*), ambient temperature (*T*), household expenditure (*HH*) and household size (*S*). Population, population density, household expenditure and household size are defined in the economic model (see Section F.2.3.2.3). Finally, the ambient temperature is expressed in average heating degree days (HDD).

#### F.3.3.2.2 Second step: estimate intermediate drivers

In a second step, intermediate drivers are estimated. Intermediate drivers include floor space per person (*FS*) and access to electricity and natural gas (*E*). Both drivers are taken from the economic model shown in Section F.2.3.2.3.

#### F.3.3.2.3 Third step: estimate energy consumption

In a third step, the demand for cooking, appliances, water heating, space cooling and lighting as well as the associated fuel shares are estimated.
*__Water heating:__* it is modeled as a Gompertz curve dependent on income, following the method developed by (Daioglou, 2010). For the particular case of water heating, the demand is not disaggregated by region and quintile and is rather estimated for the entire country.

The following equations are used to estimate the energy consumption for water heating:

Eq. 82 $ECWp = ECWp_{MAX} \cdot e^{-\kappa_4 \cdot e^{-\kappa_5 \cdot HHp}}$
Eq. 83 $ECWp_{MAX} = (0.003 \cdot HDD + 2.756) \cdot OD$
Eq. 84 $ECW = ECWp \cdot P$

Where $ECWp$ is the energy consumption for water heating per capita ($\text{MJ}_{\text{UE}}$/person/year), $ECWp_{Max}$ is the maximum energy consumption for water heating per capita ($\text{MJ}_{\text{UE}}$/person/year), $HDD$ is the heating degree days, $HHp$ is the household expenditure per capita (US$2005/person), $OD$ are the annual number of days demanding hot water and $\kappa_4, \kappa_5$ are parameters of the Gompertz function. The fuel shares are estimated using a logit function described by the following equation (same approach as in Eq. 61):

Eq. 85 $\mu_{f,t} = \frac{\left[{}^{1}/_{k_f F_{f,t}}\right]^{\gamma}}{\sum_f \left[{}^{1}/_{k_f F_{f,t}}\right]^{\gamma}} \cdot \theta + (1-\theta) \cdot \mu_{f,t-1}$
Eq. 86 $\sum_f \mu_{f,t} = 1$

Where, $F_{f,t}$ is the fuel cost (US$2005/MMBtu), $k_f$ is a cost exponent for the different fuels, $\gamma$ is the cost sensitivity coefficient, $\theta$ is the speed of adjustment and subscripts $f$ and $t$ are respectively fuel and year. The parameters of the logit function are obtained through a regression analysis to best fit the historical curve of shares. *__Appliances:__* the demand for energy associated with appliances is modeled for three categories: refrigeration, air conditioning and other appliances. Models are based on ownership and energy use per appliance. The appliance ownership is defined by the general equation:

Eq. 87 $OW_{a,r,Q} = \psi_a \cdot e^{-\kappa_6 \cdot e^{-(\kappa_7/1000) \cdot HHp_r}}$

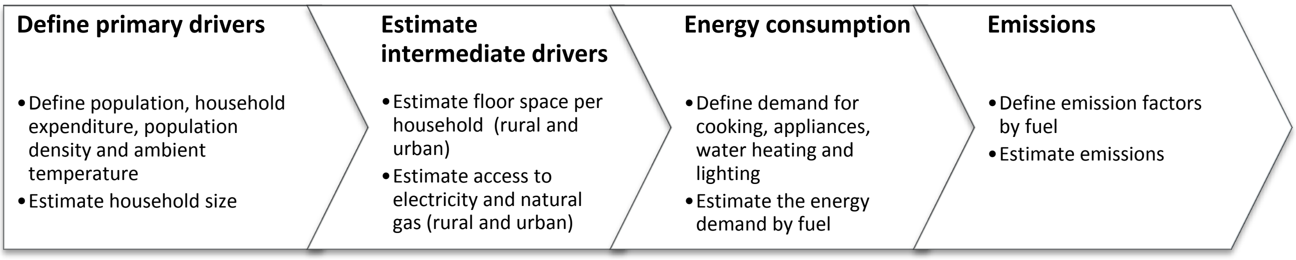

***Figure 45.*** *Method process to estimate energy demand of residential sector*

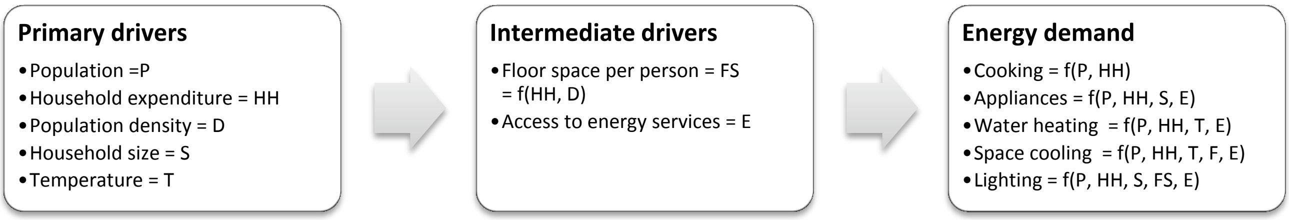

***Figure 46.*** *Relationship between energy demand and drivers, adapted from (Daioglou, 2010)*

Where $OW_{a,r,Q}$ is the ownership by appliance, region and quintile (units/household), $\psi_a$ is the saturation level by appliance (units/household), $HHp_r$ is the household expenditure per capita by region (US$2005/person), $\kappa_6, \kappa_7$ are parameters of the Gompertz function and the subscript *a* represents the type of appliance. The unit energy consumption of appliances is defined by the general equation:

Eq. 88 $$UEC_a = \vartheta_a \cdot \zeta_a^{(t-1971)} + UEC_{MAX,a}$$

Where $UEC_a$ is the unit energy consumption by type of appliance (kWh/year), $UEC_{MAX,a}$ is an assumed limit to $UEC_a$, $t$ is the year and $\vartheta_a$, $\zeta_a$ are coefficients that influence the unit energy consumption over the years. Finally, the overall energy consumption for appliances ($ECA_a$) and the overall energy consumption for appliances per capita ($ECAp_a$) are estimated through the following equations:

Eq. 89 $$ECA_a = \sum_r \sum_Q \left(OW_{a,r,Q} \cdot UEC_a \cdot H_{r,Q}\right)$$
Eq. 90 $$ECAp_a = \frac{1}{P} \cdot \left(\sum_r \sum_Q \left(OW_{a,r,Q} \cdot UEC_a \cdot H_{r,Q}\right)\right)$$

Where $H_{r,Q}$ is the number of households by region (*r*) and quintile (*Q*) and *P* is the total population.

The category of refrigerators is now analyzed in more detail. The saturation for refrigerators by region and quintile is defined as:

Eq. 91 $$\psi_{Ref} = \left(m_{Ref} \cdot (t-1970) + b_{Ref}\right) \cdot \left(0.206 \cdot ln\left(HHp_{r,Q}/HHp_r\right) + 1\right) \cdot E_{El,r,Q}$$

Where *t* is the year, $m_{Ref}$ and $b_{Ref}$ are coefficients, $HHp_{r,Q}$ is the household expenditure per capita by region and quintile, $HHp_r$ is the average household expenditure per capita by region, $E_{El,r,Q}$ is the access to electricity by region and quintile and subscript *Ref* denotes refrigerator. The parameter $\kappa_7$ of the Gompertz curve for refrigerators is then defined as:

Eq. 92 $$\kappa_{7,Ref} = \left(d_{Ref} \cdot ln(t) + e_{Ref}\right)$$

Where *t* is the year and $d_{Ref}$ and $e_{Ref}$ are constants. By substituting Eq. 91 and Eq. 92 into Eq. 87 it is possible to estimate the ownership of refrigerators. The energy demand for refrigeration per capita is then estimated using Eq. 89.
The category of air conditioners is now analyzed in more detail. The saturation for air conditioners by region and quintile is defined as:

Eq. 93 $$\psi_{AC} = \left(\frac{m_{AC}}{m_{AC}+e^{-\left(b_{AC}/1000\right)\cdot\left(HHp_r-250\right)}}\right) \cdot \left(0.206 \cdot ln\left(HHp_{r,Q}/HHp_r\right) + 1\right) \cdot E_{El,r,Q}$$

Where $m_{AC}$ and $b_{AC}$ are coefficients, $HHp_{r,Q}$ is the household expenditure per capita by region and quintile, $HHp_r$ is the average household expenditure per capita by region and subscript *AC* denotes air conditioner. For air conditioners, the parameters $\kappa_6, \kappa_7$ of the Gompertz function in Eq. 87 are zero and ownership is entirely defined by Eq. 93. For the particular case of air conditioners the unit energy consumption is not defined by Eq. 88, but rather by the following equation:

Eq. 94 $$UEC_{AC,r,Q} = \frac{\mathrm{CDD}\cdot \left(0.6053\cdot\ln\left(HHp_{r,Q}\right)-3.1897\right)}{COP_t/COP_{Re}}$$

Where $UEC_{AC,r,Q}$ is the unit energy consumption of air conditioners by region and quintile ($\text{kWh}_{\text{cooling}}$/household), CDD is the average cooling degree days, $HHp_{r,Q}$ is the household expenditure per capita disaggregated by region and quintile (US$2005/person), $COP_t$ is the coefficient of performance for air conditioners in year t and $COP_{Re}$ is the coefficient of performance for base year (2009). It is assumed that $COP_{Re}$ at base year is 2.8 and increase linearly to 3.5 in 2050 (3.19 in 2030) as described in (Rong, Clarke, & Smith, 2007). By substituting Eq. 93 and Eq. 94 in Eq. 89 it is possible to estimate the energy demand for air conditioning per capita.

All other appliances are lumped into a single group, which is analyzed now in more detail. The saturation for other appliances by region and quintile is defined as:

Eq. 95 $$\psi_{OA} = \left(m_{OA} \cdot (t-1970) + b_{OA}\right) \cdot \left(0.144 \cdot ln\left(HHp_{r,Q}/HHp_r\right) + 1\right) \cdot E_{El,r,Q}$$

Where $m_{OA}$ and $b_{OA}$ are coefficients, *t* is the year, and subscript *OA* refers to other appliances. The unit energy consumption of other appliances is modeled through the following equation:

Eq. 96 $$UEC_{OA,r,Q} = C1_{OA} \cdot \ln\left(HHp_{r,Q}\right) - C2_{OA}$$

Where, $UEC_{OA,r,Q}$ is the unit energy consumption of lumped appliances (kWh/unit), per definition higher than zero, $C1_{OA}, C2_{OA}$ are coefficients and $HHp_{r,Q}$ is the household expenditure per capita disaggregated by region and quintile (US$2005/person). The overall energy demand per capita for other appliances is then estimated by substituting Eq. 95 and Eq. 96 in Eq. 89.

*Lighting*
Energy demand for lighting is modeled through the following equation proposed by (Daioglou, 2010):

Eq. 97 $$ECLH_{r,Q} = 0.68 \cdot FS_{r,Q} \cdot W \cdot LHF_r$$

Where $ECLH_{r,Q}$ is the annual energy consumption of lighting per household by region and quintile (kWh/household), $FS_{r,Q}$ is the floor space per person, $W$ is the unit energy consumption per light bulb (W/unit) and $LHF_r$ is a lighting hours factor coefficient. In addition, the overall annual energy consumption for lighting ($ECL$) and the annual energy consumption for lighting per capita ($ECLp$) are estimated through the following equations:

Eq. 98 $$ECL = \sum_r \sum_Q \left(ECLH_{r,Q} \cdot H_{r,Q} \cdot E_{El,r,Q}\right)$$

Eq. 99 $$ECLp = \frac{1}{P} \cdot \left(\sum_r \sum_Q \left(ECLH_{r,Q} \cdot H_{r,Q} \cdot E_{El,r,Q}\right)\right)$$

Where $E_{El,r,Q}$ is the access to electricity by region and quintile and $H_{r,Q}$ is the number of households by region and quintile.

*Cooking*

The energy demand per capita for cooking is assumed to be 3 MJ of useful energy per person per day, which is the suggested value in (Daioglou, 2010).

F.3.3.2.4 Fourth step: estimate emissions

The fourth step relates to the definition of emission factor and the estimation of total emissions. Generally, the method to estimate emissions is the same as that used for road transport. The emission factors by pollutant are taken from the Technology and Environmental Database (TED) implemented in LEAP. Further, it is assumed that the $CO_2$ emissions produced during combustion of biomass resources are biogenic.

### F.3.3.3. Non-road transport, agriculture, industrial and commercial sectors

An econometric method was used to estimate the aggregate final energy consumption by fuel as a function of key drivers (e.g. sectorial GDP, energy prices, etc.) for sectors not substantially affected by bioenergy (e.g. non-road transport, agriculture, industrial and commercial sectors). For these sectors, the final energy demand by fuel is estimated using the following equation:

Eq. 100 $$ECF_{f,t,s} = e^{\left[\theta\cdot\left(\xi_1\cdot ln(F_{f,t})+\xi_2\cdot ln(GDP_{t,s})\right)+\left((1-\theta)\cdot ECF_{f,t-1,s}\right)\right]}$$

Where $ECF_{f,t,s}$ is the energy consumption by sector $s$, fuel $f$ and year $t$, $\xi_1$ and $\xi_2$ are coefficients of the equation, $F_{f,t}$ is fuel cost, $GDP_{t,s}$ is the gross domestic product by sector and year (Billion US$2005, PPP) and $\theta$ is the speed of adjustment.

### F.3.3.4. Cane and palm industries

Energy consumption in cane and palm industries relates to the production of commodities, such as sugar, palm oil and jaggery. For simplicity, in this study it is assumed that cane and palm industries are conversion processes and that their energy consumption is allocated on the transformation side. The method to estimate the energy consumption is described in more detail in following sections F.3.4.2 and F.3.4.3.

## F.3.4. Model of the transformation side

The model of energy transformation processes is divided into three main sub-models: 1) power generation, 2) sugar and bioethanol production and 3) other energy transformation processes.

### F.3.4.1. Power generation

Power generation is modeled through an optimization algorithm which orders dispatch and capacity addition to minimize the net present value of the lifetime total costs of the system (i.e. capital costs, operating costs, fuel costs, decommissioning, etc.). Optionally, the optimization algorithm can be configured to meet a renewable power target. The method to analyze power generation consists of four steps (see Figure 47), which are discussed below.

F.3.4.1.1 First step: define technology portfolio

In a first step, a technology portfolio is defined. The technology portfolio consists of two main groups: traditional technologies and new technologies. Traditional technologies are those used today (e.g. hydro power, gas turbines, coal power plants, etc.), while new technologies are those expected to become available in the future in a particular country.

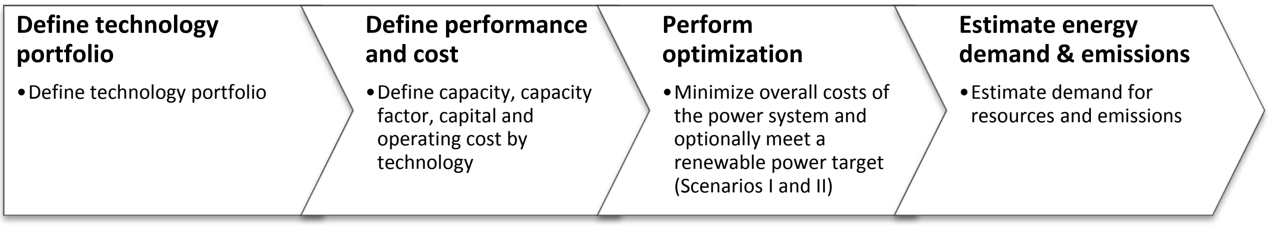

***Figure 47.*** *Method to analyze power generation*

#### F.3.4.1.2 Second step: define performance and cost

In a second step, the capacity, capacity factor, efficiency, capital and operating cost and other characteristics of the different technologies are taken from the economic model, see Section F.2.3.2.3.

#### F.3.4.1.3 Third step: perform optimization

In a third step, an optimization algorithm calculates the least cost capacity expansion and dispatch required to meet a minimum planning reserve margin and optionally a renewable power target. The optimization algorithm minimizes the net present value of the lifetime total costs of the system. For this purpose the Open Source Energy Modeling System (OSeMOSYS) algorithm incorporated into LEAP is used. The total costs of the system include capital, operation & maintenance, fuel and decommissioning costs. The objective function, taken from (Howells, 2009), is defined as:

Eq. 101 $$Min\ DC = \sum_t \sum_g \left[ \left( I_{g,t} + OM_{g,t} + F_{g,t} + DE_{g,t} \right) \cdot (1+r)^{-t} \right]$$

Where $I_{g,t}$ is the investment cost for technology type *g* in year *t* (US\$2009/kW), $OM_{g,t}$ is the operation and maintenance costs (US\$2009/kW), $F_{g,t}$ is the fuel cost (US\$2009/MMBtu), $DE_{g,t}$ is the cost for decommissioning a power plant and *r* is the discount rate. A mandatory constraint and an optional constraint are associated with this optimization problem. The mandatory constraint ensures that a minimum planning reserve margin (*RM*) is met. The optional constraint ensures that for particular scenarios an optional renewable power target is met. The planning reserve margin is defined as:

Eq. 102 $$RM_t = \frac{(\sum_g C_{g,t} \cdot CC_{g,t}) - PL_t}{PL_t}$$

Where $RM_t$ is the planning reserve margin in year *t*, $C_{g,t}$ is the installed capacity by technology in year *t*, $CC_{g,t}$ is the capacity credit by technology, i.e. the amount of firm conventional generation capacity that can be replaced by renewable power ($0 \leq CC_{g,t} \leq 100\%$) and $PL_t$ is the power peak demand throughout the year (IEA, 2012b).

Additional variables required to perform the optimization include a) exogenous capacity additions and b) maximum annual capacity and capacity addition by technology. Exogenous capacity additions include planned capacity additions and retirements that have been officially planned and are exogenously entered into LEAP for all scenarios. The maximum annual capacity addition is estimated on a case by case basis, and depends on resources and technologies available.

#### F.3.4.1.4 Fourth step: estimate energy demand and emissions

In a fourth step, the consumption of energy resources to generate power and CHP as well as the generated emissions by technology are estimated. The consumption of energy resources is estimated through the following equations:

Eq. 103 $$ECP_{g,f,t,d} = \frac{PG_{g,f,t,d}}{\eta_{g,f,t,d}}$$

Eq. 104 $$ECP_{g,f,t} = \sum_{d=0}^{365} \frac{PG_{g,f,t,d}}{\eta_{g,f,t,d}}$$

Eq. 105 $$ECP_{f,t} = \sum_g ECP_{g,f,t}$$

Where $ECP_{g,f,t,d}$ is the consumption of fuel *f* by power generation technology *g* in day *d* of year *t*. $PG_{g,f,t,d}$ and $\eta_{g,f,t,d}$ are the power generated and the efficiency of technology *g* in day *d* of year *t*, respectively. By adding the daily consumption of fuel *f* by technology *g*, it is then possible to estimate the annual fuel consumption ($ECP_{g,f,t}$). Likewise, by adding the annual fuel consumption of the different power generation technologies, it is possible to estimate the overall consumption of fuel *f* used for power generation in year *t* ($ECP_{f,t}$).

Finally, the greenhouse gas emissions are calculated through the following equation:

Eq. 106 $$GHG_{g,f,t,p} = PG_{g,f,t} \cdot EF_{g,f,t,p}$$

Where $GHG_{g,f,t,p}$ (Tons of $CO_2$ equivalent) are the annual emissions of pollutant *p* in year *t* created by power technology *g* by combusting fuel *f*. $EF_{g,f,t,p}$ is the emission factor by pollutant associated with combustion of fuel *f* in power technology *g* (kg/TJ) and $PG_{g,f,t}$ is the annual power generation by technology disaggregated by fuel and year. Overall annual emissions are calculated by adding the different levels of disaggregation through the following equations:

Eq. 107 $$GHG_{g,t,p} = \sum_f GHG_{g,f,t,p}$$

Eq. 108 $$GHG_{t,p} = \sum_g GHG_{g,t,p}$$

Eq. 109 $$GHG_t = \sum_p GHG_{t,p}$$

Pollutants analyzed in power generation include carbon dioxide ($CO_2$, both biogenic and non-biogenic), carbon monoxide (CO), methane ($CH_4$) and nitrogen oxides (NOx). It is assumed that the $CO_2$ emissions produced during combustion of biomass resources in power generation are biogenic. It is also assumed that no GHG emissions are generated by wind and hydro power technologies.

Further, it is assumed that there are four effects by burning landfill gas or biogas from biodiesel processing plants, wastewater plants and animal waste, see following equations:

Eq. 110 $GHG_{(lg,bg),p} = GHG_{(lg,bg),CO2a} + GHG_{(lg,bg),CO2b} + GHG_{(lg,bg),CH4} + GHG_{(lg,bg),Other}$

Eq. 111 $GHG_{(lg,bg),CO2a} = x_{(lg,bg),CO2} \cdot 1\, kg_{(lg,bg)}$

Eq. 112 $GHG_{(lg,bg),CO2b} = EF_{(lg,bg),CO2} \cdot PG_{(1kg:\, lg,bg)}$

Eq. 113 $GHG_{(lg,bg),CH4} = -x_{(lg,bg),CH4} \cdot 1\, kg_{(lg,bg)}$

Eq. 114 $GHG_{(lg,bg),Other} = \sum_{Other}\left(EF_{(lg,bg),Other} \cdot PG_{(1\,kg:\, lg,bg)}\right)$

Where $GHG_{(lg,bg),p}$ are the greenhouse gas emissions associated with burning 1 kg of landfill gas or biogas for power generation.

The first effect relates to the emission of biogenic $CO_2$ not produced during the combustion of landfill gas or biogas ($GHG_{(lg,bg),CO2a}$). $CO_2$ already contained in these fuels is not produced during combustion and is subsequently emitted. This first effect is calculated as the mass content of $CO_2$ in landfill gas or biogas ($x_{(lg,bg),CO2}$) per kilogram of landfill gas or biogas combusted ($1\, kg_{(lg,bg)}$).

The second effect relates to the emission of biogenic $CO_2$ by burning the combustible material (e.g. hydrogen, hydrocarbons, CO, etc.) contained in landfill gas or biogas ($GHG_{(lg,bg),CO2b}$). The second effect is calculated as the emission factor of $CO_2$ for power generation ($EF_{(lg,bg),CO2}$) multiplied by the power generated with 1 kg of landfill gas or biogas ($PG_{(1kg:\, lg,bg)}$).

The third effect relates to the reduction in methane emissions that otherwise would be released into the atmosphere by not using these resources ($GHG_{(lg,bg),CH4}$). This reduction is calculated as the mass content of methane in the landfill gas or biogas per kilogram of landfill gas or biogas combusted. The avoidance of methane emission is therefore treated here as a credit, i.e. a ‘negative’ emission following the method suggested in (den Boer, den Boer, & Jager, 2005).

The fourth effect relates to the emission of other pollutants, e.g. CO and NOx, by burning the landfill gas or biogas ($GHG_{(lg,bg),Other}$). The fourth effect is calculated as the sum of the individual emissions of other pollutants. These individual emissions are calculated as the emission factors of these pollutants for power generation ($EF_{(lg,bg),Other}$) multiplied by the power generated with 1 kg of landfill gas or biogas ($PG_{(1kg:\, lg,bg)}$). The overall emissions of burning biogas or landfill gas in year $t$ ($GHG_{(lg,bg),t}$) is calculated as follows:

Eq. 115 $GHG_{(lg,bg),t} = GHG_{(lg,bg),p} \cdot \dot{m}_{(lg,bg),p,t}$

Where $GHG_{(lg,bg),p}$ are the greenhouse gas emissions associated with burning 1 kg of landfill gas or biogas and $\dot{m}_{(lg,bg),p,t}$ is the overall mass flow of landfill gas or biogas used in power generation.

In summary, burning biogas or landfill gas in power plants would: a) generate biogenic $CO_2$ emissions proportional to the $CO_2$ content in the fuel, b) generate biogenic $CO_2$ emissions as well as NOx and CO by oxidizing (i.e. burning) the carbon contained in the fuels and c) avoid methane emissions proportional to the $CH_4$ content, which for accounting purposes are treated as negative methane emissions.

### F.3.4.2. Cane mill, sugar and bioethanol production

In the sugar cane mill, cane is crushed and cane juice, bagasse, tops and leaves are extracted. The juice is used to produce sugar and ethanol and the bagasse is mostly used to produce steam in boilers and CHP plants and to a lesser extent used as raw material in paper mills. Tops and leaves are left on the field for soil replenishment, but for simplicity here are considered a sub-product of the cane mill. The mill is mechanically driven by steam turbines fed with steam produced in bagasse-fuelled boilers. A simplified flow diagram of mass inputs and outputs of the sugar cane mill is shown in Figure 48.

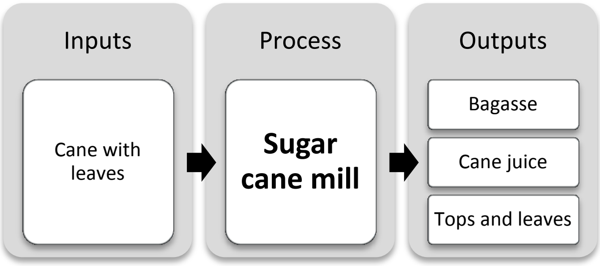

***Figure 48.*** *Inputs and outputs of sugar cane mill*

Mass and energy balance in the sugar mill is estimated through the following equations:

Eq. 116 $\dot{m}_{cwl} = \dot{m}_{ba} + \dot{m}_{cj} + \dot{m}_{tl}$

Eq. 117 $\dot{m}_{cwl} \cdot LHV_{cwl} = \dot{m}_{ba} \cdot LHV_{ba} + \dot{m}_{cj} \cdot LHV_{cj} + \dot{m}_{tl} \cdot LHV_{tl}$

Where $\dot{m}$ represents the mass flow and $LHV$ represents the lower heating value; subscripts *cwl, cnl, ba, cj and tl* represent cane with leaves, cane without leaves, bagasse, cane juice and tops and leaves, respectively. Three independent routes are considered for the co-production of sugar and bioethanol from cane juice (see Figure 49).

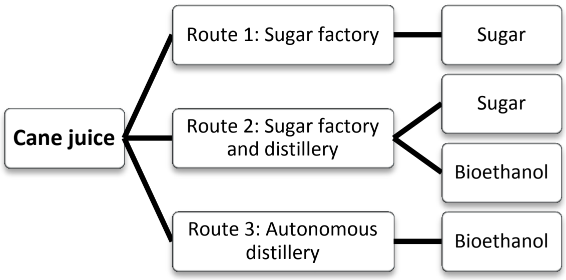

***Figure 49.*** *Sugar and bioethanol co-production routes*

In the first route only sugar is produced in a sugar factory. Cane juice is purified, filtrated and evaporated to produce molasses. This is followed by a crystallization and centrifugation process, in which sugar crystals are formed and separated from molasses. Finally, crystals are dried and refined and sugar is then produced, while molasses are sold as animal feed. A flow diagram of material and energy inputs and outputs of Route 1 is shown in Figure 50.

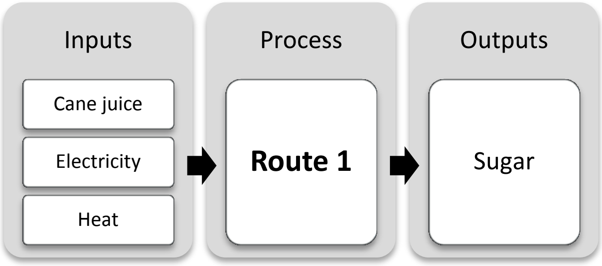

***Figure 50.*** *Inputs and outputs of Route 1*

In the second route, sugar and bioethanol are co-produced in a sugar factory with an annexed distillery (see Figure 51). In this route, sugar is produced in a similar fashion as in Route 1, but molasses are converted into bioethanol via microbial fermentation, distillation and dehydration.

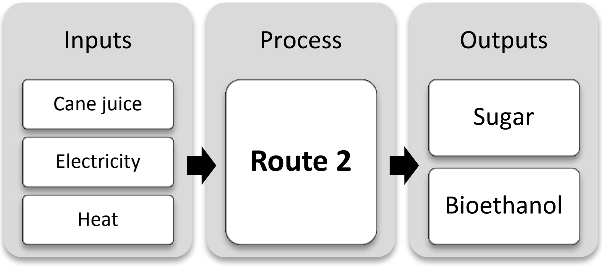

***Figure 51.*** *Inputs and outputs of Route 2*

In the third route, only bioethanol is produced by directly converting cane juice into bioethanol via fermentation, distillation and dehydration, but without co-producing sugar. This route is also known as autonomous distillery (see Figure 52).

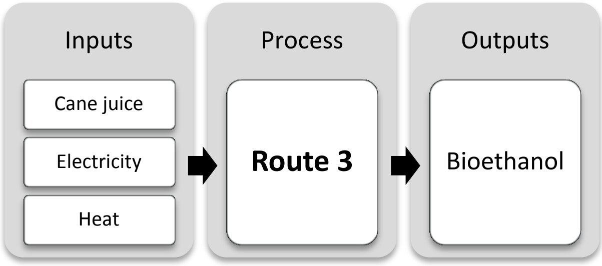

***Figure 52.*** *Inputs and outputs of Route 3*

The fraction of cane juice allocated to each of the three routes is estimated through the LUTM model explained in Section F.2.3.3. Heat and power requirements in these routes, depend on the allocation of cane for producing either sugar or bioethanol:

Eq. 118 $ECCI_{Ro,E,O,t} = \dot{m}_{cnl,RO,O,t} \cdot EIC_{Ro,E,O}$
Eq. 119 $ECCI_{E,t} = \sum_{Ro} \sum_{O} ECCI_{Ro,E,O,t}$

Where $ECCI_{Ro,E,O,t}$ is the annual energy consumption in the cane industry in year *t*, disaggregated by route *Ro* (i.e. 1, 2 or 3), by type of energy *E* (heat or power) and type of output *O* (sugar and bioethanol). $EIC_{Ro,E,O}$ is the energy intensity in route *Ro* disaggregated by type of energy *E*, i.e. the type of energy associated with the production of outputs *O* (taken from Table 18, and assumed to be constant throughout the entire period) and $\dot{m}_{cnl,Ro,O,t}$ is the mass flow of cane without leaves associated with the production of either sugar or bioethanol in route *Ro* in year *t*. $ECCI_{E,t}$ is estimated by adding the individual energy consumptions per output in each route.

***Table 18.*** *Energy intensity for producing sugar and bioethanol*

| Output | Power (MJ per ton cane w/o leaves) | Heat (MJ per ton cane w/o leaves) | Reference |
|---|---|---|---|
| Sugar | 54 | 1155 | (Macedo, Leal, & Da Silva, 2004) |
| Bioethanol | 47 | 1155 | (Macedo, Leal, & Da Silva, 2004) |

### F.3.4.3. Other conversion processes

Other conversion processes are modeled on a case-by-case basis. Some processes are analyzed in detail using data from technical reports and various sources, whereas some other conversion processes are not modeled in depth. Conversion processes that are not modeled in detail but included in the study are: natural gas works, reinjection and flaring, oil refining, coke factories, blast furnace, charcoal production, own use and energy distribution. For the sake of brevity, data associated with these processes is not shown in this thesis and can be found elsewhere (IEA, 2012b; EIA, 2014; IEA, 2012d). Some other processes are analyzed in more detail using data from technical reports and various sources. These process include: palm oil mill and production of biodiesel, biomass gasification, wood pelletization, production of renewable diesel, biomethane production and heat production in biomass boilers. A description of how these processes are modeled is presented as follows.

#### F.3.4.3.1 Palm oil mill and biodiesel production plant

In the palm oil extraction mill, the fresh fruit bunches (FFB) of the palm are crushed producing palm oil and residues. Part of the residues (e.g. fiber, stone) is commonly used as fuel in steam boilers to provide heating, while other part of the residues (e.g. rachis) is commonly returned to the field for soil replenishment. A simplified flow diagram of mass inputs and outputs of the palm oil extraction mill is shown in Figure 53.

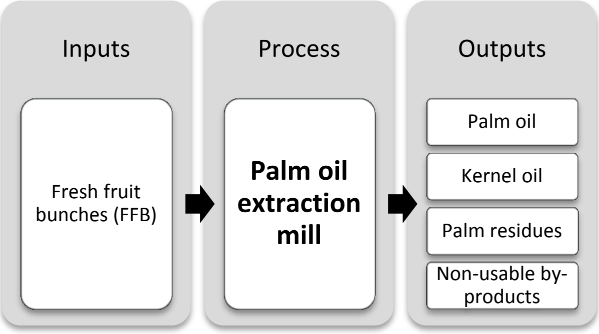

***Figure 53.*** *Inputs and outputs of palm oil extraction mill*

Mass and energy balance in the palm oil extraction mill is estimated through the following equations:

Eq. 120 $\dot{m}_{FFB} = \dot{m}_{po} + \dot{m}_{ko} + \dot{m}_{pr} + \dot{m}_{nby}$

Eq. 121 $\dot{m}_{FFB} \cdot LHV_{FFB} = \dot{m}_{po} \cdot LHV_{po} + \dot{m}_{ko} \cdot LHV_{ko} + \dot{m}_{pr} \cdot LHV_{pr} + \dot{m}_{nby} \cdot LHV_{nby}$

Where $\dot{m}$ represents the mass flow and $LHV$ represents the lower heating value; subscripts *FFB, po, ko, pr* and *nby* represent fresh fruit bunches, palm oil, kernel oil, palm residues and non-usable by-products, respectively. The process of converting palm oil into biodiesel consists of oil refining, transesterification and biodiesel purification steps. A flow diagram of material and energy inputs and outputs of the production process of biodiesel is presented in Figure 54 (adapted from (Salomon, Gonzalez-Salazar, Leal, Martin, & Fransson, 2009). Mass inputs include palm oil and methanol, while energy inputs include electricity and heat. On the other hand, mass outputs include biodiesel and glycerin. Methanol and glycerin are, however, not accounted here as energy flows. The heat and power requirements in the production of palm oil and biodiesel, depend on the allocation of feedstocks for producing either palm oil or biodiesel:

Eq. 122 $ECPI_{E,O,t} = \dot{m}_{O,t} \cdot EIP_{E,O}$

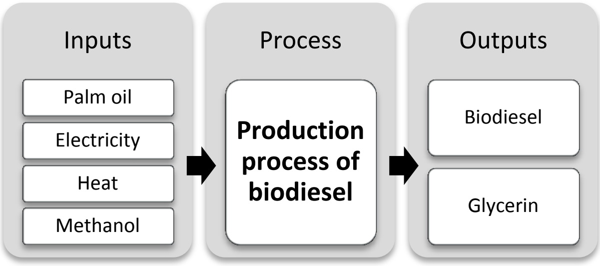

***Figure 54.*** *Inputs and outputs of the production process of biodiesel*

Eq. 123 $ECPI_{E,t} = \sum_{O} ECPI_{E,O,t}$

Where $ECPI_{E,O,t}$ is the annual energy consumption in the palm industry in year *t* disaggregated by type of energy *E* (heat or power) and type of output *O* (palm oil and biodiesel). $EIP_{E,O}$ is the energy intensity in the palm industry disaggregated by type of energy *E*, i.e. the type of energy associated with the production of outputs *O* (taken from Table 19, and assumed to be constant throughout the entire period) and $\dot{m}_{FFB,O,t}$ is the mass flow of fresh fruit bunches (FFB) associated with the production of either palm oil or biodiesel in year *t*. $ECPI_{E,t}$ is then estimated by adding the individual energy consumptions per type of output. Similarly to the case of bioethanol, the production, imports and exports of biodiesel are estimated through the LUTM model.

***Table 19.*** *Energy intensity for producing palm oil and biodiesel*

| Output | Electricity | Heat | Reference |
|---|---|---|---|
| Palm oil | 65 MJ/ton of FFB | 1400 MJ/ton of FFB | (Panapanaan, Helin, Kujanpää, Soukka, Heinimö, & Linnannen, 2009) |
| Biodiesel | 2.08 MJ/kg of biodiesel | 3.25 MJ/kg of biodiesel | (BID-MME, Consorcio CUE, 2012) |

#### F.3.4.3.2 Gasification of wood and biomass residues

Biomass gasification is a thermochemical process to convert biomass resources into a gas mixture called syngas and containing carbon monoxide, hydrogen and carbon dioxide. Syngas is used as a feedstock to produce biomethane and as a fuel in other conversion processes, including syngas co-firing in gas turbine simple and combined cycles, heat production in boilers and biomethane production. Two gasification processes are considered, one using wood and other using other biomass residues (e.g. rice husk, cane leaves and tops, bagasse and palm residues, etc.) as feedstocks. For wood gasification, it is considered a MILENA gasifier, a twin-bed gasifier with a circulating fluidized bed as gasifier and bubbling fluidized bed as combustor (Risø DTU, 2010). For gasification of biomass residues, it is considered a SilvaGas gasifier, a commercially available technology proven on a large scale (up to 40 MW) consisting of two circulating fluidized beds with sand as heat carrier (Risø DTU, 2010). This gasifier can also be fed with a wide variety of feedstocks, which makes it appropriate for gasification of biomass residues. Technical characteristics of both gasifiers are shown in Table 79 in the Appendix.

#### F.3.4.3.3 Wood pelletization

Wood pelletization is a process to convert wood into pellets via milling and mechanical compression. It is a process that demands electricity and that is required for other processes such as biomass co-firing in a coal power plant. Wood pellets have higher energy content than wood and are easier to handle, which facilitates its use in coal power plants. Technical characteristics of the wood pelletization process are shown in Table 79 in the Appendix.

#### F.3.4.3.4 Renewable diesel production

Renewable diesel is produced by hydrotreating of vegetable oils using palm oil as feedstock. In this process, hydrogen is used to remove oxygen from the triglyceride vegetable oil molecules and to split them into three separate chains, which are similar to diesel fuel components (Neste Oil, 2014). The process consumes palm oil, electricity, heat and natural gas and produces renewable diesel, renewable gasoline and renewable propane. Emissions associated with the renewable diesel conversion process include biogenic $CO_2$ (1.0884 Ton/TJ-renewable diesel), non-biogenic $CO_2$, CO, $CH_4$, NMVOC and NOx for burning natural gas as well as avoided non-biogenic emissions (emission credits) by substituting renewable fuel products (i.e. renewable diesel, renewable gasoline and renewable LPG) for fossil fuels. Characteristics of the process are summarized in Table 79 in the Appendix.

#### F.3.4.3.5 Biomethane production

Biomethane is produced through two different conversion processes: methanation and biogas gas upgrading. Methanation is a catalyst-based exothermic process in which syngas is converted into a gas stream containing mainly methane. It is chemically described by the balance:

Eq. 124 $CO + 3H_2 \rightarrow CH_4 + H_2O$

If syngas from wood is used (using a MILENA gasifier), it is then converted into biomethane in a HaldorTopsøe's TREMP® methanation process. The TREMP® methanation process is a custom-made commercially available technology using three step reactors with heat recovery from exothermic reactions. If syngas from biomass residues is used (using a SilvaGas gasifier), it is then converted into biomethane in a PSI/CTU methanation system. This is an isothermal fluidized bed methanation technology with internal regeneration of the catalyst, which is on the demonstration phase. On the other hand, biomethane production through biogas gas upgrading is a process to increase the methane content of the biogas gas in order to achieve quality characteristics to natural gas. In this process various components are removed from the biogas gas (mainly $CO_2$, $H_2O$ and $H_2S$) through a pressure swing adsorption (PSA) process, pre-purification and dehydration systems. This is a commercial and mature technology. For both processes, it is assumed that biomethane is 100% methane, but produced from organic sources. Main technical characteristics and assumptions for the different biomethane production processes are shown in Table 79 in the Appendix.

Similarly to the case of using landfill gas and biogas for power generation, there are various effects related to the production and use of the biomethane from biogas upgrading (see also Table 79 in the Appendix):

Eq. 125 $GHG_{biom,p} = GHG_{biom,CO2a} + GHG_{biom,CO2b} + GHG_{biom,CH4} + GHG_{biom,Other}$

Eq. 126 $GHG_{biom,CO2a} = \left(\frac{x_{bg,CO2}}{x_{bg,CH4} \cdot \eta_{biom}}\right) \cdot 1\,kg_{biom}$

Eq. 127 $GHG_{biom,CO2b} = EF_{biom,CO2} \cdot FU_{(1kg:\,biom)}$

Eq. 128 $GHG_{biom,CH4} = -\eta_{biom} \cdot 1\,kg_{biom}$

Eq. 129 $GHG_{biom,Other} = \sum_{Other}\left(EF_{biom,Other} \cdot FU_{(1\,kg:\,biom)}\right)$

Where $GHG_{biom,p}$ are the greenhouse gas emissions associated with producing and using 1 kg of biomethane.

The first effect relates to the emission of biogenic $CO_2$ not produced during the combustion of biomethane ($GHG_{biom,CO2a}$). $CO_2$ already contained in biogas is removed to upgrade the biogas into biomethane and subsequently vented into the atmosphere. This first effect is calculated as the $CO_2$ mass associated with the production of 1 kilogram of biomethane ($1\,kg_{biom}$) taking into account the efficiency of the biogas upgrading process ($\eta_{biom}$).

The second effect relates to the emission of biogenic $CO_2$ by burning biomethane ($GHG_{biom,CO2b}$). This effect is calculated as the emission factor of $CO_2$ for a final use, e.g. power generation, heat production, etc., ($EF_{biom,CO2}$) multiplied by the energy produced in these final uses with 1 kg of biomethane ($FU_{(1kg:\,biom)}$).

The third effect relates to the reduction in methane emissions that otherwise would be released into the atmosphere by not using these resources ($GHG_{biom,CH4}$). This reduction is calculated as the mass fraction of the methane contained in the biogas that is upgraded into biomethane after losses. Considering that the efficiency of the biogas upgrading process is assumed to be 93% (see Table 79 in the Appendix), there would be 0.93 kilogram of methane not released into the atmosphere per kilogram of biomethane produced. The avoidance of methane emission is therefore treated here as a credit, i.e. a 'negative' emission following the method suggested in (den Boer, den Boer, & Jager, 2005).

The fourth effect relates to the emission of other pollutants (e.g. CO and NOx) by burning biomethane ($GHG_{biom,Other}$). The fourth effect is calculated as the summation of the individual emissions of other pollutants. These individual emissions are calculated as the emission factors of these pollutants ($EF_{biom,Other}$) multiplied by the final energy produced with 1 kg of biomethane ($FU_{(1\,kg:\,biom)}$). The overall emissions of producing and using biomethane in year $t$ ($GHG_{biom,t}$) is calculated as follows:

Eq. 130 $GHG_{biom,t} = GHG_{biom,p} \cdot \dot{m}_{biom,t}$

Where $GHG_{biom,p}$ are the greenhouse gas emissions associated with producing and using 1 kg of biomethane and $\dot{m}_{biom,t}$ is the overall mass flow of landfill gas or biogas used in power generation.

#### F.3.4.3.6 Heat production in biomass-based boilers

Heat production in biomass-based boilers is mostly used to provide supplementary heat to various processes. Two commercially available technologies are considered, viz. residues-fuelled boiler on a small-scale and wood boiler on a small scale able to burn coal if necessary. Performance and cost of these technologies are taken from (Thermoflow, 2011).

## F.4. Application of the modeling framework to Colombia

The modeling framework to evaluate the energy, economy, emissions and land-use nexus for bioenergy exploitation is applied to the case study of Colombia. The selected base year is 2009, which is the year with the most recent statistics available. The last calculated year is 2030. Following sections present specific assumptions used in the study.

### F.4.1. Technology roadmapping and scenario analysis

Outcomes of the technology roadmapping process for Colombia such as long-term goals, milestones and strategies (shown in Chapter E) are used here as inputs. Opposing views of experts on the future of first generation biofuels led to two long-term visions: one vision focusing on new technologies in the Colombian context (e.g. biomethane and power generation and CHP) and other one combining new and traditional technologies (e.g. first generation biofuels).

A scenario analysis is proposed to evaluate the impacts of implementing these two visions, rather than selecting one or the other. Scenario analysis is an effective method for addressing uncertainty associated with future events, in which various possible alternative future storylines are considered. It is not intended to provide forecasts, but rather to represent future alternatives subject to particular conditions. Scenario analysis aims at improving the decision-making by allowing evaluation of how the different alternatives evolve over time, their effectiveness and impact.

Four scenarios representing different assumptions for deploying bioenergy technologies in the country based on findings of Section E.4 are defined:

- **Baseline**: it assumes no change in policies or deployment of new technologies
- **Scenario I:** it assumes new policy measures for biomethane and biomass-based power generation and CHP
- **Scenario II:** it assumes new policy measures for all bioenergy technology areas
- **Scenario II with expansion:** it shares the same goals with Scenario II, but assumes significant land expansion to cultivate sugar-cane on a large scale

Firstly, a baseline scenario assuming no future change in policies or technologies was created and calibrated using the national energy balances (UPME, 2011b). It allows a description of how the energy system would unfold if policy measures, patterns of supply and demand and deployment of technologies remain unchanged.

Scenario I considers new policy measures for biomethane and biomass-based power generation and CHP, but unchanged policies for transport biofuels until 2030. This is a scenario with a vanguard vision regarding the deployment of efficient power generation technologies (i.e. biomass-based CHP and co-firing) and new technologies (i.e. biomethane), but with a prudent vision regarding the deployment of first generation transport biofuels. It is therefore a scenario that aims at deploying efficient technologies in terms of environmental performance and land use, while maintaining the current deployment of first generation transport biofuels.

Scenario II considers new policy measures for all bioenergy areas, i.e. bioethanol, biodiesel, renewable diesel, biomethane and biomass-based power generation and CHP. This is a scenario that combines the vanguard vision of Scenario I with an ambitious vision to further deploy first generation transport biofuels. It is a scenario that aims at enlarging the current bioethanol and biodiesel programs, pioneer in the deployment of renewable diesel and biomethane, and deploy state-of-the-art biomass-based power generation technologies.

A further important consideration for the different scenarios is the availability of land. In the baseline scenario as well as in Scenarios I and II it is assumed that land for cultivating sugar cane is available only in the Valley of the Cauca River, the only area in the country where it is produced on a large-scale. However, experts agree that expansion to the land for cultivating sugar cane might be required to meet a growing demand for bioethanol. For this reason, a subset of Scenario II is defined to take into consideration a significant expansion in cultivation land.

This subset scenario is named Scenario II with expansion, which targets the same goals as Scenario II but assumes a significant land expansion to cultivate cane on a large-scale in other regions beyond the Valley of the Cauca River (e.g. Llanos and costa regions). A comparative overview of the definition, objective and assumptions about land for the different scenarios is shown in Table 20.

## F.4.2. Assumptions of the climate model

### F.4.2.1. Influence of climate on performance of renewable energy technologies

Climate conditions in Colombia are heavily influenced by El Niño and La Niña Southern Oscillation (ENSO). ENSO is characterized by two variations in the water temperature of the eastern Pacific Ocean (El Niño, warm and La Niña, cold). This causes extreme variations in temperatures, precipitation and wind patterns in the tropical western Pacific. ENSO cannot be predicted in the long-term, but the oscillation commonly lasts 4 to 5 years (Mora Alvarez, 2012). In this study, for simplicity it is assumed that ENSO has three phases (warm, cold and a neutral intermediate) recurring every four years. Renewable power technologies and particularly hydro power are vulnerable to ENSO variations. Detailed information of the different power generation technologies during the last 15 years has been taken from XM S.A. (XM, 2013) and further analyzed. While it is found that the capacity factor of hydro power and biomass-based power depends to certain extent on the solar radiance (see Figure 109 in the Appendix), this dependence is less clear for wind power. It is found that when the number of annual solar hours increases, the capacity factor of biomass power grows while the capacity factor of hydro power decreases. Interestingly, it is also found that the capacity factor of biomass and hydro power are to certain extent complementary.

***Table 20.*** *Comparative overview of scenarios*

| Scenario | Definition | Objective | Assumptions about policy measures | Assumptions about land |
|---|---|---|---|---|
| **Baseline** | Policies that have been adopted by 2013 continue to be unchanged | To provide a baseline that shows how the energy system would behave if trends in energy demand and supply remained unchanged | Unchanged policies | Land for cultivating sugar cane is limited to the Valley of the Cauca River |
| **Scenario I** | It considers new policy measures for biomethane and biomass-based power generation and CHP, but unchanged policies for transport biofuels | To explore the results of deploying efficient power generation technologies and biomethane production | • New biomethane policy<br>• New power generation and CHP policy | Land for cultivating sugar cane is limited to the Valley of the Cauca River |
| **Scenario II** | It considers new policy measures for all bioenergy areas, i.e. bioethanol, biodiesel, renewable diesel, biomethane and biomass-based power generation | To explore the results of implementing an ambitious enlargement of current bioethanol and biodiesel programs and a pioneering renewable diesel program on top of the goals defined for Scenario I | • New bioethanol policy<br>• New biodiesel policy<br>• New renewable diesel policy<br>• New biomethane policy<br>• New power generation and CHP policy | Land for cultivating sugar cane is limited to the Valley of the Cauca River |
| **Scenario II with expansion** | It considers the same goals as Scenario II and assumes a significant land expansion to cultivate cane on a large-scale | To explore the implications of expanding the land to cultivate cane on a large-scale beyond the Valley of the Cauca River, while aiming at the same goals defined for Scenario II | • New bioethanol policy<br>• New biodiesel policy<br>• New renewable diesel policy<br>• New biomethane policy<br>• New power generation and CHP policy | Land for cultivating sugar cane includes the Valley of the Cauca River and further expansion into other regions |

A possible explanation to this phenomenon is that when the solar radiance increases plants can absorb more solar energy and produce more biomass resources, which might cause an increase in the capacity factor of biomass power. On the other hand, when solar radiance increases there is a reduction in rainfall, which might cause a reduction in the capacity factor of hydro power. Figure 110 in the Appendix shows the capacity factor of renewable energies for arranged days in various years. The highest capacity factor of hydro power occurs at years with low solar radiance, when the capacity factor of biomass-based power is lowest. It is therefore assumed that the capacity factor of hydro and biomass-based power will remain complementary and will fluctuate between a warm-phase (using availability profiles for year 2003), an intermediate-phase (profiles for year 2004) and a cold-phase (profiles for year 2007) according to the variability caused by El Niño and La Niña Southern Oscillation (see averaged assumed profiles in Figure 111 in the Appendix). For wind power it is assumed that the capacity factor is not dependent on ENSO variations and the profile corresponding to year 2008 is used.

#### F.4.2.2. Influence of climate change on yields and prices of commodities

In the external climate model developed by IIASA (Fischer, 2011) the influence of climate change on agricultural yields and global price of commodities is evaluated. However, these two projections were not included when adapting the economic and LUTM models to the conditions of Colombia. This topic is recommended for further investigations.

### F.4.3. Application of the economic model

As shown in Figure 40, the LUTM, ESM and climate models are connected on the macroeconomic scale. Assumptions about future population, GDP, energy prices, prices of commodities, access to energy services and costs of technologies, do not change across scenarios and are estimated by the economic model.

#### F.4.3.1. Population

The current population is taken from (World Bank, 2013), while projected growth is taken from (DANE, 2005) for the period 2010-2020 and from (World Bank, 2013) for the period 2020-2030. Urban population was estimated using a linear regression function dependent on the total population. This function was calibrated with reported data over the last sixty years and a coefficient of determination $R^2$ of 99.99% was obtained. The population density ($D$, inhabitant/km$^2$) and its regional disaggregation are calculated using the population projections shown in Table 21 and the land area (Table 49 in the Appendix).

***Table 21.*** *Assumed population*

| Million | 2009 | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|
| Population | 45.65 | 46.19 | 48.93 | 51.68 | 54.11 | 56.17 |
| Urban pop. | 34.12 | 34.63 | 37.16 | 39.71 | 41.96 | 43.87 |
| Rural pop. | 11.54 | 11.56 | 11.76 | 11.97 | 12.15 | 12.30 |

Household size ($S$) represents the number of inhabitants per household and significant differences exist by region (rural vs. urban) and by household income. The historical average household size is taken from available statistics for years 1973, 1985, 1993 and 2005 (DANE, 2006), which have decreased over the years. The exponential correlation is obtained with a coefficient of determination $R^2$ of 99.15%.:

Eq. 131 $S = 6.2324E10 \cdot e^{-0.01173 \cdot t}$

Where $S$ is the household size in inhabitants per household and $t$ is the year. This correlation is then used to estimate the average household size in the future. Next, the allocation of household sizes across quintiles is defined using the approach defined in Section F.2.3.2.3. The obtained household size by region and quintile for Colombia is then presented in Figure 116 in the Appendix.

#### F.4.3.2. GDP & household expenditure

Current GDP in purchasing power parity (PPP) terms is taken from (World Bank, 2013), while projected real GDP growth through 2030 is taken from (UPME, 2012b). GDP is disaggregated into three main economic sectors, e.g. agriculture, services and industry. Growth in GDP for the sector of services is assumed to be equal to the overall growth in GDP, while growth in agricultural GDP was taken from (Gonzalez-Salazar, et al., 2014b)[19]. Growth in GDP for the industrial sector was then assumed to be dependent on the growth of the other sectors. Table 22 shows the estimated growth in GDP and GDP in PPP terms for all sectors.

***Table 22.*** *Assumed GDP [PPP] and GDP growth*

| | 2009 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| Agriculture | 32.77 | 48.37 | 51.96 | 60.20 | 68.52 |
| Services | 206.76 | 273.11 | 348.57 | 434.37 | 528.47 |
| Industry | 137.92 | 177.09 | 235.80 | 298.39 | 367.76 |
| Total | 377.45 | 498.58 | 636.33 | 792.96 | 964.75 |
| Agriculture | 2.03% | 1.69% | 1.69% | 3.59% | 2.71% |
| Services | 1.50% | 4.75% | 5.00% | 4.00% | 4.00% |
| Industry | 1.79% | 5.62% | 5.76% | 4.08% | 4.24% |
| Overall | 1.50% | 4.75% | 5.00% | 4.00% | 4.00% |

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[19] Growth in agricultural GDP is assumed to be equal to the growth in profits perceived by the agriculture sector as calculated by (Gonzalez-Salazar, et al., 2014b). Results for the scenario FAO-REF-01 are used.

Historical household final consumption expenditure –$HH$– (US$2005 in PPP) is taken from (World Bank, 2013). It is found that the historical household expenditure is linearly correlated with the GDP in the following form (coefficient of determination R$^2$ = 99.53%):

Eq. 132 $HH = 0.5327 \cdot GDP + 2.3E10$

The future household expenditure is then estimated by using this correlation and the assumed future GDP shown in Table 22. The household expenditure widely varies across the different segments of the income distribution. Therefore, the future household expenditure is further disaggregated into income quintiles and expressed as household expenditure per person (expenditure by quintile divided by the quintile population, i.e. 20% of the total population). The historical income shares by quintiles are taken from (World Bank, 2013), but this data is not available by region (i.e. urban vs. rural). Income shares by quintile and region are available for Colombia at the Global Income Distribution Dynamics Dataset (World Bank, 2009), although for year 1999 only (see Table 63 in the Appendix). Due to lack of more data, it is therefore assumed that the income share by region remains constant across the period analyzed. The future income shares by quintile are estimated using time-series analysis (i.e. autoregressive integrated moving average model –ARIMA–) to mathematically fit historical data whose trend is assumed to continue into the future. For this purpose the Predictor tool of Oracle® Crystal Ball 11.1.2.1 is used (see Table 64 in the Appendix). Finally, the future household expenditure per person-quintile is estimated using Eq. 43. Past and estimated future income share by quintile ($IS_Q$) are shown in Table 64 in the Appendix. The obtained household expenditure per person by quintile and region ($HHp_{r,Q}$) is shown in Table 65 in the Appendix.

### F.4.3.3. Price of energy resources

Energy prices are exogenous inputs to the ESM models. Ideally, it is advisable to forecast energy prices for each scenario in order to evaluate the impact of implementing different energy policies (IEA, 2012d; EIA, 2011). However, a dedicated forecast of energy prices is beyond the scope of this investigation. As a consequence, it is assumed that energy prices do not vary across policy scenarios.

Price forecasts of primary and secondary energy resources were taken from three main sources, namely (Rodríguez J. , 2013) for local prices, (EIA, 2011) for international prices and (DECC, 2011) for oil price projections. Prices were estimated for a few energy resources whose price forecasts were not readily available. These resources include bioethanol, biodiesel and woodfuel, whose prices were estimated using the procedure described below.

For bioethanol and biodiesel, the domestic price was calculated following the pricing structure defined by various regulations (DNP, 2008; MME, 2009a; MME, 2009b). According to these regulations, the price of biofuels is a function of the international price of oil, feedstock commodities (e.g. sugar in the case of ethanol and palm oil in the case of biodiesel), exchange rate and taxes. The domestic price of wood fuel was taken from (UPME, 2005) and updated; no statistics or price projections for wood fuel were found in literature and it was assumed that future prices would follow the growth in the price of coal, which is a direct substitute for wood. Table 48 in the Appendix shows the assumed price of energy expressed U.S. dollars of 2005 unless otherwise noted. Table 48 in the Appendix shows also the Manufactures Unit Value (MUV) Index published by the World Bank (World Bank, 2012), which was used to calculate the discounted prices of energy to account for the effect of price change over time.

### F.4.3.4. Access to electricity, natural gas and biofuels

Regarding access to electricity and natural gas, historical data disaggregated by region for various years is collected from several sources (see Table 67 in the Appendix). Gompertz curves are then created using regression analysis to best fit historical data and subsequently used to estimate future values. The parameters of the Gompertz function are positive numbers estimated through a regression analysis for electricity and natural gas by region (i.e. rural and urban). These parameters are shown in Table 68 in the Appendix, along with their coefficients of determination. Obtained results from the Gompertz models and historical data are plotted in Figure 55.

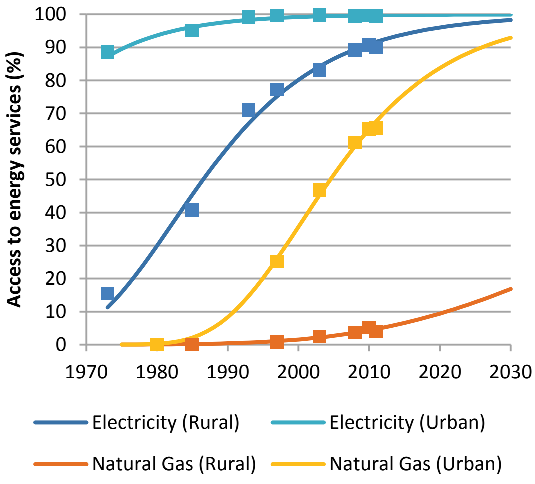

***Figure 55.*** *Estimated access to electricity and natural gas*

Finally, obtained access to electricity and natural gas disaggregated by energy type, quintile and year are shown in Figure 117 and Figure 118 in the Appendix. The supply coverage of biofuels ($Cov_{t,bio}$) is a variable that describes the effect of having a limited availability of biofuels nationwide (particularly in remote and border regions). The supply coverage of the different biofuels is here modeled through a Gompertz functions with a maximum value of 85%, which is shown in Figure 114 in the Appendix.

#### F.4.3.5. Capital and operational costs of technologies

Assumptions about capacity, capacity factor, efficiency, capital and operating cost and other characteristics of traditional and new technologies are collected from several sources and defined (see Table 73 in the Appendix).

The investment cost for technology type $g$ in year $t$ ($I_{g,t}$ in US$2009/kW) is taken from Table 73 in the Appendix), the operation and maintenance costs ($OM_{g,t}$ in US$2009/kW) is taken from Table 73 and the fuel cost ($F_{g,t}$ in US$2009/MMBtu, converted from US$2005/MMBtu) is taken from Table 48.

#### F.4.3.6. Global use of biofuels

In Chapter D and in (Gonzalez-Salazar, et al., 2014b) various scenarios describing different levels of global biofuel use were taken from the external models and used as inputs. Here, the conditions of a single scenario, the FAO-REF-01, are considered. This is a scenario developed by IIASA-FAO, which assumes that the global future use of biofuels follows the same trend as in the past (Fischer, 2011). Prices of commodities (see Table 38 in the Appendix) are considered only for this scenario.

#### F.4.3.7. Price of commodities and fertilizers

Future prices of commodities and fertilizers for different scenarios with varying degrees of global biofuel use are taken from different external models (see Section D.3.2.2 and Table 38 in the Appendix). Only prices corresponding to the scenario FAO-REF-01 are here considered.

### F.4.4. Application of the LUTM model

Availability of land for the different uses is an exogenous input to the LUTM model and is based on statistical information. Assumptions about availability of land are taken from Section D.3.2.3 and are shown in Table 49 in the Appendix. The method to build the LUTM model is the same as described in detail in Chapter D and in (Gonzalez-Salazar, et al., 2014b) with minor modifications. Firstly, cultivation of sugar cane on a large-scale is not limited to the Valley of the Cauca River as in Chapter D and in (Gonzalez-Salazar, et al., 2014b). Here, expansion into the Llanos and Costa regions is possible. Secondly, costs and yields of sugar cane, bioethanol, palm oil and biodiesel are updated using data published in (BID-MME, Consorcio CUE, 2012). This data and other assumptions about potential expansion in land to cultivate sugar cane in the Llanos and Costa regions are summarized in Table 60 to Table 62 in the Appendix.

### F.4.5. Application of the ESM model

#### F.4.5.1. General assumptions

The national energy balances (UPME, 2011b; UPME, 2011c; UPME, 2011d), developed by the Mining and Energy Planning Unit (UPME), an agency affiliated to the Ministry of Mines and Energy, have been used as the primary source of information to build and calibrate the ESM model for Colombia (see Section F.4.5.12 for more details on the model validation and calibration). While the abovementioned national energy balances provide information with a significant level of detail, data and statistics for various branches of the energy system are often not readily available. This is the case for the industrial, commercial and agricultural sectors, where time series describing specific energy demand and technology efficiency are not available. For these sectors, econometric methods were used to estimate the aggregated energy demand by fuel.

In various sectors the required capacity for bioenergy technologies can be calculated in a straightforward manner, as according to the assumptions no competition among multiple supply technologies exist. Sectors where bioenergy is produced by single supply technologies include biofuels (e.g. bioethanol, biodiesel and renewable diesel), biogas and wood pellets. In these cases, the capacity and operation of the bioenergy technologies is estimated based on the requirements from the demand side and for bioenergy technologies can be calculated the data on technology performance taken from literature. There are other sectors where competition among different bioenergy technologies exist and is modeled in a different manner. Sectors where multiple bioenergy technologies compete and interact with conventional technologies include power generation and CHP, heat production and biomethane. For heat production and biomethane, the competition is modeled through a merit order, in which the capacity and operation of technologies depend on the availability and price of biomass resources. The competition between multiple technologies in the particular case of power generation and CHP was simulated with an optimization approach. In this approach, an optimization algorithm orders electricity dispatch and capacity addition to minimize the net present value of the total costs of the system over the entire period (i.e. capital costs, operating costs, fuel costs, externalities, etc.).

### F.4.5.2. Boundary conditions

For the demand side of the ESM model, the country's economy is divided into seven main sectors, namely residential, commercial, industrial, transport, agriculture, non-energy and non-specified. The demand for primary and secondary energy resources is estimated in a disaggregated level for each of these sectors. Primary energy resources are raw energy forms that have not been transformed, including coal, oil, natural gas, biomass and renewables (hydro, wind, etc.). On the other hand, secondary energy resources are derived from primary energy resources through conversion processes. Secondary energy resources include electricity, heat, gasoline, diesel fuel, fuel oil, coke, kerosene, jet fuel, liquefied petroleum gas (LPG), charcoal, bioethanol and biodiesel, among others.
Conversion technologies are modeled as much on the demand side as on the transformation side of the model. On the demand side of the model, conversion technologies are modeled only for the road transport sector (e.g. vehicles) and the residential sector (e.g. lighting, cooking, etc.). On the transformation side of the model, conversion technologies are modeled for all conversion processes. Current conversion processes include power generation and CHP, heat production, oil refining, gas processing, charcoal and coke production, blast furnace, bioethanol and biodiesel production facilities and biomass processing. Conversion processes added for Scenarios I and II include biomethane production, co-firing in coal power plants and gas turbines, and renewable diesel production.

In addition to conversion processes, distribution losses and own use are also modeled on the transformation side of the model. Own use is the primary or secondary energy consumed by conversion technologies. In this study, the own use is included on the transformation side of the model, in contrast to the national energy balances that include it on the demand side (UPME, 2011b). For calculating the greenhouse gas (GHG) emissions, the approach used in (UPME, 2011b) was followed. In this approach, the emissions associated with the combustion of fuels in each branch of the demand and the transformation sides of the model are accounted for. $N_2O$, $CH_4$, $CO_2$ biogenic and non-biogenic emissions as well as Global Warming Potential (GWP) were evaluated for 100 years. The guidelines of the Intergovernmental Panel on Climate Change (IPCC) included in the technology and environmental database (TED) in LEAP are employed to calculate the emissions associated with the combustion of fuels. One important difference is that this study includes the emissions associated with all conversion processes of the transformation side, while in (UPME, 2011b) only emissions related to power generation and coke production were estimated.

### F.4.5.3. Limitations

An acknowledged source of uncertainty is that the ESM model is calibrated using the latest available national energy balances, which correspond to the year 2009 and predate the present study by five years. Another limitation is that only direct impact from pollution emissions associated with combustion of fuels is counted in LEAP. As a consequence, indirect emissions associated with processes including transport, exposure, dose/response effects, and also land-use change, cultivation, irrigation, etc. are not considered. Finally, overall costs were estimated only for power generation and CHP technologies. Environmental externality costs were not included in the costing analysis.

### F.4.5.4. Assumptions of the road transport sector

Available data disaggregates the number of vehicles in four types (ACP, 2012; MinTransporte-CEPAL, 2010; UPME, 2010b): a) motorcycles, b) gasoline road vehicles with at least four wheels, c) diesel road vehicles with at least 4 wheels (including trucks) and d) CNG-fuelled vehicles. The number of vehicles is divided by the population to obtain the vehicle ownership per type, which is shown in Table 23.

***Table 23.*** *Number of vehicles by type*

| **Vehicles per 1000 people** | **1990** | **1995** | **2000** | **2005** | **2009** |
|---|---|---|---|---|---|
| Gasoline vehicles | 32.58 | 40.77 | 46.18 | 48.12 | 49.13 |
| Diesel vehicles | 6.08 | 8.33 | 10.38 | 12.03 | 17.37 |
| CNG vehicles | 0.00 | 0.11 | 0.15 | 2.23 | 6.51 |
| Motorcycles | 7.36 | 13.84 | 21.87 | 28.70 | 58.46 |
| Total | 46.02 | 63.06 | 78.59 | 91.09 | 131.47 |
| Population (mio) | 33.20 | 36.45 | 39.76 | 43.04 | 45.65 |

**References:** (ACP, 2012; Ciudad Humana, 2012; MinTransporte-CEPAL, 2010; UPME, 2010b)

In the original study by (Dargay, Gately, & Sommer, 2007) the relationship between vehicle ownership and income growth was estimated for 45 countries for the period 1960-2002. Colombia was excluded from this study due to the lack of consistency in found data. In the present study, the model is re-evaluated using data shown in Table 24. In (Dargay, Gately, & Sommer, 2007) only the maximum saturation level $\psi_{MAX}$ and the parameter $\beta$ are country-specific, while all other parameters of the Gompertz function are the same for all countries. Using original parameters published by (Dargay, Gately, & Sommer, 2007) a $\beta$ value of -0.1169 and a coefficient of determination $R^2$ of 99.3% were estimated using a regression analysis.

***Table 24.*** *Comparison of model parameters for the vehicle ownership model*

| **Model parameters** | **Dargay et al.** | **This study** |
|---|---|---|
| Parameter $\alpha$ | -5.8970 | -4.8400 |
| Parameter $\beta$ | -0.1169 | -0.0925 |
| Maximum saturation $\psi_{MAX}$ | 852 | 827 |
| Constant $\lambda$ | -0.000388 | -0.000388 |
| Constant $\varphi$ | -0-007765 | -0-007765 |
| Speed of adjustment $\theta_R$ | 0.095 | 0.095 |
| Speed of adjustment $\theta_F$ | 0.084 | 0.084 |
| Coefficient of determination $R^2$ | 99.3% | 99.6% |

However, a modification in the parameters of the Gompertz function led to an improved fit of the model data compared to historical data. If $\alpha$, $\beta$ and $\psi_{MAX}$ are specifically estimated for Colombia with all the remaining parameters unmodified, a slightly higher coefficient of determination of $R^2$ of 99.6% can be obtained. A comparison of the model parameters of (Dargay, Gately, & Sommer, 2007) and this study is shown in Table 24. The improved parameters are therefore used to estimate the future ownership of vehicles with at least four wheels until 2030 in Colombia.

The fuel cost required for each vehicle type to drive 100 km ($F_{c,t}$) is estimated as the fuel cost per year (US$2005/MJ, see Table 48 in the Appendix) for the different vehicle types multiplied by the fuel economy (MJ/100 km, see Table 28). The parameters of the logit function in Eq. 61 are obtained through a regression analysis to best fit the historical curve of shares. Table 25 shows the values of the fuel cost used and Table 26 summarizes the results of the regression analysis.

***Table 25.*** *Historical fuel cost by vehicle*

| **Fuel cost US$2005/100 km** | **1990** | **1995** | **2000** | **2005** | **2009** |
|---|---|---|---|---|---|
| CNG vehicles | 0.1807 | 0.1502 | 0.2337 | 0.2547 | 0.3711 |
| Gasoline vehicles | 2.2382 | 2.9469 | 4.4550 | 7.6093 | 10.2489 |
| Diesel vehicles | 4.8226 | 6.3282 | 7.8072 | 11.4985 | 18.4029 |

***Table 26.*** *Parameters of the logit function to estimate vehicle shares*

| **Model parameters** | **Gasoline vehicles** | **Diesel vehicles** | **CNG vehicles** |
|---|---|---|---|
| Parameter $k_c$ | 0.2104 | 0.0999 | 50 |
| Parameter $\gamma$ | 50 | 50 | 50 |
| Speed of adjustment $\theta$ | 0.015 | 0.0076 | 1 |
| Coefficient of determination $R^2$ | 88.25% | 85.35% | 80.41% |

The parameters used to evaluate the motorcycle ownership in Colombia are estimated using a regression analysis to best fit the historical data, similarly to the case of vehicle ownership, and are shown in Table 27.

***Table 27.*** *Model parameters of the motorcycle ownership model*

| **Model parameters** | **Value** |
|---|---|
| Parameter $\alpha$ | -25 |
| Parameter $\beta$ | -0.3602 |
| Maximum saturation $\psi_{MAX}$ | 200 |
| Speed of adjustment $\theta$ | 0.4874 |
| Coefficient of determination $R^2$ | 93.6% |

To estimate the number of legacy vehicles of different types produced in different years and surviving in the first year of modeling (2009), historical data is collected from literature (MinTransporte, 2005). Historical data show irregular trends that reflect past vehicle context. However, it is uncertain whether these contexts will repeat exactly in the future. Therefore, modified curves with smoother trends are created by vehicles (see Figure 56).

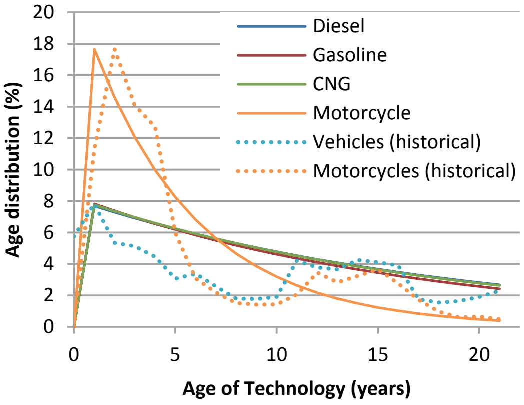

***Figure 56.*** *Age distribution by vehicle (MinTransporte, 2005)*

Subsequently, the survival rate per vehicle type is taken from literature, see Figure 57. While survival rates for motorcycles and 4 wheeled vehicles are found in (UPME, 2010b), further disaggregation is not available. It is therefore assumed that the survival for 4 wheeled vehicles is the same for diesel, gasoline and CNG vehicle.

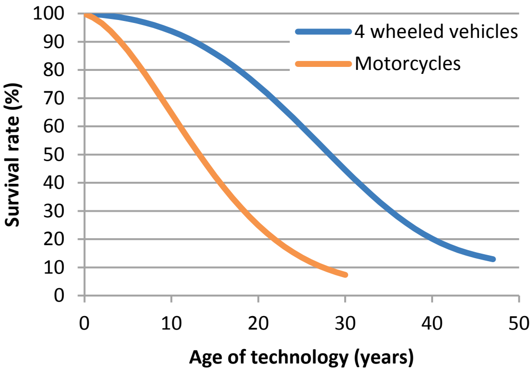

***Figure 57.*** *Survival rate by vehicle type (UPME, 2010b)*

Data on fuel economy per vehicle type is only available as an average and not disaggregated by vintage (Econometria - UPME, 2010). Reported data for base year (2009) is summarized in Table 28. The degradation factor is not available and it is therefore assumed that the average fuel economy remains constant for the different vintages (i.e. $FE_{c,t,v} = FE_{c,v}$). The future fuel economy is estimated using the fuel economy by vehicle for the base year and future projections for decline. An annual projected rate of decline of -0.7% in fuel economy for all vehicle types in Latin America until 2030 is taken from (OPEC, 2004; Dargay, Gately, & Sommer, 2007). The supply coverage of biofuels ($Cov_{t,bio}$) is taken from the economic model (see Section F.4.3.4 and Figure 114 in the Appendix). Next, the mileage is estimated. Mileage is the annual distance traveled per vehicle (km/vehicle). For the base year, average mileage by vehicle type for all vintages is calculated using the following equation:

Eq. 133 $Mil_{c,2009} = \frac{ECV_{c,2009}}{Stock_{c,2009} \cdot FE_{c,2009}}$

Where, $ECV_{c,2009}$ is the energy consumption by vehicle type in 2009 taken from (UPME, 2011a), $Stock_{c,2009}$ is the number of stocks by type in 2009 taken from Table 28 and $FE_{c,2009}$ is the fuel economy by vehicle type taken also from Table 28. While it is desirable to include a mileage degradation factor that considers the reduction in travelled distance as a vehicle ages, this data is not readily available for the country. Thus, it is assumed that the mileage by vintage is constant. Future mileage is estimated using available projections. A 0.4% annual growth for gasoline vehicles and motorcycles and a 0.5% annual growth for diesel vehicles and CNG vehicles are taken from (E4tech, 2013).

The competition of E85 with gasohol occurring by launching the E85 program in 2030 in Scenario II is modeled through the following equations:

Eq. 134 $VE85_t = VEFF_t \cdot Cov_{E85,t}$

Eq. 135 $\mu_{E85,t} = \frac{\left[{}^{1}/_{F_{E85,t}}\right]^{\gamma}}{\left[{}^{1}/_{F_{E20,t}}\right]^{\gamma} + \left[{}^{1}/_{F_{E85,t}}\right]^{\gamma}}$

Eq. 136 $\mu_{E20,t} = 1 - \mu_{E85,t}$

In Eq. 134 $VE85_t$ is the percentage of vehicles in year $t$ that are able to run with E85 and have access to it, $VEFF_t$ is the percentage of vehicles that are flex fuel (assumed to enter into the market in 2015 and further calculated by LEAP considering the survival rate and new acquisitions, see Figure 114 in the Appendix), $Cov_{E85}$ is the supply coverage of E85 by year (shown in Figure 114 in the Appendix).

On the other hand, in Eq. 135 $\mu_{E85,t}$ is the energy share of E85 used in flex fuel vehicles, which is modeled as a function of $F_{E20,t}$, i.e. the cost of E20 (fuel that compete with E85 in 2030 in US\$2005/MMBtu), $F_{E85,t}$, i.e. the cost of E85 (US\$2005/MMBtu) and $\gamma$, i.e. the cost sensitivity coefficient, which is assumed to be 2. This is a low degree of sensitivity, which implies that in the first year of implementation (i.e. 2030) the substitution of E20 for E85 is not likely to happen easily even if major price changes occur.

Finally, the emission factors by pollutant are taken from the Technology and Environmental Database (TED) implemented in LEAP, which refers to the default Tier 1 emissions factors suggested by IPCC in 1996 (Heaps, 2012). These factors are provided by fuel and application in Table 80 Table 81 in the Appendix.

***Table 28.*** *Energy intensity by vehicle type in year 2009*

| | **Motorcycles $^{A}$** | **Gasoline vehicles $^{A}$** | **Diesel vehicles $^{A}$** | **CNG vehicles $^{B}$** |
|---|---|---|---|---|
| Vehicles (thousand) | 2669[1] | 2243[2] | 793[2] | 297[3] |
| Fuel type | Gasoline | Gasoline | Diesel fuel | CNG |
| Fuel LHV (MJ/l) | 32.87[4] | 32.87[4] | 36.71[4] | 0.04[5] |
| Fuel density (kg/liter)[6] | 0.740 | 0.740 | 0.837 | 0.185 |
| Average fuel economy $FE_{c,2009}$ ($^{A}$ km/l, $^{B}$ km/cubic meter)[7] | 40.89 | 8.17 | 3.80 | 28.10 |
| Average fuel economy $FE_{c,2009}$ (MJ/100km)[8] | 80.39 | 402.33 | 964.95 | 140.62 |
| Average mileage (km/vehicle)[9] | 12426 | 11773 | 18908 | 65349 |

[1] (Ciudad Humana, 2012)

[2] (MinTransporte-CEPAL, 2010; UPME, 2010b)

[3] (ACP, 2012)

[4] (UPME, 2010b)

[5] It is taken the average of natural gas produced in the Cusiana field and the Guajira region according to data from (UPME, 2010b)

[6] Data taken from (MIT, 2010). The density of CNG is at a pressure of 200 bar.

[7] (Econometria - UPME, 2010)

[8] Calculated using the fuel economy published by Econometria and the assumed fuel LHV

[9] Mileage is calculated as: energy consumed by fuel/ (Stocks · fuel economy). The energy consumed by fuel is taken from (UPME, 2011b)

The degradation factors $Deg_{c,t-v,p}$ for NOx, NMVOC, $N_2O$, CO and $CH_4$ by vehicle are taken from (Toro Gómez, Molina Vásquez, Londoño Largo, & Acevedo Cardona, 2012), see Figure 115 in the Appendix.

Acknowledged limitations of the approach suggested above include a restricted number of vehicle categories with limited statistical information about performance, vehicle use, emissions, etc. This is a natural consequence of lack of available data in a more disaggregated form. Recommendations for further studies include creating databases that include detailed information for past and existing fleet, fuel economy, mileage, emissions, costs, etc.

### F.4.5.5. Assumptions of the residential sector

#### F.4.5.5.1 First step: define primary drivers

Five primary drivers are defined for Colombia: population (*P*), household expenditure (*HH*), population density (*D*), household size (*S*) and Temperature (*T*). Future urban and rural populations are taken from Table 21. The first four drivers are provided by the economic model shown in Section F.4.3. Ambient temperature is expressed in heating degree days (HDD), which in average for Colombia are 677 (ChartsBin, 2014). Household size disaggregated by region and quintile is taken from Figure 116 in the Appendix.

#### F.4.5.5.2 Second step: estimate intermediate drivers

Obtained floor spaces by region and quintile for Colombia are shown in Table 66 in the Appendix. Access to electricity and natural gas disaggregated by region, quintile and year is addressed in Section F.4.3.4 (see also Figure 117 and Figure 118 in the Appendix).

#### F.4.5.5.3 Third step: estimate energy consumption

*Water heating*
The average heating degree days (HDD) are assumed to be 677 for Colombia according to (ChartsBin, 2014). Obtained Gompertz function and historical data for water heating are compared in Figure 119 in the Appendix, along with parameters of the Gompertz function. The energy consumption for water heating ($ECW$) is then estimated by multiplying the energy consumption for water heating per capita (*ECWp)* by the population. Next, the fuel shares are calculated by dividing the demand into two groups, group #1 with access to electricity, natural gas and other fuels and group #2 with access only to electricity. For both groups the fuel shares are estimated using Eq. 85. Historical and estimated fuel shares along with parameters of the Gompertz curves are shown in Figure 120 in the Appendix.

*Appliances*
The average cooling degree days (CDD) are assumed to be 2119 for Colombia according to (ChartsBin, 2014). There is neither available data for ownership of refrigerators in Colombia nor for unit energy consumption, therefore the models described above are validated with the overall energy demand for refrigeration per capita taken from (UPME, 2011b; UPME, 2011c; UPME, 2011d). Model parameters and obtained results through regression analysis are shown in Figure 121 and Figure 122 in the Appendix.

Similarly to refrigerators, there is neither available data for ownership of air conditioners nor for unit energy consumption, therefore the models described above are validated with the overall energy demand for air conditioning per capita available in (UPME, 2011b; UPME, 2011c; UPME, 2011d). Model parameters and obtained results through regression analysis are shown in Figure 123 and Figure 124 in the Appendix.

Regarding other appliances, models are calibrated with published data in (UPME, 2011b; UPME, 2011c; UPME, 2011d). Model parameters and obtained results through regression analysis are shown in Figure 125 and Figure 126 in the Appendix.

*Lighting*
The unit energy consumption per light bulb is assumed to be 60 W/unit. The lighting hours factor coefficient ($LHF_r$) is estimated through regression analysis to best fit historical data available in (UPME, 2011b; UPME, 2011c; UPME, 2011d). Obtained results and parameters are shown in Figure 127 in the Appendix.

*Cooking*
Historical data on energy for cooking available in (UPME, 2011b; UPME, 2011c; UPME, 2011d) differs from the constant 3 $MJ_{UE}$/person/day proposed by (Daioglou, 2010) and shown in Section F.3.3.2.3. Thus, it has been decided to estimate the energy demand for cooking in urban and rural regions separately. For urban regions, the energy demand for cooking per capita is assumed to be a constant and is estimated as the average for the period 1975-2009 using historical data available in The obtained value is 1.8225 $MJ_{UE}$/person/day (standard deviation = 0.1722), see Figure 128 in the Appendix. For rural regions, the energy consumption for cooking is estimated through the following equations:

Eq. 137 $ECCH_{Q,ru} = CK1 \cdot CK2^{t-1970} + CK3$
Eq. 138 $ECCp_{ru} = \frac{1}{P} \cdot \left(\sum_Q ECCH_{Q,ru} \cdot H_{Q,ru}\right)$
Eq. 139 $ECC_{ru} = \left(\sum_Q ECCH_{Q,ru} \cdot H_{Q,ru}\right) \cdot 365$

Where $ECCH_{Q,ru}$ is the daily energy consumption for cooking per household in rural areas disaggregated by quintile ($MJ_{UE}$/household/day), $ECCp_{ru}$ is the daily energy consumption for cooking per person in rural areas ($MJ_{UE}$/person/day), $ECC_{ru}$ is the overall annual energy consumption for cooking in rural areas, $H_{Q,ru}$ is the number of households in rural areas and $CK1$, $CK2$ and $CK3$ are function coefficients. Obtained parameters and results for the model are presented in Figure 129 in the Appendix.

Fuel shares for cooking both in rural and urban regions are estimated using Eq. 85. Fuel shares by region are calculated by dividing the demand into two groups, group #1 with access to electricity, natural gas and other fuels and group #2 with access only to electricity. Models are calibrated using historical data and obtained results are shown in Figure 130, Table 69, Figure 131 and Table 70 in the Appendix.

### F.4.5.6. Assumptions of the non-road transport, agriculture, industrial and commercial sectors

Econometric methods were used for estimating the energy demand in non-road transport, agriculture, industrial and commercial sectors. In Eq. 100, the coefficients $\xi_1$ and $\xi_2$ and speed of adjustment $\theta$ are calibrated through regression analysis to best fit historical data available in (UPME, 2011b; UPME, 2011c; UPME, 2011d). The fuel cost by year is taken from Table 48 in the Appendix, while the GDP by sector is taken from Table 22. Results of the regression analysis are presented in Table 71 in the Appendix. In a few cases the results of the regression analysis were not satisfactory, i.e. the coefficient of determination was lower than 60%. In these cases, the energy demand was not substantial and it was assumed that the average demand of last ten years would continue until 2030. These assumptions are shown in Table 72 in the Appendix.

### F.4.5.7. Assumptions of cane and palm industries

While the accounting methodology of national energy balances (UPME, 2011b) considers the energy consumption in cane and palm industries, it provides limited details on how this consumption is estimated and where is allocated. The consumption by energy type (heat, power, etc.) for a particular process (e.g. palm oil production or sugar production) is not always available. In addition, the consumption of energy for these processes is allocated both on the demand side and on the transformation side and it is unclear how this allocation is calculated. For simplicity, in this study it is assumed that cane and palm industries are conversion processes and that their energy consumption is allocated on the transformation side. The method to estimate the energy consumption is described in more detail in following sections F.3.4.2 and F.3.4.3.

### F.4.5.8. Assumptions of the power generation model

#### F.4.5.8.1 First step: define technology portfolio

Traditional technologies include large and small hydro power plants (<10 MWe), simple and combined cycle gas turbines, coal power plants, diesel and gas reciprocating engines, wind turbines, bagasse-fuelled steam CHP power plants, palm residues-fuelled steam CHP power plants and small power generation units burning a wide range of fuels (UPME, 2011b). From these technologies only bagasse- and palm residues-fuelled steam CHP power plants are able to co-produce combined heat and power (CHP).

New technologies include: biomass co-firing in coal power plants, syngas co-firing in gas turbine simple and combined cycles, biomass-fuelled CHP power plants on a small scale (up to 10 MWe), biogas- and landfill gas-fuelled reciprocating engines. New technologies able to co-produce heat and power include biomass-fuelled CHP power plants on a small scale, biogas- and landfill gas-fuelled reciprocating engines.

#### F.4.5.8.2 Second step: define performance and cost

Assumptions about capacity, capacity factor, efficiency, capital and operating cost and other characteristics of traditional and new technologies are taken from the economic model in Section F.4.3.5 (see also Table 73 in the Appendix).

#### F.4.5.8.3 Third step: perform optimization

General assumptions to perform optimization include:

- A discount rate of 10% is assumed. A wide variation was found in literature regarding the appropriate discount rate for Colombia. Values between 5% and 18% were found (UPME, 2005; Correa Restrepo, 2008), which represent an important source of uncertainty. A discount rate of 10% is assumed here, which is in between the limits mentioned above, but which is also close to a discount rate of 9-12% described in (UPME, 2005) for energy projects in the country.
- A decommissioning cost of 5% of capital cost is assumed (IEA-NEA, 2010).
- Investment cost includes owner's costs but exclude interest during construction (IEA, 2012a).

Capacity credit by technology is shown in Table 73 in the Appendix. The assumed minimum planning reserve margin is 40%, which has been the average value between 1998 and 2010 in Colombia (UPME, 2011a). This value is significantly higher than in other countries, where typically ranges between 15 and 25%

(IEA, 2007; NERC, 2012; EIA, 2014). The annual electricity loads are divided into daily slices, for which a load shape is assigned. The load shape is taken from the state-owned transmission firm Interconexión Eléctrica S.A. for year 2009 (XM, 2013) and is shown in Figure 132 in the Appendix. When compared to data of 1996 the load shape of 2009 has virtually no differences and therefore it has been decided to keep the load shape constant until 2030.

For Scenarios I and II, a renewable power target reflecting a new power generation policy (see details in Section E.4.3) is imposed on the optimization. This renewable power target linearly increases from 0% in 2015 to 10% in 2025 and remains at this level afterwards. Technologies that qualify as renewable energy to meet the renewable power target include: wind power, small hydro (< 10 MWe), biomass fuelled CHP plants, biomass co-firing in coal power plants, syngas co-firing in gas turbine simple and combined cycles, biomass-fuelled CHP power plants on a small scale (up to 10 MWe), biogas-fuelled reciprocating engines and landfill gas fuelled reciprocating engines.

It is worth mentioning that from all the capacity added to the system, one part is optimized by the algorithm, while another part is entered exogenously and reflect officially planned additions and retirements, more details are given below.

Official capacity additions by technology until 2019 are assumed for all scenarios, summing in total 7.53 GW according to various sources (IFC, 2008; UPME, 2009; Portafolio, 2012a; Portafolio, 2013; Sector Electricidad, 2012; BNamericas, 2013; El Colombiano, 2013). Technologies planned to be added include large hydro (5.6 GW), small hydro (0.15 GW), coal (0.57 GW), natural gas turbines (1.1 GW) and diesel engines (0.12 GW), see details in Table 74 in the Appendix. In addition to that, further capacity is exogenously added for Scenarios I and II to comply with two of the long-term targets: 1) exploit 5% of the biogas from animal waste and municipal wastewater plants, 2) exploit 100% of the biogas from biodiesel production plants and 3) exploit 10% of the landfill gas. In order to comply with these targets, further capacity of reciprocating engines is exogenously added in Scenarios I and II (see Table 75 in the Appendix).

For technologies that are officially planned to be added until 2019 (e.g. large and small hydro, coal, natural gas simple cycle gas turbines and diesel reciprocating engines), a maximum annual capacity addition is imposed beyond 2019. This maximum annual addition is assumed to be the maximum planned addition observed during the period 2009-2019 (see Table 76 in the Appendix). For technologies not planned to be added until 2019 (e.g. gas turbines on a small-scale, coal power plants on a small-scale, natural gas reciprocating engines, wind power and biomass-based power generation), some assumptions are taken. Based on discussion with experts, a maximum annual capacity addition of 100 MWe is assumed for gas turbines on a small-scale, coal power plants on a small-scale and natural gas reciprocating engines, while 50 MWe is assumed for wind power given its slow-paced deployment. For biomass-based power generation technologies, the maximum annual capacity addition is related to the future technical biomass energy potential described in detail in Section F.4.5.11. It is estimated through the following equations:

$$\text{Eq. 140} \quad CAD_{MAX,g} = \left(\frac{TEP_{MAX,b}}{20}\right) \cdot \left(\frac{\eta \cdot AF}{CF}\right)$$

Where $CAD_{MAX,\mathrm{g}}$ is the maximum annual capacity addition by technology (MW), $TEP_{Max,\mathrm{b}}$ is the maximum technical energy potential by biomass resource (TJ) (taken from Table 54 in the Appendix), subscripts $g$ and $b$ respectively represent power technology and type of biomass resource, $\eta$ is a generalized efficiency for biomass-based power generation technologies (assumed to be that of biomass CHP on a small scale, i.e. 30%), $CF$ is a generalized capacity factor (assumed to be the average of 2004-2011 for bagasse-based CHP, i.e. 59.19%) and $AF$ is a factor that attempts at considering that most likely not all technical biomass energy potential can be exploited (assumed to be 40%). Note that the maximal annual increment of biomass-based power technologies is assumed to be lineal, which is described in Eq. 140 by dividing the maximum technical energy potential ($TEP_{Max,\mathrm{b}}$) by the 20 years span from 2010 to 2030. Obtained maximum annual capacity additions for biomass-based power generation technologies are shown and compared to other technologies in Table 76 in the Appendix. The maximum annual capacity is also limited for some technologies. This is the case of biomass co-firing in coal power plants in which the capacity is limited to 10% of the overall coal power capacity and for syngas co-firing in gas turbines the capacity is limited to 5% of the overall gas power capacity.

#### F.4.5.8.4 Fourth step: estimate emissions

The emission factors by pollutant are taken from the TED database implemented in LEAP, which refers to the Tier 1 emissions factors for power generation suggested by IPCC (Heaps, 2012). Detailed characteristics of all fuels used in the power generation module are shown in Table 77 in the Appendix.

For Scenarios I and II, emissions associated with power plants burning landfill gas or biogas from biodiesel processing plants, wastewater plants and animal waste are estimated with Eq. 110-Eq. 114 and using the specific data for Colombia shown in Table 78 and Table 79 in the Appendix.

### F.4.5.9. Assumptions about cane mill, sugar and bioethanol production

Regarding the general mass balance in the cane mill, the following assumptions are taken, using data from Table 78 in the Appendix:

Eq. 141 $\dot{m}_{ba} = 0.2588 \cdot \dot{m}_{cwl}$
Eq. 142 $\dot{m}_{cj} = 0.5182 \cdot \dot{m}_{cwl}$
Eq. 143 $\dot{m}_{tl} = 0.2229 \cdot \dot{m}_{cwl}$
Eq. 144 $\dot{m}_{cnl} = \dot{m}_{cwl} - \dot{m}_{tl} = 0{,}7771 \cdot \dot{m}_{cwl}$

For Route 1, it is assumed a constant yield of 0.12 tons of sugar per ton of sugar cane without leaves, taken from (BID-MME, Consorcio CUE, 2012):

Eq. 145 $\dot{m}_{s,R1} = 0.12 \cdot \dot{m}_{cnl}$

Where $\dot{m}_{s,R1}$ is the mass flows of produced sugar in Route 1. Additional assumptions for this route are presented in Table 78 in the Appendix.

For Route 2, constant yields of 0.093 tons of sugar and 0.019 tons of bioethanol per ton of sugar cane without leaves are assumed, taken from (BID-MME, Consorcio CUE, 2012):

Eq. 146 $\dot{m}_{s,R2} = 0.093 \cdot \dot{m}_{cnl}$
Eq. 147 $\dot{m}_{et,R2} = 0.019 \cdot \dot{m}_{cnl}$

Where $\dot{m}_{s,R2}$ and $\dot{m}_{et,R2}$ are the mass flow of produced sugar and bioethanol in Route 2, respectively. Additional assumptions for this route are presented in Table 78 in the Appendix.

For Route 3, it is assumed a constant yield of 80 liters of bioethanol (0.095 tons) per ton of cane without leaves, taken from (Ferreira-Leitao, Fortes Gottschalk, Ferrara, Lima Nepomuceno, Correa Molinari, & Bon, 2010):

Eq. 148 $\dot{m}_{et,R3} = 0.095 \cdot \dot{m}_{cnl}$

Where $\dot{m}_{et,R3}$ is the mass flow of produced bioethanol in Route 3. Additional assumptions for this route are presented in Table 78 in the Appendix.

### F.4.5.10. Assumptions about other conversion processes

Conversion processes that are not modeled in detail but included in the study include: natural gas works, natural gas reinjection and flaring, oil refining, coke factories, blast furnace, charcoal production, own use and energy distribution. For these processes, the installed capacities, efficiencies, inputs and outputs are calculated and calibrated using official data published in (UPME, 2011b; UPME, 2011c; UPME, 2011d). For the sake of brevity this data is not shown in this thesis.

#### F.4.5.10.1 Assumptions about palm oil mill and biodiesel production plant

Regarding the general mass balance in the palm oil mill, the following assumptions are taken, using data from Table 78 in the Appendix:

Eq. 149 $\dot{m}_{po} = 0.2138 \cdot \dot{m}_{FFB}$
Eq. 150 $\dot{m}_{ko} = 0.020 \cdot \dot{m}_{FFB}$
Eq. 151 $\dot{m}_{pr} = 0.4240 \cdot \dot{m}_{FFB}$
Eq. 152 $\dot{m}_{nby} = 0.3422 \cdot \dot{m}_{FFB}$

Regarding emissions, methane produced in wastewater as by-product of the biodiesel conversion processes is assumed to be 1.03 Ton-$CH_4$/Ton-FFB as published in (BID-MME, Consorcio CUE, 2012), which according to the source is released to the atmosphere. Other assumptions considered for the palm oil mill and the biodiesel production process are also shown in Table 78 in the Appendix.

#### F.4.5.10.2 Assumptions about heat production in biomass-based boilers

Heat production in biomass-based boilers is mostly used in the jaggery cane industry, but can also be used to provide supplementary heat to other industries (i.e. sugar cane and palm oil industries). Two commercially available technologies are considered, viz. bagasse-fuelled boiler on a small-scale and wood boiler on a small scale able to burn coal if necessary. The assumed efficiency for these technologies is 30% for bagasse boilers (Velásquez, Chejne, & Agudelo, 2004), and 60% for wood boilers (Thermoflow, 2011). The capacity factor of a bagasse boiler is assumed to be that shown in Figure 111 in the Appendix, whereas the capacity factor of a wood boiler is assumed to be 55%. For the operation of the system, a merit order based on the fuel price is set. Thus, first bagasse is burned, followed by wood and then coal. Regarding emissions, it is assumed that the $CO_2$ emissions produced during combustion of biomass resources in heat production are biogenic.

### F.4.5.11. Estimation of biomass potential to meet the biomethane and biomass-based power generation targets

The current biomass energy potential is estimated following the method described in Chapter C and in (Gonzalez-Salazar, et al., 2014a), while the future potential is estimated following the method explained in Chapter D and in (Gonzalez-Salazar, et al., 2014b). Two levels of biomass energy potential are evaluated, the theoretical potential (green area in Figure 7) and the technical potential including current uses (grey and blue areas in Figure 7, respectively). The theoretical potential is defined as the maximum amount of biomass that can be used for energy purposes, explicitly excluding biomass used for food, fiber (e.g. round wood) and feedstock for the industry (e.g. co-products). The technical potential is defined as the fraction of the theoretical potential that is available for energy production (including current uses) after considering various constraints.

Volumes of biomass resources produced in the country between 2010 and 2030 are estimated with the LUTM model and are shown in Table 50 in the appendix. On the other hand, the specific energy and availability factors associated with these biomass resources are taken from various references and are shown in Table 51 and Table 52 in the appendix, respectively. Finally, the estimated theoretical potential is shown in Table 53 in the appendix, while the technical biomass potential including current uses is shown in Table 54 in the appendix. Note that these potentials are slightly different than those presented in Chapter C and Chapter D, as new categories of biomass resources have been added and production volumes of biomass resources have been updated. The theoretical biomass energy potential is then used to estimate the primary energy targeted in the long-term goals of biomethane and biomass-based power generation in Scenarios I and II (see Table 55) and the technical potential is used to estimate the capacity.

#### F.4.5.12. ESM model validation

The ESM model is calibrated and validated using data published in the national energy balances (UPME, 2011b; UPME, 2011c; UPME, 2011d). The model is validated at different levels. At a first level, the primary and secondary energy demands are validated by fuel and branch. The validation of the primary energy demand in the ESM model against official statistics by fuel is shown in Table 56, Table 57 and Figure 112 in the Appendix. Results of the ESM model for the overall primary energy demand between 1975 and 2009 are in agreement with official statistics and an overall coefficient of determination $R^2$ of 99.2% is estimated. Results for most of the fuels agree with statistics and estimated $R^2$ range from 98.4% to 100%. However, model results for the biomass primary energy deviate between -8% and 26% from official statistics. This disagreement is believed to be caused by different methodologies used to account for biomass resources. While the ESM model uses the accounting method shown in Chapter C and in (Gonzalez-Salazar, et al., 2014a), the method used in official statistics is unknown.

At a second level, the overall GHG emissions by branch are validated against official statistics and are shown in Table 58, Table 59 and Figure 113 in the Appendix. Most of the estimated GHG emissions by branch in the ESM model fully agree with official statistics. For instance, emissions associated with the demand side and power generation show $R^2$ of 99.8% and 97.4%. However, emissions associated with own use in the ESM model are 25% to 41% lower than those reported in official statistics. This difference is caused by additional emissions from combustion of refinery gas in the own use branch in the national energy balances, whose origin is not reported.

In addition, the national energy balances only estimate GHG emissions associated with power generation and coke production on the transformation side. Thus, no emissions are estimated in the national energy balances for other transformation processes (e.g. oil refining, heat production, bioethanol and biodiesel production, blast furnace, charcoal factories, etc.). In contrast, the ESM model estimates the GHG for all these branches. Hence, the emissions estimated in the ESM model are 3% to 13% higher than those reported in the national energy balances and a $R^2$ of 88% is estimated. If the emissions of these other conversion processes are not included in the ESM model, the estimated coefficient of determination is 96%.

## F.5. Summary and discussion

This chapter presents a modeling framework to evaluate the impacts that long-term deployment of bioenergy technologies might cause on the energy supply and demand, emissions and land use at a country level. It combines a quantitative and a qualitative element.

The qualitative element integrates two components: a) technology roadmapping to identify long-term technology targets through expert judgment and b) scenario analysis to investigate different future storylines. Technology roadmapping offers the advantage of transforming expert judgment into key recommendations to nations in order to make better technology investment decisions (see details in Chapter E). One challenge of technology roadmapping is to address the lack of consensus about a certain topic among experts. To overcome this challenge, scenario analysis is proposed for considering various possible storylines identified by experts.

On the other hand, the quantitative element comprises four integrated tools, namely the energy system model (ESM), the land use and trade model (LUTM), an economic model, and an external climate model. In the proposed modeling framework, energy is the entry point and it is proposed to develop an energy model as comprehensive as possible. In contrast, simple models for analyzing land use, trade, economy and climate are proposed. For the land use and trade it is proposed to use a simple resource-focused statistical model (LUTM), which is non-spatially explicit analysis and thus easy to implement and inexpensive. The economic model aims at describing in a simple way economic growth, population growth, prices of energy resources and commodities, as well capital cost of technologies. For climate, projections from external models are taken and use as drivers for the ESM and the LUTM models. This combination of quantitative tools ensures a high level of accuracy for the entry point (i.e. energy) and a relatively simple approach that can provide preliminary assessment for the nexus between energy, land use, emissions and economy.

This proposed modeling framework offers multiple advantages:

1. It combines qualitative and quantitative methods, which offers the possibility of simultaneously identifying potential long-term solutions and assessing the nexus between energy, economy, emissions and land-use
2. It uses various bottom-up modeling techniques to simulate with high accuracy the energy sector
3. It uses relatively simple land-use, economic and climate models
4. It uses well-known and widely recognized platforms (i.e. LEAP and Microsoft Excel), which may increase the level of accessibility and reproducibility
5. It is transparent, robust and adapted to the conditions of developing countries.

However, as other mathematical models, this modeling framework involves some limitations. Firstly, the ESM model estimates only energy-related GHG emissions associated with combustion of fuels and therefore indirect emissions (e.g. fuel transport, exposure, dose/response effects, land-use change, cultivation, irrigation, etc.) are not considered. Secondly, top-down techniques were used in sectors not relevant for bioenergy (e.g. industrial, commercial, etc.), which are less accurate than bottom-up approaches. Thirdly, a complete analysis of the social (i.e. job creation, improvement of the Human Development Index, etc.), environmental (i.e. life cycle GHG emissions, water footprint, impact on biodiversity, etc.) and economic impacts of long-term strategies is not covered and is considered beyond the scope of this study.

The proposed modeling framework is applied to the case study of Colombia. For this purpose, outcomes of the technology roadmapping process described in Chapter E have been used as inputs for the qualitative element of the modeling framework. Subsequently, the LUTM and ESM models as well as the climate and economic models are also applied to the specific conditions of Colombia. Energy, agriculture, land use, economic, macroeconomic and climate data are collected from multiple sources and entered into the different models as inputs.

An analysis of prior art shows that the application of the proposed modeling framework to the case of Colombia may be one of the first attempts at assessing the nexus between energy, economy, emissions and land-use in the country. This application also involves some limitations. Firstly, models are calibrated using the latest available statistics, which correspond to year 2009 and predate the present study by five years. Secondly, a complete economic analysis was only performed for power generation and CHP technologies. Therefore, a full economic analysis of other bioenergy technologies (e.g. biofuels, biomethane, etc.) remains to be investigated.

# Chapter G. Roadmap impacts

## G.1. Overview

This chapter presents the impacts that implementing roadmap targets might cause on the energy supply and demand, emissions and land use. These impacts are the result from the modeling method presented in last chapter. The chapter is divided into four sections: Section G.2 presents the impacts on the energy system, Section G.3 describes the impacts on land use, Section G.4 shows the impacts on emissions and finally Section G.5 presents a summary and discussion.

## G.2. Impacts on the energy system

### G.2.1. Primary energy demand

#### G.2.1.1. Trend and influence of GDP

The primary energy demand is found to be somewhat proportional to the Gross Domestic Product (GDP) and describes a trend that is consistent with historical data (see Figure 58). In the past, the primary energy demand grew moderately as a result of a modest increase in GDP. In contrast, a substantial increase in primary energy demand is expected when the future GDP growth predicted by the government is considered. In fact, an increase of 139% in the primary energy demand is expected between 2009 and 2030 for the baseline scenario, as a consequence of the assumed growth in GDP of 156%. This represents an increase from 39.39[20] to 94.16 mio TOE by 2030.

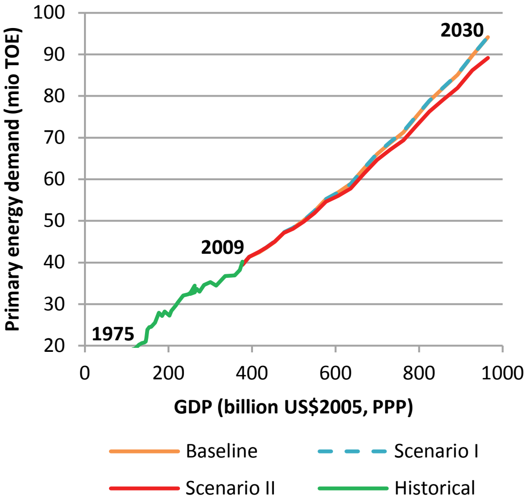

***Figure 58.*** *Primary energy demand vs. GDP*

On the other hand, the primary energy demand for Scenarios I and II follows a similar path to that of the baseline and reaches 94.18 and 89.18 mio TOE in 2030 respectively. The differences in primary energy between Scenarios I and II compared to the baseline will be highlighted in the next section.

#### G.2.1.2. Primary energy demand by fuel

The primary energy demand for the baseline scenario disaggregated by fuel is shown in Figure 59.

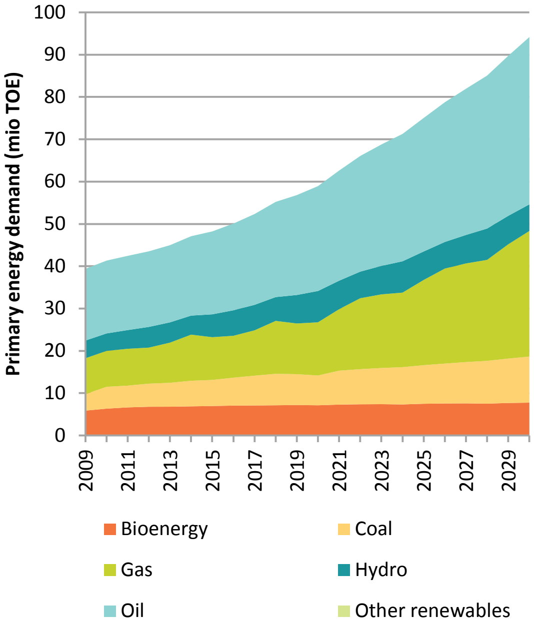

***Figure 59.*** *Primary energy demand by fuel for baseline scenario*

Fossil fuels (i.e. natural gas, coal and oil) continue dominating the primary fuel mix until 2030. The demand for fossil fuels is expected to grow from 29 to 80 mio TOE, which represents an increase in their share from 74% in 2009 to 85% in 2030. The demand for hydro and bioenergy increases, although their share in the primary energy mix reduces. Demand for hydro grows from 4.2 to 6.3 mio TOE between 2009 and 2030, but its share reduces from 10.6% to 6.7%. The demand for bioenergy[21] increases from 5.9 to 7.7 mio TOE, although its share reduces from 14.9% to 8.2%. The demand for other renewables is marginal (0.005 mio TOE) and remains unchanged until 2030.

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[20] Note that this value is slightly higher than the value shown in Table 56 in the Appendix, because the energy associated with bagasse from jaggery is included.

[21] In these calculations, the demand for bioenergy covers bagasse from sugar cane and jaggery cane, palm oil residues and wood. In contrast, UPME does not account for the energy content of bagasse from jaggery cane. As a consequence, results in 2009 are slightly different from those presented in (UPME, 2011b) and also those shown in Figure 3.

The dominance of fossil fuels and the decreased importance of bioenergy and hydro in the baseline scenario agree with historical trends (see Figure 3) and are consequences of maintaining current energy policies in the future.

The differences in primary energy demand by fuel between Scenario I and the baseline are shown in Figure 60.

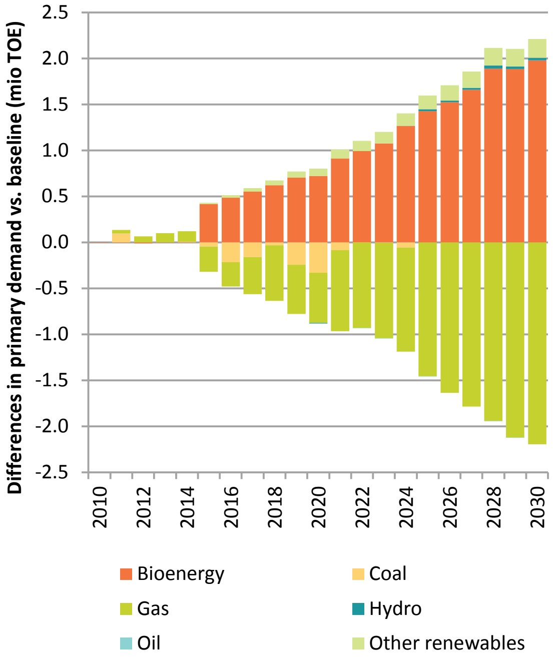

***Figure 60.*** *Differences in primary energy demand by fuel between Scenario I and baseline*

Demand for fossil fuels also dominates the primary energy mix in Scenario I. However, this dominance is slightly more moderate than in the baseline, causing a slower reduction in the share of renewables. In fact, while the share of renewables reduces from 25.6% to 14.9% in the baseline, it reduces from 25.6% to 17.2% in Scenario I.

Demand for fossil fuels (mostly natural gas) is expected to reduce in Scenario I compared to the baseline, amounting to 2.2 mio TOE in 2030. Consequently, the share of fossil fuels grows less rapidly than in the baseline, from 74.4% in 2009 to 82.7% in 2030. This reduction in demand for fossil fuels is explained by the implementation of policy measures supporting the substitution of biomethane for natural gas and the replacement of natural gas-based power by biomass-based power and wind power.

On the other hand, demand for bioenergy, hydro and other renewables (i.e. wind) is expected to grow in Scenario I compared to the baseline. The increment in demand for bioenergy reaches 2 mio TOE by 2030. Consequently, the share of bioenergy slightly increases compared to the baseline and accounts for 10% of the primary energy demand by 2030. Demand for wind grows 0.2 mio TOE by 2030 relative to the baseline, and its share of the primary energy demand slightly increases from 0.04% to 0.2%. The increment in demand for hydro is marginal (only small hydro) and amounts to 0.03 mio TOE by 2030, while its contribution reduces to 6.7%.

Differences in primary energy demand by fuel between Scenario II and the baseline are shown in Figure 61. Demand for fossil fuels in Scenario II is expected to reduce even further than in Scenario I, amounting to 7.4 mio TOE. Apart from the 2 mio TOE reduction in demand for natural gas, similarly to Scenario I, there is a further reduction of 5.4 mio TOE in demand for oil.

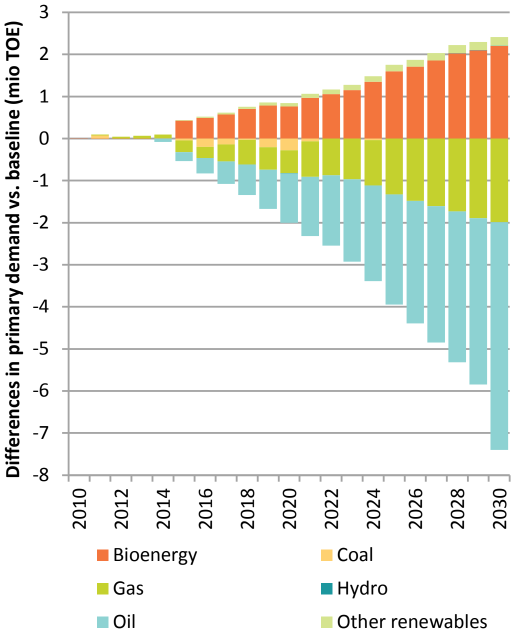

***Figure 61.*** *Differences in primary energy demand by fuel between Scenario II and baseline*

This reduction in demand for oil is explained by the implementation of policy measures supporting the substitution of bioethanol for gasoline and biodiesel and renewable diesel for diesel fuel. It is important to note that, while there is an increase in demand for liquid transport biofuels, this increase is not reflected in a higher demand for primary bioenergy. The reason for this is that in order to be consistent with the accounting method of UPME, only bagasse and solid biomass are accounted as primary energy. Consequently, primary energy required to produce liquid transport biofuels (i.e. cane juice to produce bioethanol and palm oil to produce biodiesel and renewable diesel) is not accounted for.

## G.2.2. Impacts on the demand side

### G.2.2.1. Sectorial demand

The final energy demand (i.e. secondary energy and non-transformed primary energy used on the demand side) by sector for the baseline scenario is shown in Figure 62.

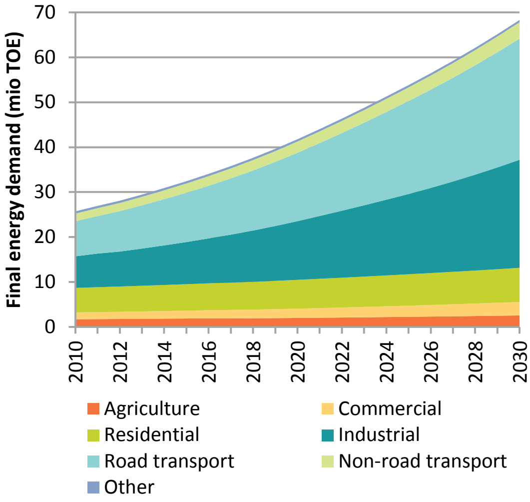

***Figure 62.*** *Final energy demand by sector for baseline*

Sectors experiencing the highest growths in final energy demand between 2009 and 2030 include road transport with 20 mio TOE (+270%) and industry with 18 mio TOE (+287%). These two sectors alone would contribute 75% of the overall final energy demand by 2030. Sectors experiencing moderate growth in this period include non-road transport (+125%, 2 mio TOE), commercial (+97%, 1.5 mio TOE) and residential (+47%, 2.4 mio TOE).

The final energy demand for the baseline disaggregated by fuel is shown in Figure 63.

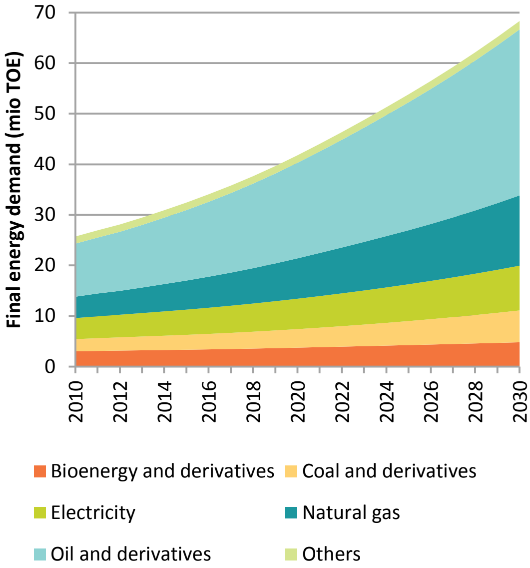

***Figure 63.*** *Final energy demand by fuel for baseline*

The highest growth in final demand between 2009 and 2030 corresponds to natural gas (+281%, 10.2 mio TOE) followed by oil and derivatives (+237%, 23 mio TOE), and to a lesser extent by coal and derivatives (+177% 4 mio TOE) and electricity (+116%, 4.7 mio TOE). Demand for bioenergy and derivatives is expected to increase 67% (1.9 mio TOE) during this period. It is expected that the final energy demand will grow from 24 to 68 mio TOE, which would represent an annual average growth rate of 5.1%. Various differences in the final energy demand by fuel arise for Scenarios I and II relative to the baseline. For Scenario I, there is a substitution of biomethane for natural gas, causing a reduction in the overall demand for natural gas. For Scenario II, in addition to the substitution of biomethane for natural gas, there is a substitution of bioethanol for gasoline and of biodiesel and renewable diesel for diesel fuel. Details of these differences in final energy demand are described as follows.

### G.2.2.2. Road transport

The estimated number of road vehicles for all scenarios is shown in Figure 64. Since it is assumed that vehicle ownership is a function of GDP per capita (which does not change across scenarios), the estimated number of vehicles is the same for all scenarios. The number of vehicles is expected to grow from 6 to 27 mio between 2009 and 2030 according to the assumptions made. The largest growth by 2030 is expected for gasoline motorcycles (11.6 mio), followed by gasoline four-wheeled vehicles (7.4 mio), diesel vehicles (2 mio) and CNG-fuelled vehicles (0.2 mio). Only one study estimating ownership of gasoline vehicles and motorcycles in Colombia was found in literature (Echeverry, J., Bocarejo, Ospina, Lleras, & Rodriguez, 2008). It did not estimate ownership of diesel- and CNG-fuelled vehicles and generally reported lower growth rates than the present study (see Figure 133 in the Appendix). The estimated secondary energy demand (i.e. energy forms which have been transformed from primary energy sources) by vehicle type is shown in Figure 65. The secondary energy demand is expected to grow in road transport from 7.3 to 27 mio TOE. The vehicles that most contribute to this increase are gasoline- and diesel-fuelled vehicles, whose demands by 2030 amount to 10.5 and 12.2 mio TOE respectively. These two types of vehicles account on average for 80% of the overall energy demand in road transport. The energy demand from motorcycles is expected to increase from 0.6 to 3.2 mio TOE between 2009 and 2030 as a consequence of their growth in number. The demand for energy from CNG-fuelled vehicles also grows, but less rapidly than for the other vehicles. It increases from 0.65 to 1 mio TOE in this period.

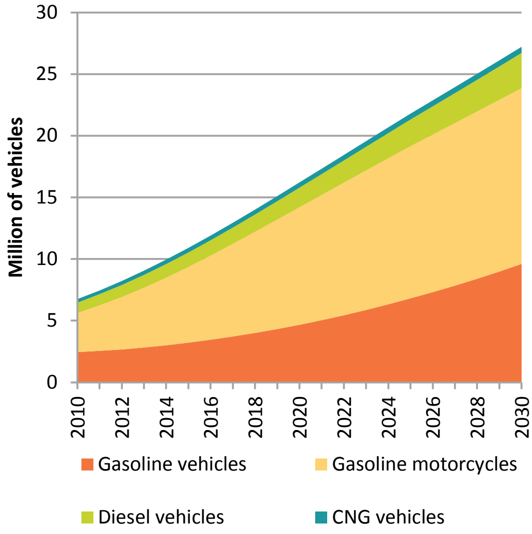

***Figure 64.*** *Estimated number of vehicles*

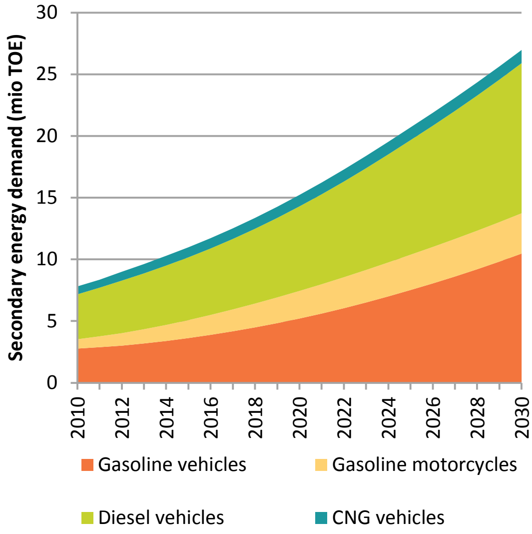

***Figure 65.*** *Secondary energy demand in road transport by vehicle type*

The secondary energy demand by fuel for the baseline scenario is shown in Figure 66. The demand for all the fuel types continuously increases between 2009 and 2030, but gasoline and diesel fuel strongly dominate. Demand for gasoline grows almost four-fold from 3 to 13 mio TOE by 2030, while the demand for diesel fuel triples from 3.3 to 11.2 mio TOE. The share of these two fuels in the overall demand for secondary energy account for more than 85%. Demand for CNG is expected to grow but at a slower pace than gasoline and diesel, i.e. from 0.65 to 1 mio TOE, which causes a reduction in its share from 9% to 4%. A considerable increase in demand for bioethanol and biodiesel is also expected. It grows from 0.34 to 1.7 mio TOE, while its share also grows from 4.7% to 6.3%.

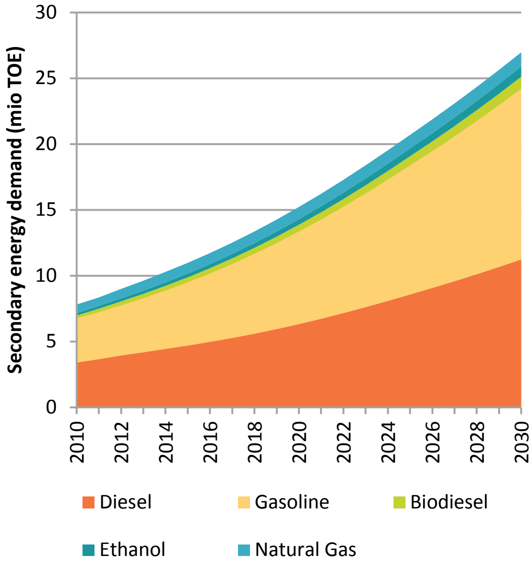

***Figure 66.*** *Secondary energy demand in road transport by fuel for baseline scenario*

No policies to further deploy liquid transport biofuels are implemented in Scenario I. For this reason, its secondary energy demand by fuel remains unchanged compared to the baseline scenario. On the other hand, Scenario II does implement various policies to further deploy bioethanol (e.g. increase the quota mandate from E10 to E20 by 2025 and implement an E85 program), biodiesel (e.g. increase the quota mandate from B10 to B30 by 2030) and renewable diesel (e.g. achieve a 10% energy contribution from renewable diesel in the total diesel production). The differences in secondary energy demand by fuel between Scenario II and the baseline are shown in Figure 67.

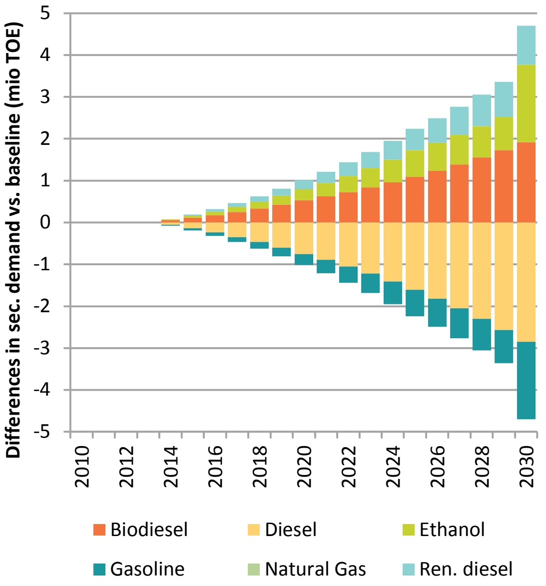

***Figure 67.*** *Differences in secondary energy demand in road transport between Scenario II and baseline*

Demand for gasoline and diesel fuel is expected to decrease by 1.85 and 2.85 mio TOE by 2030 compared to the baseline, as these fuels are being substituted by liquid transport biofuels. As a result, their share in the overall demand reduces from 86% in 2009 to 72% in 2030. On the contrary, the demand for biofuels in Scenario II significantly increases compared to the baseline. Bioethanol grows by 1.85 mio TOE, biodiesel by 1.9 mio TOE and renewable diesel by 0.9 mio TOE relative to the baseline. The share of biofuels in the road transport energy demand also grows from 4.6% in 2009 to 24% in 2030. The demand for CNG remains unchanged compared to the baseline.

### G.2.2.3. Residential sector

One of the sectors traditionally demanding substantial biomass resources for traditional cooking and water heating is the residential sector. The final energy demand in the residential sector disaggregated by fuel for the baseline scenario is shown in Figure 68. The demand for final energy disaggregated by type, i.e. cooking, air conditioning, hot water, refrigeration, etc., is shown for the residential sector in Figure 134 in the Appendix.

Final energy demand grows at an average rate of 1.9% per annum in the residential sector, i.e. from 5 to 7.6 mio TOE (+47%) between 2009 and 2030. This annual growth rate is nearly twice as much the average annual growth rate of population (1%) and half of the annual growth rate of GDP per person (3.5%). Two main effects are observed. Firstly, the demand for modern energy forms such as electricity and natural gas is expected to increase (+99% and +86%, respectively) due to two reasons: a) a more urban and wealthier population using more electric appliances and demanding more natural gas for cooking and heating water and b) higher access to electricity and natural gas services nationwide. Secondly, the demand for other energy forms such as gasoline, coal, LPG and wood are expected to reduce or at best maintain constant. These energy forms have been traditionally used for cooking and lighting especially, but not exclusively, in rural regions, where access to electricity or natural gas have been limited. Thus, an increasing urbanization and access to modern energy services nationwide motivate a substitution of electricity and natural gas for these traditional energy forms.

Impacts of implementing Scenarios I and II on the energy demand in the residential sector are limited to the substitution of biomethane for natural gas. The overall effects of substituting biomethane for natural gas are analyzed in more detail in the next section.

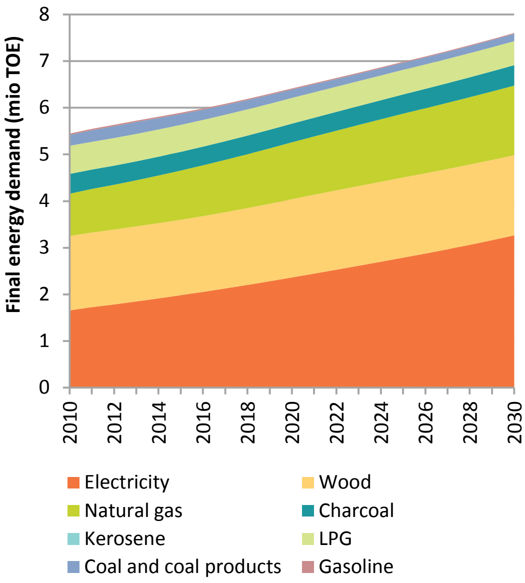

***Figure 68.** Final energy demand in the residential sector for baseline scenario*

### G.2.2.4. Substitution of biomethane for natural gas

As shown in Figure 63, the final demand for natural gas in the baseline scenario is expected to grow from 3.6 to 13.9 mio TOE between 2009 and 2030. This is a result of the modernization of the energy capacity in the country combined with the low prices of natural gas relative to other fuels. Scenarios I and II introduce biomethane into the energy matrix, which is a direct substitute for natural gas. The supply of biomethane for Scenarios I and II is estimated to grow from 0 to 0.9 mio TOE between 2015 and 2030 (see Figure 69). Consequently, the demand for natural gas for these scenarios is reduced in the same proportion. Moreover, the contribution of biomethane to the overall energy content in natural gas grows from 0% to 6.7% within this period.

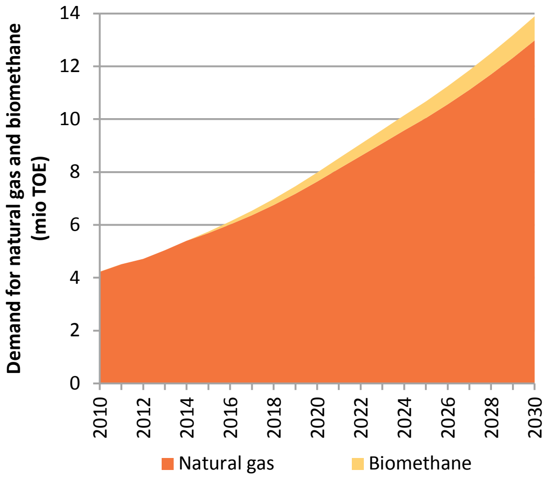

***Figure 69.** Demand for natural gas and biomethane for Scenarios I and II*

## G.2.3. Impacts on power generation and combined heat and power (CHP)

### G.2.3.1. Electricity demand

The electricity supply[22] and demand by sector for the baseline scenario is shown in Figure 70. Electricity demand in final uses doubles between 2009 and 2030, growing from 4.1 to 8.9 mio TOE. The bulk of this demand arises in the residential and industrial sectors, whose aggregated contribution amounts to nearly 80% of the overall demand. The remaining portion of the end-use demand corresponds to commercial and other sectors (agriculture, transport, etc.). Distribution losses and own use by power generation units amount to 15% and 3% of the electricity supply throughout the entire period.

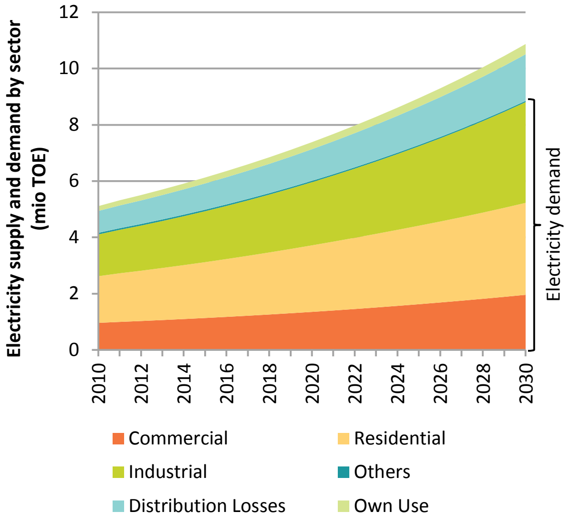

***Figure 70.*** *Electricity supply and demand by sector for baseline scenario*

### G.2.3.2. Electricity supply

Electricity supply or gross electricity generation is expected to double between 2009 and 2030, growing from 5.1 to 10.9 mio TOE (see Figure 71). Among sources, hydro dominates power generation with an average contribution of 68%. Gross generation from hydro power increases from 3.5 to 5.3 mio of TOE between 2009 and 2030. Small hydro grows also from 18 to 240 kTOE during this period. While hydro's share starts growing in 2010 and reaches 85% in 2020, it decreases to 50% by 2030. The behavior of the system between 2010 and 2020 is explained by a significant increase in the planned expansion capacity of hydro power plants (5.7 GW). However, between 2020 and 2030 electricity from hydro is displaced to a certain extent by electricity generated in natural-gas fired power plants, given that their overall production cost is lower than that of hydro (see calculated values in Table 82 in the Appendix).

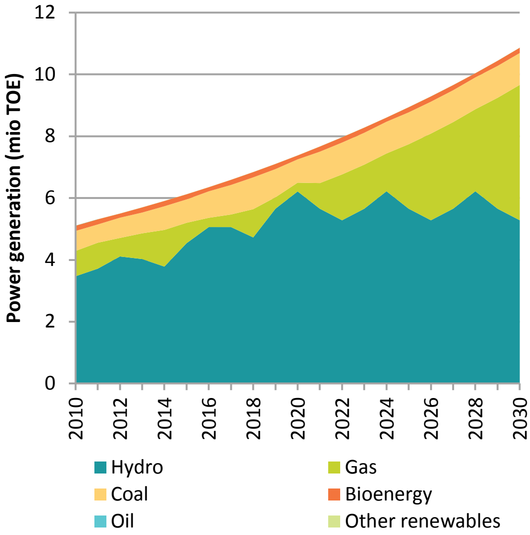

***Figure 71.*** *Power generation by source for the baseline scenario*

It is important to note that the contribution of the different technologies to power generation does not only depend on the net present value of the lifetime costs, but also on the installed capacity by technology and the availability of energy resources. The contributions by technology to power generation thus reflect capacity additions that are optimized according to the net present value of the lifetime costs (see Section F.3.4.1) as well as officially planned capacity additions and retirements (exogenously added in LEAP). The observed fluctuations in power generation from year to year are explained by the varying availability of hydro resources caused by El Niño oscillation. Hydro power generation is followed by natural gas, coal and to a smaller extent by bioenergy, oil and other renewables. Natural gas-based power generation grows from 0.9 to 4.4 mio TOE, and its contribution increases from 18% to 40% within this period. Coal power generation grows from 0.5 to 1 mio TOE and its contribution slightly reduces from 10 to 9.5% by 2030. Power generation from biomass grows from 130 to 170 kTOE, although its contribution reduces from 2.5% to 1.6%. Power generation from oil and other renewables is marginal and accounts for less than 1% of the gross generation between 2009 and 2030. The energy balance (defined as the energy inputs and outputs of the power generation module) for the baseline scenario is shown in Figure 72. Energy outputs include electricity and heat, while energy inputs are power imports. Heat co-produced in CHP power plants is expected to slightly increase from 0.83 to 1.08 mio TOE between 2009 and 2030, which represents a growth of nearly 30%. No electricity imports are expected throughout the entire period, which means that the system is self-sufficient in power generation.

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[22] The electricity supply is defined as gross power generation including own use to cover the demand in final uses (commercial, industrial, residential, etc.) and distribution losses (IEA, 2012b).

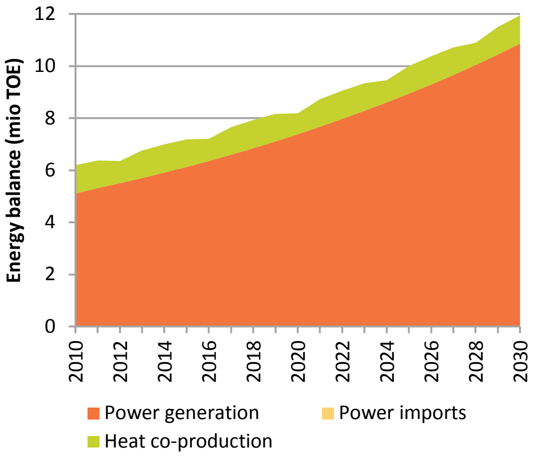

***Figure 72.** Energy balance in power generation for the baseline scenario*

Power generation by source is shown for Scenario I in Figure 73. In Scenario I Power generation continues being mostly dominated by hydro, with an average share similar to that of the baseline (68.3%).

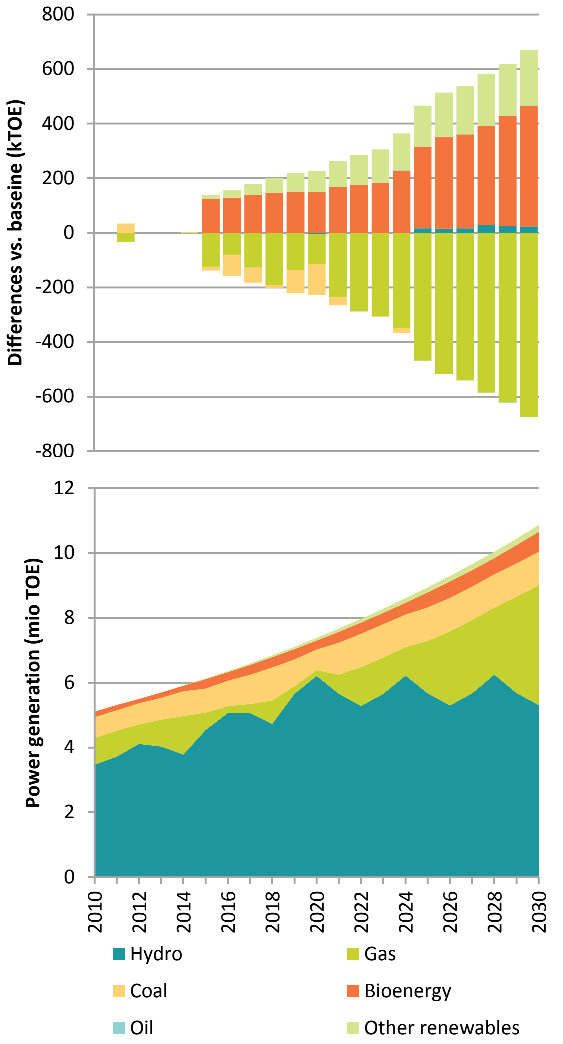

***Figure 73.** Power generation by source for Scenario I*

Scenario I is also characterized by an increased participation of other renewables that replace gas-based power generation. An increment of 0.44 mio TOE is expected for bioenergy by 2030 relative to the baseline, which causes an increase in its share from 2.5% to 5.6% in this period. Wind grows from 15 to 210 kTOE and its share increases from 0.3% to 2%. The growth of bioenergy and wind is a result of implementing the power generation & CHP targets between 2015 and 2030. Small hydro grows in a similar way as in the baseline scenario from 18 to 263 kTOE and its share increases from 0.3% to 2.4%. The aggregated contribution of renewables (excluding large hydro) grows from 3.2% in 2009 to 10% in 2030. Simultaneously, gas-based power generation reduces 0.67 mio TOE by 2030 compared to the baseline. The share of gas in power generation in 2030 then reduces from 40% in the baseline to 34% in Scenario I. Power generation in Scenario II presents nearly the same behavior as that in Scenario I with almost negligible modifications. For the sake of brevity, it is not shown here but included in the Appendix (see Figure 135).

### G.2.3.3. Capacity

The installation of additional power generation capacity is required to meet the continuously growing demand and replace retired capacity until 2030. The installed power generation capacity by source for the baseline scenario is presented in Figure 74.

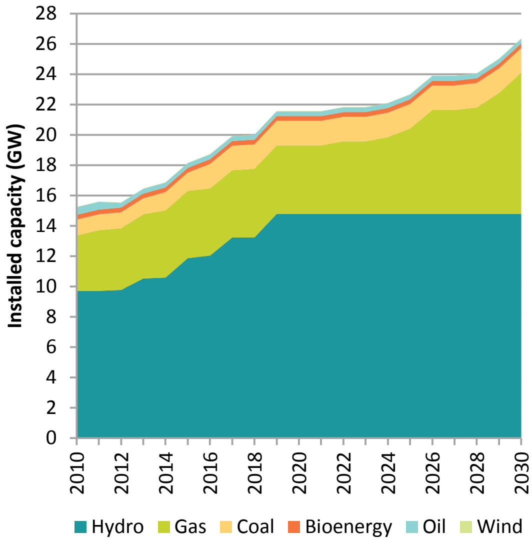

***Figure 74.** Installed power generation capacity by source for baseline scenario*

It is expected that the overall power generation capacity will grow from 13.5 to 26.4 GW between 2009 and 2030. The bulk of the capacity additions estimated by 2030 comes from natural gas, hydro, coal and oil. Of the 13.2 GW of capacity additions, 6.8 GW correspond to gas-fired power plants (49% simple cycles, 51% combined cycles), 5.75 GW correspond to hydro power plants, 0.57 GW to coal-fired power plants and 0.12 GW to oil-fired power plants. About

46% of the expected capacity additions between 2009 and 2030 are already in construction or planned (6 GW), while the remaining 54% are expected after 2019. It is interesting to note that after the planned expansion of 5.75 GW of hydro between 2009 and 2019, no further capacity is added between 2020 and 2030. This is most likely a consequence of the higher production cost of hydro relative to other technologies (particularly gas), according to the assumptions. Nonetheless, these results must be interpreted with caution. Results are obtained through a cost minimization approach, which does not necessarily take into consideration other drivers, such as the influence of politics, future energy and environmental regulations, sudden depletion of energy reserves, etc. Regarding capacity retirements, official plans estimate that 434 MW of hydro power will be withdrawn by 2015 and no other retirements are expected until 2030. Differences in installed power generation capacity between Scenario I and the baseline scenario are shown in Figure 75.

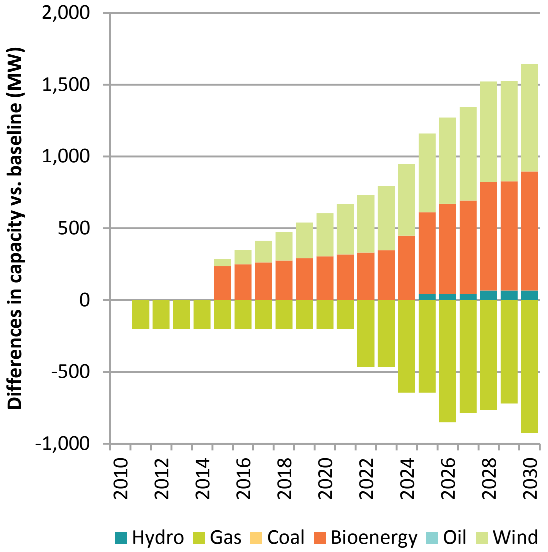

***Figure 75.*** *Differences in installed power generation capacity between Scenario I and baseline*

Two important trends are observed. Firstly, additional capacity is required for renewables to comply with the power generation & CHP targets as of 2015. In fact, 0.75 GW of additional capacity is required for wind by 2030, while 0.83 GW is required for biomass-based power generation and 0.07 GW for small-hydro. Secondly, an increase in installed capacity of renewables causes a less rapid growth of gas-fired power plants until 2030. In fact, while in the baseline the capacity of gas-fired power plants grows 6.8 GW between 2009 and 2030, it grows 5.9 GW in Scenario I (i.e. 0.92 GW less). Installed power generation capacity in Scenario II presents nearly the same structure as that in Scenario I with almost negligible modifications. For the sake of brevity, the differences relative to the baseline are not shown here but included in the Appendix (see Figure 136).

### G.2.3.4. Complementarity of hydro and bioenergy

In the last 15 years a complementarity in the capacity factor of hydro and biomass-based power generation has been documented (XM, 2013) but has not been fully exploited. This complementarity relates to the fact that the highest capacity factor of hydro power occurs in years with low solar radiance, when the capacity factor of biomass-based power is lowest (see Figure 110 in the Appendix). Assumptions about this complementarity have been included into models to evaluate the extent at which it can be used to mitigate the effects of the El Niño oscillation. Scenarios I and II attempt to exploit this complementarity, assuming that it will continue in the future. A reduction in fossil-fuel based power generation is expected for Scenarios I and II relative to the baseline. This reduction is maximal in wet years when hydro can deliver more power, but it is actually critical in dry years when hydro becomes less available. Figure 76 shows the aggregated contribution of hydro and bioenergy to the overall power generation for the baseline and Scenario I.

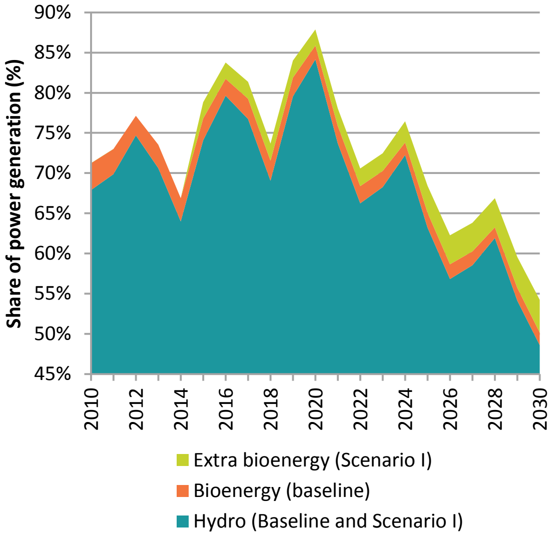

***Figure 76.*** *Contribution of hydro and bioenergy to power generation in Scenario I and baseline scenario*

### G.2.3.5. Costs

The cost of producing electricity is expected to increase until 2030 in order to meet a continuously growing demand (see Figure 77). The overall cost almost doubles, growing from 1094 to 2056 mio US$2005 between 2009 and 2030. The total cost of producing electricity is expected to be higher for Scenarios I and II relative to the baseline. This is a consequence of deploying renewables (i.e. wind and bioenergy), which are more expensive than gas-fired power plants and hydro. The cost of producing electricity grows to 2194 mio US$2005 in Scenario I and to 2225 mio US$2005 in Scenario II.

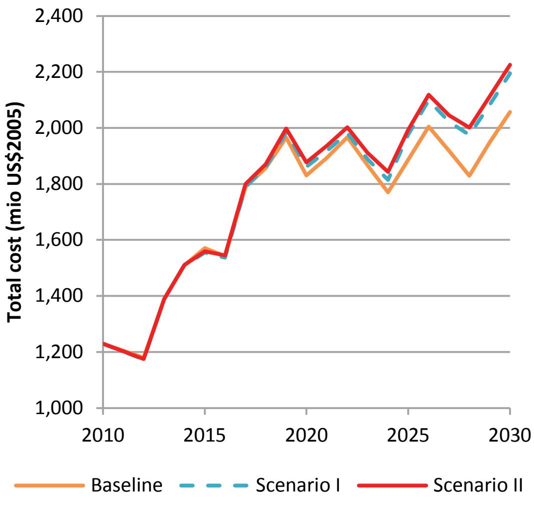

***Figure 77.*** *Cost of producing electricity by scenario*

The cost of electricity is then obtained by dividing the total cost of producing electricity by the power generation for the different scenarios. The obtained cost of electricity (US$2005/MWh) for the different scenarios is presented in Figure 78. It is worth mentioning that this cost of electricity should not be confused with the levelized cost of electricity (LCOE). The LCOE is a method to compare the lifetime cost of power generation technologies, which is an alternative to the method presented in Section F.3.4.1. For comparative purposes the LCOE for the different power generation technologies is presented in Table 82 in the Appendix.

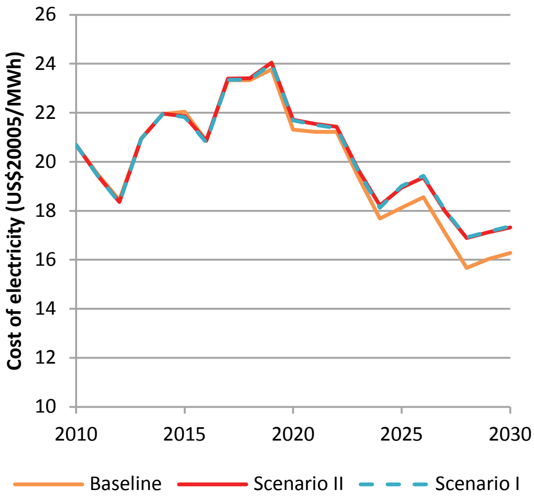

***Figure 78.*** *Cost of electricity by scenario*

For all scenarios, the cost of electricity fluctuates over the entire period, which to a certain extent is a consequence of El Niño oscillation. Between 2010 and 2020 there is an upward trend for all scenarios, while after 2020 the trend is downward. By 2030 the cost of electricity decreases to 16.3 US$2005/MWh for the baseline and to 17.3 US$2005/MWh for Scenarios I and II. Note that there are almost no differences in the cost of electricity for Scenarios I and II, given that the policies on power generation for these two scenarios are the same. The causes for these trends are better explained by disaggregating the cost of electricity by technology for the different scenarios. Figure 79 shows the cost of electricity disaggregated by technology for the baseline scenario. It can be seen that the upward trend between 2010 and 2020 is motivated by a large expansion of hydro power generation, which contributes 74% of the cost of electricity by 2020. On the other hand, the downward trend after 2020 is explained by the reduced relevance of hydro power generation since no additional capacity is installed, in contrast with the situation of gas-fired power generation.

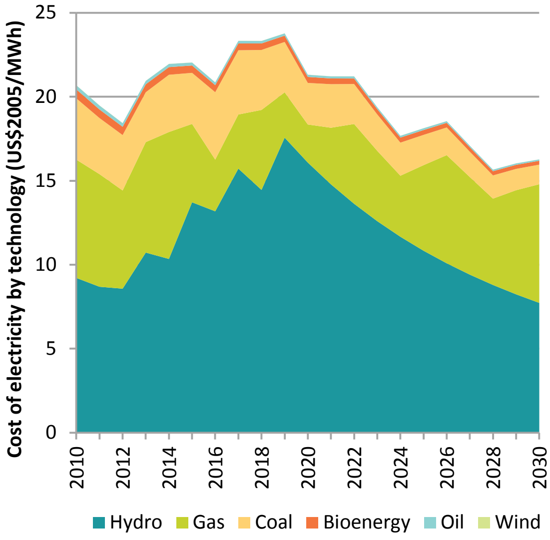

***Figure 79.*** *Cost of electricity by technology for baseline*

The differences in the cost of electricity by technology between Scenario I and the baseline are shown in Figure 80.

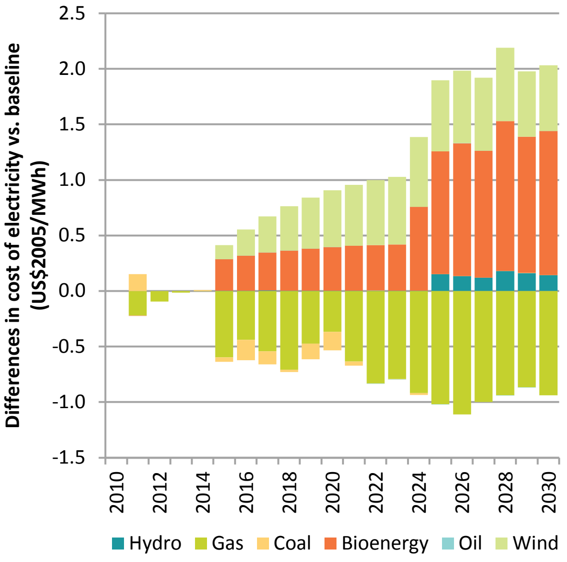

***Figure 80.*** *Differences in cost of electricity by technology between Scenario I and baseline*

This figure shows that there is a positive difference in the cost of electricity between Scenario I and the baseline, caused by deploying and operating renewables (particularly bioenergy and to a lesser extent wind and small-hydro). Simultaneously, there is a negative difference caused by savings in operating and fuel costs for reducing the use of gas-fired power plants. However, the positive difference in the cost of electricity for operating renewables is twice as much as the negative difference for not operating gas-fired power plants. This event results in a higher cost of electricity for Scenario I compared to the baseline. The differences in cost of electricity by technology between Scenario II and the baseline are very similar to those for Scenario I and, for the sake of brevity, are shown in the Appendix (see Figure 137).

Disaggregation of the cost of electricity by type of cost (i.e. capital cost, O&M and fuel cost) is shown in Figure 81 for the baseline scenario.

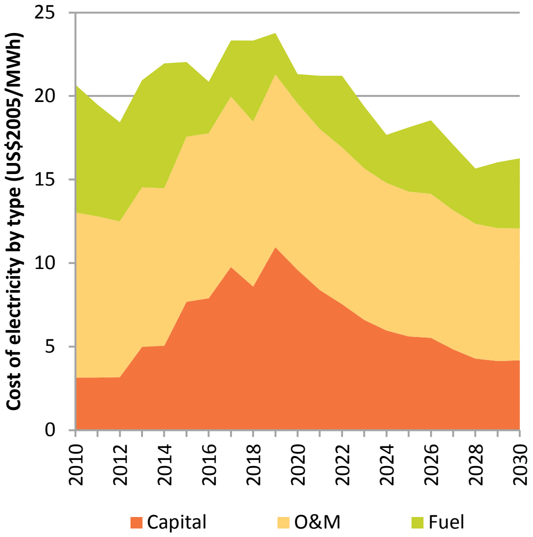

***Figure 81.*** *Cost of electricity by cost type for the baseline*

This graph shows that the contribution of capital costs significantly grows from 15% in 2010 to 45% in 2020 and then decreases to 25% in 2030. The upward trend is again caused by the expansion of hydro power generation between 2010 and 2020, while the downward trend is caused by a replacement of hydro power by less expensive gas power generation. On the other hand, the strongest contributor is the cost of operation and maintenance (O&M), which on average accounts for 47% of the cost of electricity. This share is quite high but not uncommon for energy systems based on a large hydro power plants. The share for fuel costs decreases from 37% to 8% between 2010 and 2020 due to the hydro expansion and then increases to 26% by 2030 as a consequence of increased gas-fired power generation.

Finally, the differences in cost of electricity by cost type between Scenario I and the baseline are shown in Figure 82. This graph shows that after 2015 there is mostly an increase in capital costs relative to the baseline, while at the same time there is a reduction in fuel costs. By 2030 the increase in capital and O&M costs amounts to 1.6 US$2005/MWh, while the reduction in fuel cost reaches 0.5 US$2005/MWh. This results in an aggregated higher cost of electricity for Scenario I compared to the baseline. The differences in cost of electricity by type between Scenario II and the baseline are very similar to those for Scenario I and, for the sake of brevity, are not shown here but included in the Appendix (see Figure 138).

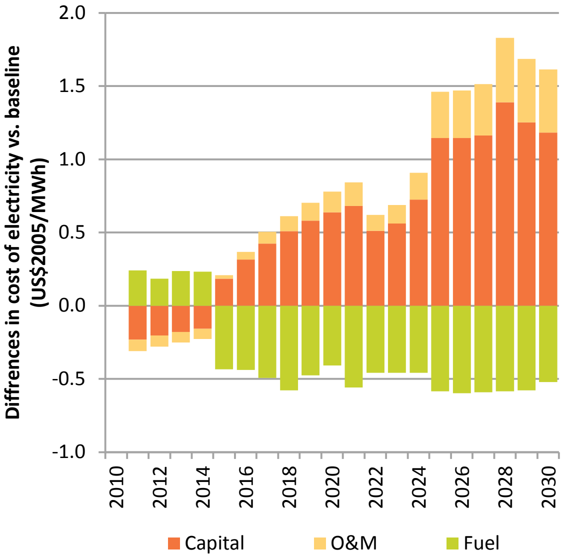

***Figure 82.*** *Differences in cost of electricity by cost type between Scenario I and baseline*

## G.2.4. Bioenergy outlook by scenario

### G.2.4.1. Share of bioenergy by category

Scenarios I and II describe long-term visions in which the role of bioenergy in the future energy mix of the country becomes more relevant. Scenario I represents a long-term vision that: a) focuses on new technologies for the production of biomethane and biomass-based power generation & CHP and b) fixes the current blend mandate of first generation liquid biofuels. Its long-term goals by area include:

- Biomethane: use 5% of biomass residues and 1% of biogas from animal waste nationwide to produce biomethane to be injected into the natural gas network by 2030.
- Power generation and CHP: a) achieve a renewable power target of 10% by 2025, b) use 5% of the biogas from animal waste and municipal water treatment plants nationwide by 2030, c) use 100% of the biogas produced in the water treatment process of biodiesel production plants by 2030, d) use 10% of the municipal landfill gas produced nationwide by 2030.

On the other hand, Scenario II represents a long-term vision that combines new technologies for the production of biomethane and biomass-based power generation and CHP (the same as in Scenario I) with further growth of first generation transport biofuels:

- Biodiesel: increase the quota mandate to B20 in 2020 and B30 in 2030.
- Bioethanol: a) increase the quota mandate to E20 in 2025 and b) implement an E85 fuel program in 2030.
- Renewable diesel: achieve a 10% contribution (on an energy basis) of renewable diesel to the total diesel fuel production in 2030.

Consequently, the future role of bioenergy differs for these two storylines. An overview of the share of bioenergy by category and scenario is presented in Figure 83. In the baseline scenario, the share of bioenergy is expected to reduce from 15.2% (note that this share is higher than the 10% shown in Figure 3, given that bagasse from jaggery cane has been included in the calculation) to 8.1% in the primary energy demand and from 3.3% to 1.6% in power generation between 2010 and 2030. These events are consequences of a combination of factors including increasing urbanization, higher access to electricity and natural gas services nationwide, rapid growth of road vehicle ownership and the associated demand for oil-based fuels, as well as an increased deployment of gas- and coal-fired power plants. The share of bioenergy in road transport marginally increases from 5.4% to 6.3% over this period, as a consequence of higher supply coverage of biofuels (i.e. bioethanol and biodiesel) at a national level. Finally, the share of bioenergy in the natural gas supply is nil.

The implementation of policies supporting the deployment of new technologies for producing biomethane and power generation in Scenario I motivate an increase in the share of bioenergy (in the form of biomethane) from 0% to 6.6% in the natural gas supply and from 3.3% to 5.6% in power generation between 2010 and 2030. For Scenario I the shares in road transport remain unchanged relative to the baseline, given that the biofuel policies are not modified. As a result, the share of bioenergy in the primary energy demand for Scenario I decreases less rapidly than in the baseline, from 15.2% in 2010 to 10.2% in 2030.

In Scenario II the share of bioenergy in power generation and in natural gas supply is almost the same as in Scenario I. The further implementation of policies supporting additional deployment of first generation biofuels results in a boost of the share of bioenergy in road transport from 5.4% in 2010 to 24% in 2030. However, this only translates into a slightly higher share of bioenergy in the primary energy demand compared to the baseline and Scenario I. In summary, the contribution of bioenergy in road transport, power generation and natural gas supply grows in Scenarios I and II relative to the baseline. However, despite the somewhat ambitious goals envisioned in the present roadmap, a decreased share of bioenergy and an increased share of fossil fuels in the primary energy demand of the country occur in all scenarios. This suggests that, irrespective of the chosen scenario, the demand for fossil fuels would continue to grow motivated by a more urban and wealthier population and a more modern and oil- and gas-dependent energy system.

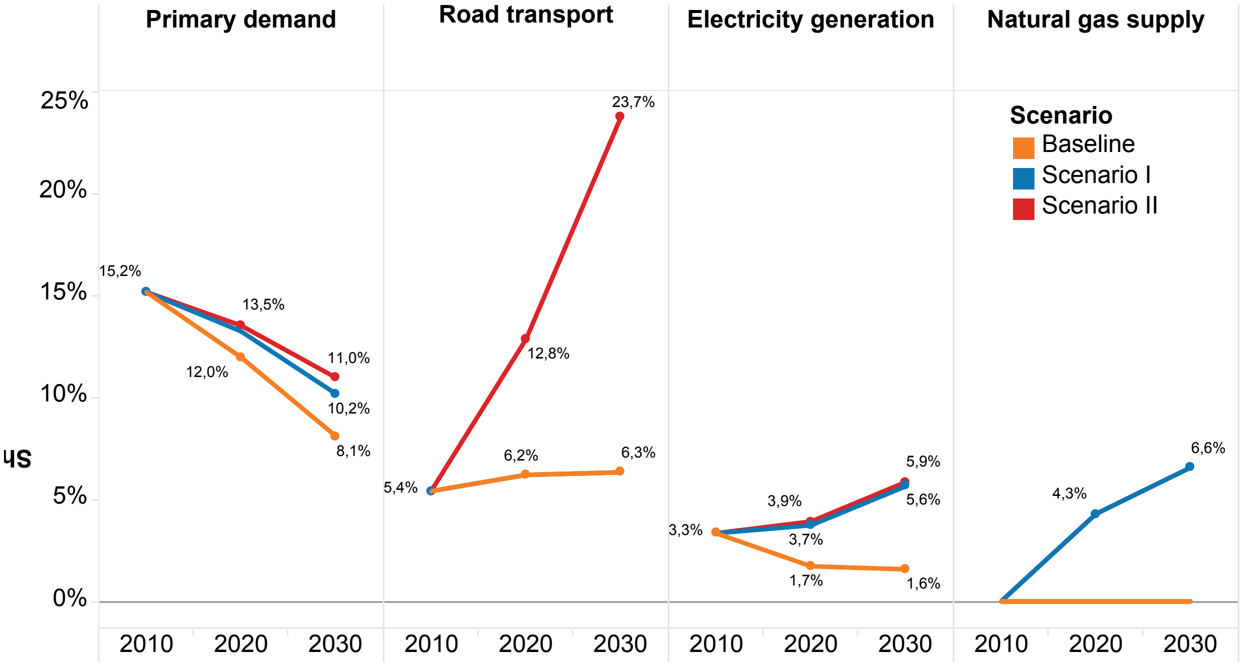

*Figure 83. Share of bioenergy by category and scenario*

### G.2.4.2. Reduction in demand for fossil fuels

The overall reduction in the use of fossil fuels by 2030 relative to the baseline amounts to 2.2 mio TOE by implementing Scenario I (see Figure 84) and 7.4 mio TOE by implementing Scenario II (see Figure 85).

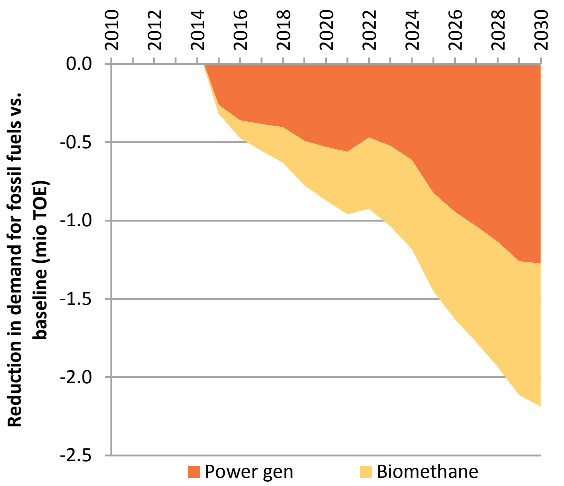

***Figure 84.*** *Reduction in demand for fossil fuels in Scenario I vs. baseline*

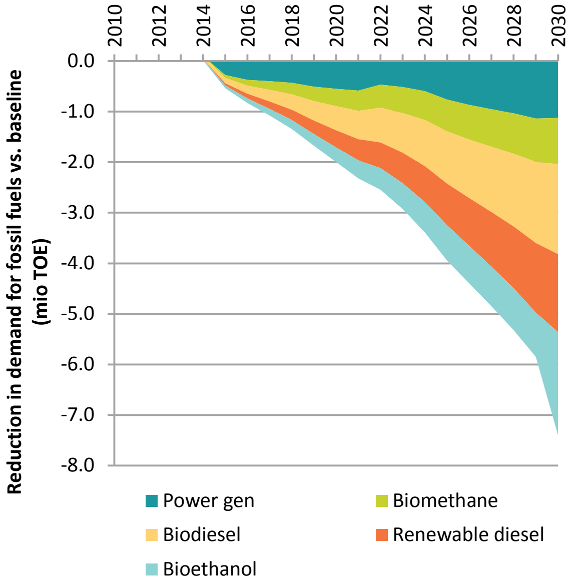

***Figure 85.*** *Reduction in demand for fossil fuels in Scenario II vs. baseline*

The reduction in demand for fossil fuels is dependent on the policy measures implemented in each scenario. In Scenario I the policy on power generation and CHP contributes 59% of the overall reduction in the demand for fossil fuels between 2009 and 2030, while the policy on biomethane contributes the remaining 41%. In Scenario II the contribution of the different policy measures to the overall reduction in demand for fossil fuels is quite even: biodiesel (25.6%), power generation and CHP (20.9%), renewable diesel (20.4%), bioethanol (17.5%) and biomethane (15.4%).

# G.3. Impacts on land use

## G.3.1. Land uses

Estimated uses of land for the different scenarios are shown in Figure 86. The land for producing biofuels[23] is expected to grow from 0.1 mio ha in 2010 to a value ranging from 0.6 to 1.2 mio ha, depending on the scenario. The largest growth is expected for Scenario II with expansion with 1.2 mio ha, followed by Scenario II with 0.7 mio ha and lastly by the baseline and Scenario I with 0.6 mio ha. It is important to note that the land for producing biofuels covers the production of biofuels for local consumption and for exports. A disaggregation into land for producing biofuels for local consumption and for export is presented in the next section.

The land for producing wood in forestry plantations is expected to increase from 0.31 mio ha in 2010 to about 0.5 mio ha in 2030 for all scenarios. This accounts for a small portion of the total forest land (58.5 mio ha in 2030), which, as described in Table 49, is expected to decrease by 2 mio ha between 2010 and 2030 as a consequence of deforestation.

The land for cattle is expected to increase for all considered scenarios. In the baseline and in Scenario I it increases from 38.16 mio ha in 2009 to 40.51 mio ha in 2030. In Scenario II and Scenario II with expansion it respectively increases to 40.47 and 40.18 mio ha in 2030. This increase in land for cattle is explained by a change in land use. Two types of changes in land use are foreseen: a) agricultural land transformed into land for cattle and b) forest land transformed into land for cattle. Transformation of agricultural land into land for cattle occurs for all scenarios, accounting for 0.7 to 1 mio ha. Transformation of forest land into land for cattle via deforestation occurs, therefore, in all scenarios to cover the remaining gap, accounting for 1 to 1.7 mio ha. Agricultural land (excluding biofuels) is expected to be reduced for all scenarios as a consequence of three factors. Firstly and most important, agricultural land is transformed into cattle land as a consequence of the higher cost competitiveness of cattle products (i.e. meat and milk) compared to other agricultural products. Secondly, the assumed international prices for key export commodities (e.g. coffee) decrease in the long term and cause a significant reduction in harvested area. Thirdly, more cost-competitive duty-free imports from the U.S., available as of 2012, cause a further reduction in harvested area for some crops (e.g. rice and corn).

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[23] Including bioethanol, biodiesel and renewable diesel for local production and exports but excluding woodfuel.

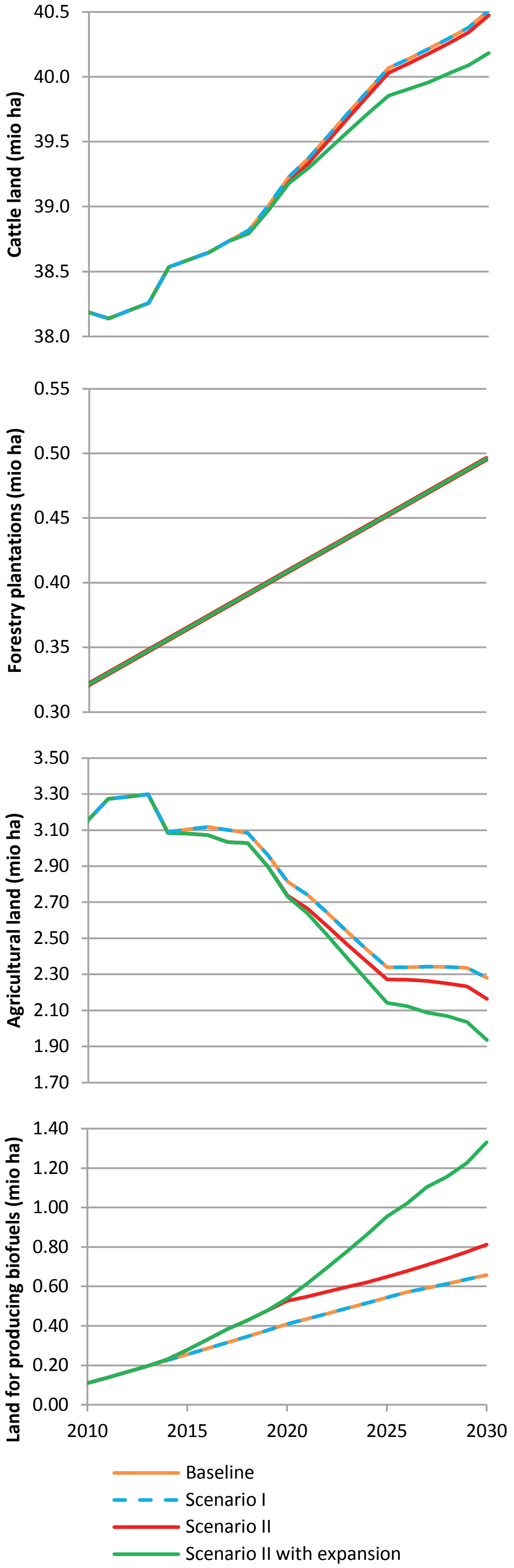

***Figure 86.*** *Land uses by scenario*

## G.3.2. Land for biofuels and woodfuel for local consumption

The land for producing biofuels and woodfuel for local consumption is shown in Figure 87.

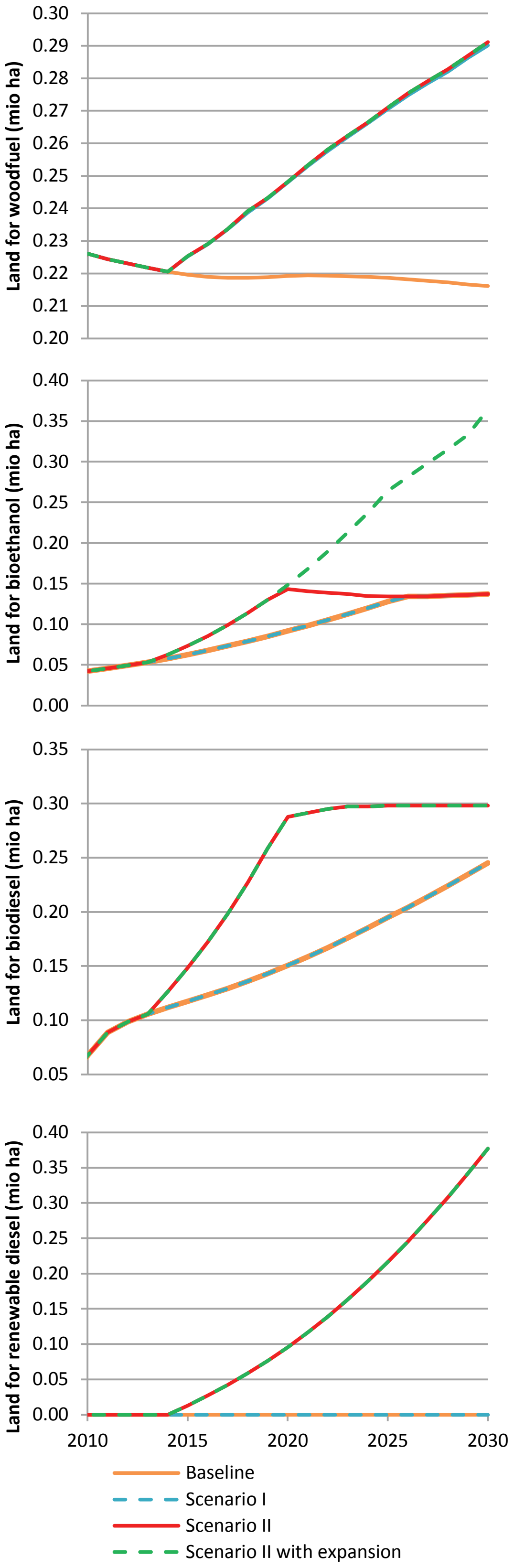

***Figure 87.*** *Land for producing biofuels and woodfuel for local consumption*

The land for producing biofuels and woodfuel for local consumption between 2015 and 2030 is characterized by marked changes caused by: a) the implementation of scenario policies or b) reaching the maximum land available for cultivating a particular biomass resource (e.g. palm, cane, wood, etc.). The land for producing locally consumed biodiesel is expected to increase until 2030 at varying degrees, depending on the scenario. For the baseline and Scenario I, it grows from 67 kha in 2010 to about 245 kha in 2030. For Scenario II and Scenario II with expansion, it rapidly grows to 0.3 mio ha by 2020 and then remains somewhat constant until 2030.

This value appears to be the limit in land for local production of biodiesel, as after 2020 it would be required to import it for Scenario II and Scenario II with expansion (see next section). For these two scenarios, the amount of land for producing locally consumed renewable diesel starts growing in 2015 and progressively reaches 0.37 mio ha in 2030. The baseline and Scenario I do not consider deployment of renewable diesel and consequently no land is required.

The amount of land for producing locally consumed bioethanol grows for all scenarios until 2030. For the baseline and Scenario I, it grows from 42 kha in 2010 to around 130 kha in 2025 and then remains constant. For Scenario II it grows slightly faster than for Scenario I, reaches about 140 kha in 2020 and then stabilizes at 130 kha by 2030. It appears that 130 kha is the limit in land for local production of bioethanol using the two routes described in Section F.3.4.2. Once this limit is reached, it is necessary to import bioethanol (see next section). Finally, for Scenario II with expansion, the amount of land for producing bioethanol for local consumption continuously grows from 42 kha in 2010 to 364 kha in 2030. This substantial growth proves insufficient, however, to avoid imports in 2030, when the E85 program is launched (see next section).

The amount of land for producing locally consumed woodfuel grows at varying degrees until 2030, depending on the scenario. For the baseline scenario it is expected to slightly reduce from 226 kha in 2010 to 216 kha in 2030. This trend appears to agree with forecasts from UPME, which foresee a reduction in woodfuel demand as it continues being substituted by LPG in rural areas. On the other hand, for Scenario I, Scenario II and Scenario II with expansion, it slightly decreases to 216 kha in 2015 and subsequently grows to 291 kha in 2030. This is a consequence of the implementation in 2015 of a new policy to exploit woodfuel and residues for power generation & CHP and biomethane production. The aggregated land to produce locally consumed biofuels and woodfuel is shown in Figure 88.

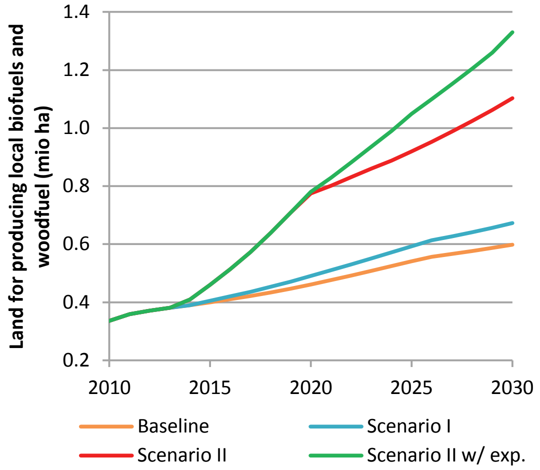

***Figure 88.*** *Aggregated land for producing biofuels and woodfuel for local consumption*

## G.3.3. Trade balance of biofuels

The trade balance of bioethanol and biodiesel is shown in Figure 89. The trade balance is defined here as exports minus imports, since they do not occur simultaneously for these commodities. Therefore, positive curves represent exports and negative curves represent imports. The trade balance of bioethanol for all scenarios is negative, meaning that imports are expected in the future.

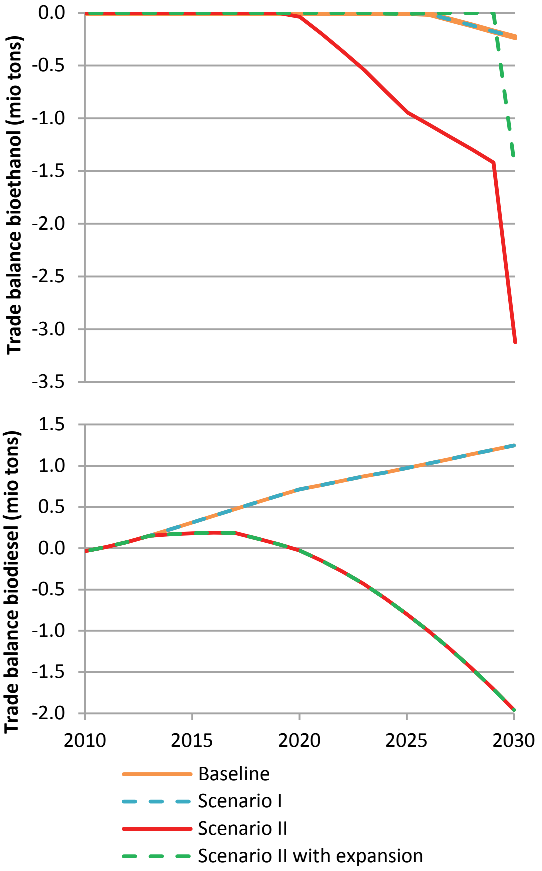

***Figure 89.*** *Trade balance of liquid biofuels by scenario*

For scenarios not supporting further deployment of biofuels (i.e. the baseline and Scenario I), imports of bioethanol are expected after 2025 and might amount to 230 ktons by 2030. Scenario II envisages an ambitious increase in demand for bioethanol, but it requires significant imports since no expansion in land is considered. Imports start in 2020 with 37 ktons and reach 3.1 mio tons in 2030. When expansion in land is considered, imports of biofuels in Scenario II are not avoided but delayed to 2030. In this case imports are required to meet the bioethanol demand when the E85 program is launched and amount to 1.5 mio tons.

The trade balance of biodiesel varies depending on the scenario. For the baseline and Scenario I, the trade balance is positive until 2030, meaning that biodiesel is exported. Biodiesel exports might start in 2011 and grow to 1.25 mio tons in 2030. For Scenario II and Scenario II with expansion, the trade balance is positive until 2019 and then becomes negative until 2030. There are various reasons for this behavior. Between 2010 and 2019, Scenario II starts producing renewable diesel and consuming more biodiesel, which reduces biodiesel exports compared to the baseline. By 2020 the growth in the production of biodiesel and renewable diesel reaches the limit in land for cultivating palm oil and thus imports are required until 2030.

Finally, the relation of imports to total demand for bioethanol and biodiesel is shown in Figure 90. This graph shows that, in Scenario II, imports of bioethanol might account for more than 70% of the demand by 2030, while imports of biodiesel might reach 60% of the demand. This shows that the available land is insufficient to accomplish the proposed long-term goals. Imports can even account for 35% of the demand in Scenario II with expansion, which suggests that expanding the cultivation land beyond the Valley of the Cauca River might also be insufficient to accomplish the targets.

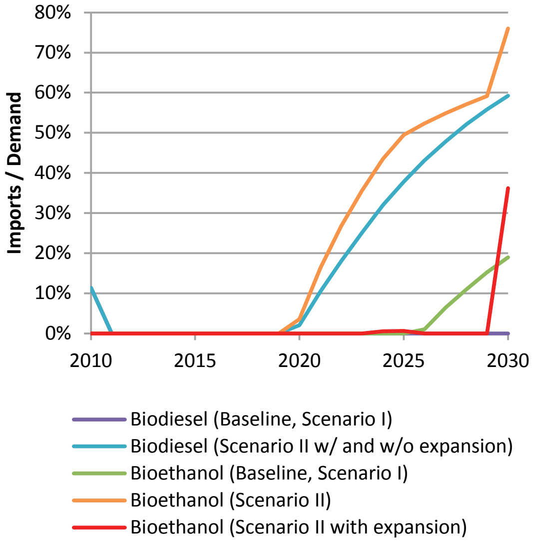

***Figure 90.*** *Imports vs. demand for biofuels by scenario*

# G.4. Impacts on emissions

## G.4.1. Overall emissions by scenario

One of the main potential advantages associated with the deployment of bioenergy technologies is the reduction in greenhouse gas emissions. The Global Warming Potential (GWP) for the different scenarios, as well as the reductions for Scenarios I and II relative to the baseline, are plotted in Figure 91.

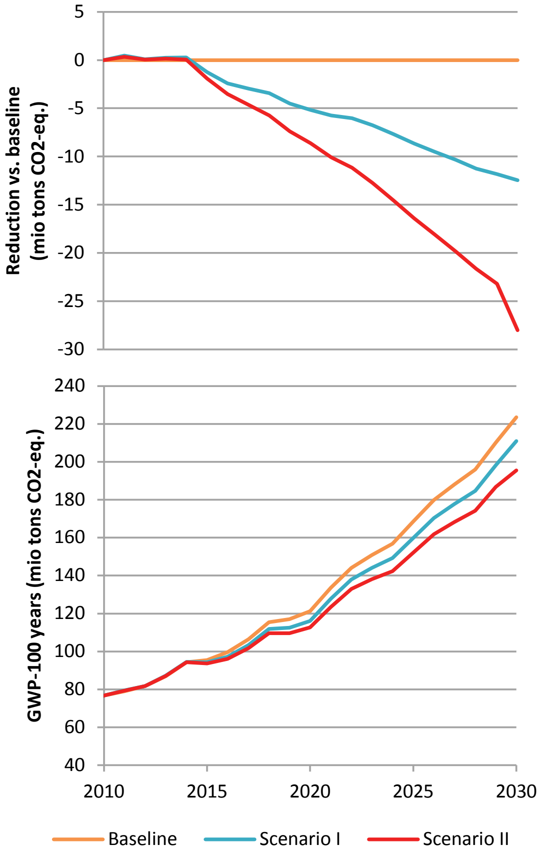

***Figure 91.*** *Global warming potential by scenario*

For the baseline, a significant growth in the GWP is expected. It increases from 72 to 223 mio ton $CO_2$-eq. between 2009 and 2030. Disaggregation of the GWP by fuel and branch respectively for the baseline scenario is shown in Figure 139 and Figure 140 in the Appendix. The bulk of the emissions is caused by combustion of oil and gas (76%) and is associated with the energy use in road transport, industry final demand and power generation.

Greenhouse gas emissions reduce in Scenario I relative to the baseline. Reduction in emissions starts in 2015 and reaches 12.5 mio tons of $CO_2$-eq. by 2030. In order to visualize the impact of implementing the different individual policy measures in Scenario I, this reduction is further disaggregated by policy in Figure 92. The bulk of the reduction in GWP for Scenario I comes from implementing new policy measures on power generation and CHP (76%), followed by new policy measures on biomethane (24%).

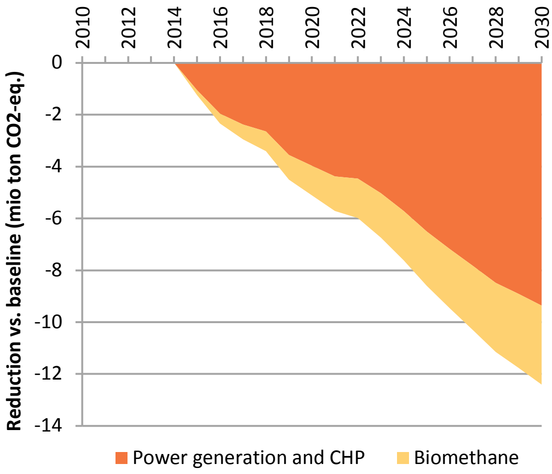

***Figure 92.*** *Reduction in GWP by policy measure for Scenario I*

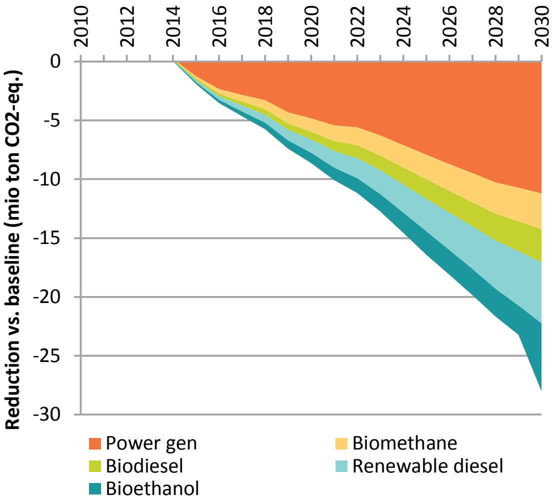

***Figure 93.*** *Reduction in GWP by policy measure for Scenario II*

For Scenario II the reduction in GWP relative to the baseline is shown in Figure 93. In this scenario the reduction starts in 2015 and amounts to 28.5 mio tons of $CO_2$-eq. by 2030. Similarly to Scenario I, the bulk of the reduction comes from implementing new policy measures on power generation and CHP (48%). The remaining 52% of the reduction relates to the implementation of new policies on renewable diesel (16.5%), biomethane (12.3%), bioethanol (12.1%) and biodiesel (11.2%).

It can be deduced that the most effective policy measure to reduce greenhouse gas emissions is the one on power generation and CHP, which accounts for more than 50% in emissions reduction for Scenarios I and II relative to the baseline. Its impact is followed by the aggregated effect of implementing policies on first generation biofuels (i.e. bioethanol, biodiesel and renewable diesel), which contribute 39% of the reduction in Scenario II. It is remarkable that, while the impact of power generation and CHP is the strongest, its set of long-term goals is less ambitious than that of first generation biofuels.

By disaggregating the emissions reduction by technology, it is possible to better observe how emissions are avoided in the power generation and CHP sector. Figure 94 shows the emissions reduction by technology in the power generation and CHP sector for Scenario I.

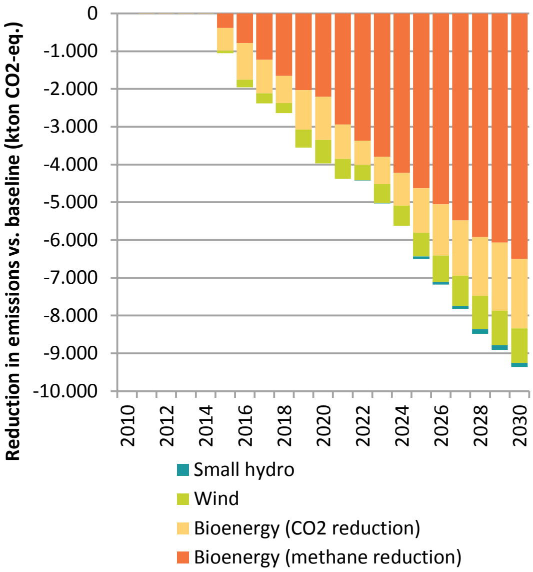

***Figure 94.*** *Reduction in GWP in the power generation and CHP sector for Scenario I*

Three events can be observed. Firstly, 67.5% of the reduction comes from avoiding methane release in landfill gas and biogas from animal waste/wastewater through combustion in reciprocating engines. Secondly, the reduction in $CO_2$-eq. emissions through the replacement of gas- by biomass-based power is less impactful than the methane reduction and accounts for 21.2% of the reduction. Thirdly, wind and small-hydro also replace gas-fired power, and their aggregated impact accounts for 11% of the reduction. The emissions reduction by technology in the power generation and CHP sector for Scenario II is shown in Figure 95. Similarly to Scenario I, the bulk of the reduction (77.2%) comes from avoiding methane release in landfill gas and animal waste/wastewater through combustion in reciprocating engines. It is followed by a reduction in $CO_2$-eq. emissions in biomass-based power generation (15.7%) as well as in wind and small-hydro (7%). In summary, the most effective policy measure to reduce greenhouse gas emissions is the one on power generation and CHP. Its impact is twofold: it avoids methane release in landfill gas and animal waste/wastewater through combustion in reciprocating engines, and, at the same time, it reduces $CO_2$ emissions by replacing gas-fired electricity. It is followed in order of impact by the policies on renewable diesel, bioethanol, biomethane and biodiesel.

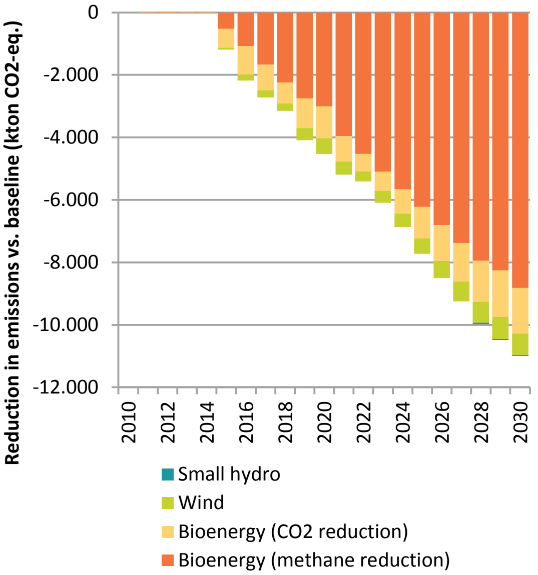

***Figure 95.*** *Reduction in GWP in the power generation and CHP sector for Scenario II*

## G.4.2. Domestic bioenergy-induced emissions reductions

Overall emissions for Scenarios I and II, shown in Figure 91, are rearranged in order to highlight the emissions reduction resulting only from bioenergy deployed within the country. To rearrange the domestic bioenergy-induced emissions reductions, the following procedure was followed:

- Emissions reductions caused by wind and small-hydro are subtracted from the overall reduction for Scenarios I and II shown in Figure 91.
- Emissions reductions caused by imported bioethanol and biodiesel are subtracted from the overall reduction for Scenarios I and II shown in Figure 91.

The obtained domestic bioenergy-induced emissions reductions are respectively shown in Figure 96 for Scenarios I, II and II with expansion relative to the baseline. The domestic bioenergy-induced emissions reductions amount to 11.4 mio ton $CO_2$-eq. in Scenario I, 20.3 mio ton $CO_2$ in Scenario II, and 22.6 mio ton $CO_2$ in Scenario II with expansion. In a similar fashion, the savings in fossil fuel demand shown in Section G.2.4.2 are rearranged to highlight the savings resulting only from bioenergy deployed within the country. Figure 97 shows the obtained results, which amount to 1.9 mio TOE in Scenario I, 4.6 in Scenario II and 5.4 in Scenario II with expansion.

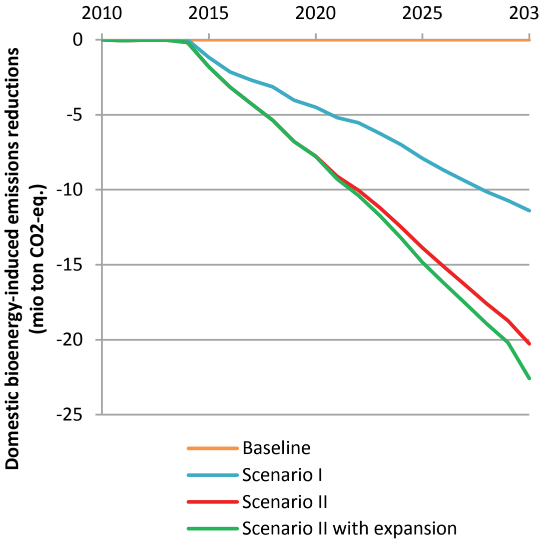

***Figure 96.*** *Domestic bioenergy-induced emissions reductions by scenario*

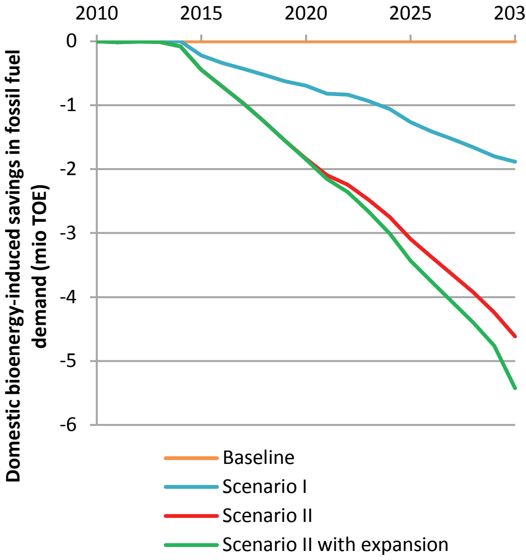

***Figure 97.*** *Domestic bioenergy-induced savings in fossil fuel demand by scenario*

Finally, to visualize the effectiveness of the different scenarios in reducing emissions as a function of the required land, the emissions reductions per required incremental land are defined for each year *t*:

Eq. 153 $$\frac{(Emissions_{Scenarios,t} - Emissions_{Baseline,t})}{(Land_{Scenarios,t} - Land_{Baseline,t})}$$

Results are plotted for the different scenarios in Figure 98. Among the scenarios, Scenario I offers the highest emissions reduction per additional hectare of land used to cultivate biomass resources, i.e. nearly 150 tons of $CO_2$-eq. per additional ha. This high value is a consequence of the ability of some biomass-based power technologies, such as landfill gas and biogas-fuelled reciprocating engines, not only to reduce $CO_2$ emissions relative to fossil-fired power plants but also to capture methane otherwise released via landfill and manure. An additional advantage of exploiting landfill gas and biogas for energy purposes is that, in contrast to first generation biofuels, these routes do not require additional land to produce biomass.

Note that a sharp increase occurs in 2015, which is the year when the policies supporting the deployment of biomethane and power generation & CHP technologies are implemented. In contrast, Scenario II and Scenario II with expansion respectively achieve 40 and 30 tons of $CO_2$-eq. per additional ha. These results suggest that despite the fact that Scenario II and Scenario II with expansion achieve higher reduction in emissions and fossil fuels than Scenario I, they are less effective to reduce GHG emissions per additional hectare of land use.

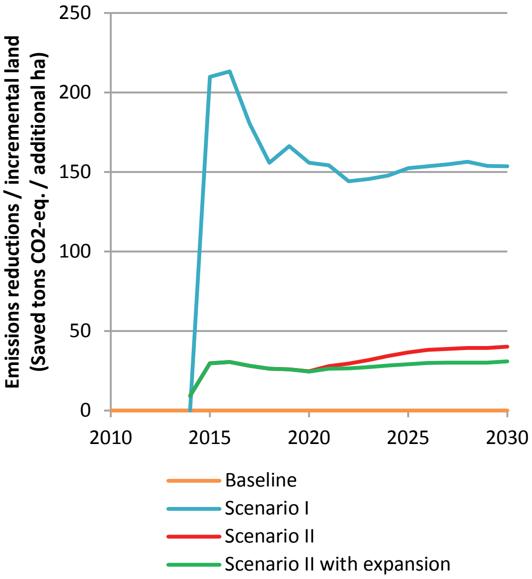

***Figure 98.*** *Emissions reductions per incremental land*

## G.5. Supplementary material

An exemplary analysis of the performance and cost of some of the most attractive technologies identified in the roadmap was included as supplementary material the Appendix. This exemplary analysis does not intend to perform an exhaustive cost comparison of all the technologies proposed in the roadmap, but rather to provide a preliminary evaluation of some of the most attractive technologies. For this purpose, a simplified approach accounting for lifetime costs and energy-related emissions of some selected technologies was formulated. Three technology routes, exploring different uses of biogas from anaerobic digestion of animal waste were analyzed: 1) biogas for biomethane production, 2) biogas for CNG production and 3) biogas for power generation & CHP. While results are very similar for the three routes, Route 3 offers the lowest cost of reducing emissions (34.75 US$2005/ton $CO_2$-eq.) followed by Route 1 and 2 (35.36 and 37.55 US$2005/ton $CO_2$-eq.), respectively.

## G.6. Summary and discussion

This chapter describes the impacts of implementing various future scenarios with different underlying assumptions on policy measures on three main areas: a) energy demand and supply, b) land use and c) greenhouse gas (GHG) emissions.

Scenarios I and II describe long-term visions, in which the role of bioenergy in the future energy mix of the country becomes more relevant than in the baseline. The baseline is characterized by a reduction in the share of bioenergy in the primary demand (from 15% in 2009 to 8% in 2030) and in power generation (from 3.3% to 1.6%) and by a slight increase in the share in road transport (from 5.4% to 6.3%). In contrast, Scenarios I and II are characterized by an increased share of bioenergy in various sectors. In both Scenarios I and II, the share of bioenergy grows to 5.6-5.9% in power generation and to 6.6% in natural gas supply by 2030. The share of bioenergy in road transport remains unchanged for Scenario I relative to the baseline but grows to 24% in Scenario II. This progress is, however, not sufficient to avoid a reduction in the share of bioenergy in the primary demand by 2030 for these scenarios (10% and 11%, respectively).

Regarding impacts on land use, an increase is expected in land for producing liquid biofuels and woodfuel at varying degrees, depending on the scenario. While a portion of this land is used to produce liquid biofuels for export, the bulk of it is used to produce biofuels and woodfuel for local consumption. In the baseline, the amount of land for producing non-export biofuels and woodfuel grows to 0.6 mio ha by 2030, while it grows to 0.67 mio ha in Scenario I, to 1.1 mio ha in Scenario II and to 1.3 mio ha in Scenario II with expansion. In Scenario II and Scenario II with expansion, this increase comes at the expense of a reduction in agricultural and cattle land relative to the baseline. This significant growth in land for producing non-export liquid biofuels and woodfuel is, however, insufficient to accomplish the proposed long-term goals. As a consequence, imports are needed in all scenarios. In the baseline and Scenario I, bioethanol imports might achieve 20% of the domestic demand by 2030. In Scenario II, imports of bioethanol might account for more than 70% of the demand by 2030, while imports of biodiesel might reach 60% of the demand. Imports can even account for 35% of the demand in Scenario II with expansion by 2030, which suggests that expanding the cultivation land beyond the Valley of the Cauca River might also be insufficient to accomplish the targets.

Imports of biofuels occurring in Scenario II and Scenario II with expansion are not considered appropriate because they transfer the positive and negative impacts of producing biofuels to other countries. While importing biofuels might contribute to reducing GHG emissions, it does not enhance domestic rural development, it does not generate local employment, R&D and know-how, it requires additional energy to be transported from abroad and it transfers potential social and environmental negative impacts to other countries.

Regarding impacts on emissions, reductions are expected in Scenarios I and II relative to the baseline. Reductions amount to 12.5 mio ton $CO_2$-eq. in Scenario I (-5.6% in 2030 compared to baseline) and 28.5 mio ton $CO_2$-eq. in Scenarios II and II with expansion (-12.7% in 2030 compared to baseline). However, these reductions include decrements caused by non-bioenergy resources (e.g. wind and small-hydro) as well as by imported biofuels. When rearranged, emissions reductions caused by local bioenergy reach 11.4 mio ton $CO_2$-eq. in Scenario I (-5% in 2030 vs. baseline), 20.3 mio ton $CO_2$-eq. in Scenario II (-9% in 2030 vs. baseline) and 22.6 mio ton $CO_2$-eq. in Scenario II with expansion (-10% in 2030 vs. baseline). In a similar fashion, the savings in fossil fuel demand caused by local bioenergy amount to 1.9 mio tons of oil equivalent (TOE) in Scenario I, 4.6 in Scenario II and 5.4 in Scenario II with expansion.

Among the different policy measures, the most effective to reduce greenhouse gas emissions is the one on power generation and CHP (in particular technologies using biogas and landfill gas), which accounts for more than 50% in reduction for Scenarios I and II relative to the baseline. Its impact is twofold: it avoids methane release in landfill gas and animal waste/wastewater through combustion in reciprocating engines, and, at the same time, it reduces $CO_2$ emissions by replacing gas-fired electricity. Another advantage of biogas and landfill gas power plants relates to their ability to significantly reduce GHG emissions without using additional land. Power generation and CHP are followed in order of impact by the policies on renewable diesel, bioethanol, biomethane and biodiesel.

Among the different scenarios, it is found that Scenario I offers the highest emissions reduction per additional hectare of land used to cultivate biomass resources, i.e. nearly 150 tons of $CO_2$-eq. per additional ha. In contrast, Scenarios II and II with expansion respectively achieve 40 and 30 tons of $CO_2$-eq. per additional ha. These results suggest that, despite Scenarios II and II with expansion achieving higher reductions in emissions and fossil fuels than Scenario I, they are less effective per additional hectare of land use.

# Chapter H. Conclusions & recommendations

## H.1. Conclusions

This thesis examined methods for strategic planning of biomass and bioenergy technologies in developing countries. Conclusions for the different methods proposed in the thesis are presented as follows.

### H.1.1. Method of assessing current biomass energy potential

Firstly, a method of assessing current biomass energy potential when quality and availability of data are limited was proposed. Key advantages of this method include simplicity, reproducibility and low cost, while its main disadvantage is the inability to produce regionally disaggregated results. The main novelty aspect of the method compared to prior art is the ability to estimate uncertainty (not a common practice in biomass potential assessments) and reduce it when quality and availability of data are limited. It does so by combining a probability function with multiple levels of uncertainty, a sensitivity analysis to identify key parameters and a set of sub-models to improve estimations. Various lessons were learnt by applying the method to Colombia. Firstly, it is possible to reduce the uncertainty in the estimation of the theoretical energy potential from ±19% to ±7% and of the technical biomass energy potentials from ±38% to ±23%. Secondly, it is possible to envision a theoretical biomass energy potential of 0.74 EJ ±7% at 95% probability, which is higher than prior art estimations. This potential can grow to 219 EJ if above-ground biomass in forests is included, although the uncertainty rises to ±46% at 95% probability. Thirdly, the technical biomass energy potential is estimated to be 59 PJ ±23% at 95% probability, which is lower than most prior art estimations.

### H.1.2. Method of assessing future biomass energy potential

A method of assessing future biomass energy potential was proposed. In this method, the biomass energy potential is influenced by the demand for commodities and their associated yield, price and land use. The fundamental driver of land use and commodity trade is the maximization of the profit that can be perceived by local actors. Advantages of the method include its ability to link the biomass energy potential to the land use and macro-economic effects (i.e. influence of global biofuel use on agricultural prices, production and demand), while its main disadvantage is the lack of accurate supply curves for commodities and price elasticities. The novelty of this method is its simple mathematical structure to link trade, land use and biomass potential, which is advantageous for countries at an early stage of strategic planning. Lessons learnt by applying this method to Colombia are summarized as follows. Firstly, the influence of agricultural yields, demand for commodities, and specific energy of biomass resources on the biomass energy potential was found stronger than that of the global biofuel use. Secondly, results show that agricultural land and forestry land would change into land for cattle as a consequence of a higher competitiveness of cattle products compared to various agricultural and forestry products. Thirdly, an increase in the theoretical biomass energy potential from 0.74 EJ in 2010 to a value ranging from 1.08 to 1.18 EJ in 2030 depending on the global biofuel use can be expected. Fourthly, the method requires significant amounts of data and resources to calibrate the models and run the optimization algorithm.

### H.1.3. Development of a technology roadmap for bioenergy exploitation

Having estimated the current and future biomass energy potential led to the next challenge: how to exploit it. A method for technology roadmapping adapted to the conditions of developing countries is proposed. The method is based on a simplified approach, which is derived from prior art and further improved. One of the improvements over prior art is the use of a new strategy to build consensus based on the Delphi method. In this strategy, the opinion of individual experts about long-term technology strategies is influenced by the opinion of the group of experts, which facilitates reaching consensus.

The method was applied to the case study of Colombia, where technology roadmapping involving multiple stakeholders has not been used extensively. A group of 30 bioenergy experts from the government, academia, industry and NGOs identified long-term goals to deploy bioenergy until 2030. Experts considered five key bioenergy technology areas: 1) bioethanol, 2) biodiesel, 3) renewable diesel, 4) biomethane and 5) biomass-based power generation and combined heat & power (CHP). While there was agreement on the long-term vision for biomethane and biomass-based power generation, there were opposing views on the long-term vision for liquid transport biofuels. This dilemma led to the definition of two different long-term visions.

Experts identified various actions required to accomplish long-term goals: 1) implement a bioenergy sustainability scheme to be bound to the deployment of bioenergy technologies, 2) implement new regulations and policies, 3) implement incentive programs and financial mechanisms to encourage technology transfer combined with local development and 4) mitigate technical risks by engaging all stakeholders and local communities, acknowledging past international experiences and following best practices.

Some limitations of the proposed roadmap are acknowledged. Firstly, the number of participants is relatively small compared to similar initiatives, but sufficient for the academic purposes of this study. Secondly, because this roadmap is the result of an academic initiative, it does not have forcing mechanisms to put it into place.

### H.1.4. Framework for evaluating the energy, emissions and land-use nexus

The next challenge was how to estimate the impacts of implementing long-term targets on the country's energy demand and supply, GHG emissions and land use and trade. A modeling framework combining a quantitative and a qualitative element was proposed. The qualitative element integrated two components: 1) technology roadmapping to identify long-term technology targets through expert judgment and 2) scenario analysis to investigate different future storylines. The quantitative element comprised four integrated tools, namely the energy system model (ESM), the land use and trade model (LUTM), an economic model, and an external climate model. The novelty of the method is explained as follows. Firstly, the proposed framework combines qualitative and quantitative methods to investigate long-term deployment of bioenergy and its associated impacts, whereas prior art concentrate in one or the other. Secondly, the proposed framework offers a comprehensive approach to investigate the energy sector and a relatively simple approach to investigate the economy, land use and climate linkages. This allows the possibility to provide preliminary assessments. In contrast, most prior art is characterized by having complex frameworks that do not allow preliminary assessments.

The flexibility of the proposed method allows the possibility of implementing alternative scenarios or testing new technologies, and more importantly, of being adapted to other countries. However, these implementations would require significant amounts of data to adapt and calibrate the models. Other acknowledged limitations of the method include: 1) the ESM does not estimate lifecycle emissions and does not perform sophisticated modeling of branches not influenced by bioenergy and 2) the impacts on rural development, generation of employment, water demand and supply were considered out of scope.

### H.1.5. Roadmap impacts

The application of this modeling method to the specific conditions of Colombia led to various important findings. Four scenarios were defined:

- Baseline scenario: assumes no change in policies or deployment of new technologies
- Scenario I: assumes new policy measures for biomethane and biomass-based power generation & CHP
- Scenario II: assumes new policy measures biomethane, biomass-based power generation and CHP, cane-based bioethanol, palm-based biodiesel and palm-based renewable diesel
- Scenario II with expansion: shares targets with Scenario II but considering an enlargement in cultivation land of sugar cane on a large-scale beyond the Valley of the Cauca River, which is not examined in the other scenarios

In the baseline scenario, a significant growth in primary energy demand (129%), road transport demand (237%), electricity generation (120%) and natural gas supply (250%) between 2010 and 2030 was estimated. In this period, the share of fossil fuels in the primary energy demand increases from 75% to 85%, while in power generation it increases from 29% to 50%. In contrast, the share of bioenergy during the same period reduces from 15% to 8% in the primary energy demand and from 3% to 1.6% in power generation. This is a consequence of a combination of factors including increasing urbanization, greater access to electricity and natural gas services, rapid growth of road vehicle ownership and increased deployment of gas- and coal-fired power plants. New policies on biomethane and power generation in Scenarios I and II can increase the share of bioenergy to ~6% in these sectors by 2030, while further deployment of first-generation biofuels in Scenario II can boost the share in road transport to 24%. Despite this, the share of bioenergy in primary energy demand still declines to ~10% in all scenarios. This suggests that, the demand of energy grows more quickly than bioenergy supply in the scenarios considered here, resulting in increased demand for fossil fuels.

Regarding land use and trade, results show that in order to accomplish the proposed targets, the land for producing woodfuel and feedstocks for biofuels should grow. Between 2010 and 2030, the forestland for producing woodfuel in plantations grows in all scenarios from 0.29% to 0.45% of coverage. In the same period, the cropland for cultivating feedstocks for biofuels grows from 0.1% to 0.6% of coverage in the baseline and Scenario I, to 0.7% in Scenario II and to 1.2% in Scenario II with expansion. In addition, cropland for food production and natural forestland (via deforestation) transform into pastures for cattle farming, forest plantations and cropland for producing feedstocks for biofuels. Increases in cropland for producing feedstocks for biofuels, are however, insufficient to accomplish long-term goals and imports of biofuels are expected in all scenarios. Imports are even expected in Scenario II with expansion, which suggests that expanding the cultivation land of sugar cane beyond the Valley of the Cauca River might also be insufficient to accomplish the targets. Importing biofuels raise additional concerns as a definitive solution, because it transfers both positive and negative impacts to other countries.

Regarding emissions, the analysis indicates that technologies for biomethane production, power generation & CHP can reduce more GHG emissions and more emissions per incremental hectare of land than first-generation biofuels. The advantage over biofuels is threefold: avoiding methane release (a gas with 21 times more impact on GHG emissions than $CO_2$) in landfills and biogas from animal waste and wastewater, contributing to the reduction of $CO_2$ emissions by replacing fossil fuels in gas or electricity supplies and not requiring additional dedicated land. This result is not obvious given that currently power generation is mostly renewable (68% hydro-based in 2010) and road transport is ~95% fossil fuel-based. However, the results are consistent since power generation and transport only contributed to 20% of the national GHG emissions in 2004, while animal waste and residues (responsible for most methane emissions) contribute to 25%, similarly to other Latin American countries. Despite the ambitious goals of this roadmap, bioenergy alone cannot significantly reduce emissions by 2030 (maximum 10% reduction relative to baseline) and effective climate change mitigation requires a portfolio of additional measures. These results agree with conclusions from earlier studies conducted for other countries, which confirms the technical soundness of these findings. Results are novel for Colombia and provide key pieces of information to policymakers evaluating the role of bioenergy and to other countries with significant bioenergy potential and similar compositions of national GHG emissions.

## H.2. Policy recommendations

Firstly, it is recommended to initiate a technology roadmapping process for deploying bioenergy. Results from the proposed roadmap suggest that a plan to exploit bioenergy in Colombia should prioritize the deployment of technologies for biomethane production, power generation & CHP (in particular, landfill gas- and biogas-fuelled power plants). These technologies avoid methane release, substitute fossil fuels in power generation, reduce $CO_2$ emissions and maximize the GHG emission reductions per incremental land of bioenergy. It is also recommended to pursue policy measures for renewable diesel, which also proved to be attainable and effective in reducing emissions. Renewable diesel presents various advantages compared to biodiesel, e.g. higher energy content, higher cetane number, no detrimental effect on engines and ability to use a current refining infrastructure. However, it is critical to identify feedstocks other than palm oil to address concerns about food vs. biofuels and single crop farming. Moreover, it is recommended to re-evaluate the policy measures in the proposed roadmap for bioethanol and biodiesel. The proposed long-term goals could not be attained under current land conditions, and they appear less effective for reducing emissions than other options. In addition, the proposed timeline to ensure the operability of new and legacy vehicles with high biofuel blends should be reconsidered and adjusted to a 5- to 10-year horizon.

## H.3. Recommendations for further studies

Regarding the assessment of current biomass energy potential, aspects that require further attention in future work include: 1) scenario analyses to understand the influence of technology deployment on the technical biomass energy potential and 2) performing specific measurement campaigns to assess the availability of biomass resources (e.g. rachis of palm oil tree, cane leaves at tops, forestry residues, etc.) on a local scale. Regarding the assessment of future biomass energy potential, recommendations for future work include: 1) development of methods to estimate market behavior more accurately, 2) development of cost supply curves for relevant commodities, 3) implementation of climate effects, environmental impacts and storage of commodities and 4) development of methods to endogenously link demand and yield and to include the impact of land demand on land price. Regarding the impacts of bioenergy, various aspects require further investigation. Firstly, it is recommended to perform life cycle assessment (LCA) of GHG emissions associated with different bioenergy technologies under the specific conditions of Colombia. Secondly, it is also recommended to perform a detailed economic analysis of deploying novel bioenergy technologies under the specific conditions of the country. Thirdly, it is recommended to identify modeling frameworks, tools and methodologies for evaluating the impacts of implementing different bioenergy technologies on rural development, water supply, biodiversity, etc.

# Glossary

Biodiesel: mixture of fatty acid alkyl esters (FAAE) (mainly methyl esters) produced from lipids via transesterification of the acylglycerides or esterification of fatty acids for use in compression diesel engines (Verhé, Echim, De Greyt, & Stevens, 2011).

Bioenergy: secondary energy resource or carriers such as electricity and biofuels derived from biomass (Slade, Saunders, Gross, & Bauen, 2011).

Bioenergy potential: amount of energy associated with secondary energy resources/carriers such as electricity and biofuels after conversion (Slade, Saunders, Gross, & Bauen, 2011).

Bioethanol (ethyl alcohol): a liquid oxygenated biofuel produced by fermentation of sugars and employed either as a fuel or as an additive in gasoline-fuelled vehicles (Pinzi & Dorado, 2011).

Biofuel: liquid and gaseous fuels produced from biomass, e.g. organic matter (IEA, 2011b).

Biogas: gaseous mixture consisting mainly of methane and carbon dioxide and produced by the degradation of organic matter in the absence of oxygen (Stamatelatou, Antonopoulou, & Lyberatos, 2011).

Biogenic: produced or originating from living organisms or biological processes

Biomass: biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste (EC, 2008).

Biomass energy potential: amount of energy contained in biomass before any type of conversion (Slade, Saunders, Gross, & Bauen, 2011).

Biomass technical energy potential: fraction of the biomass theoretical energy potential that is available for energy production at current conditions and constraints, after considering current energy utilization and competition with other uses and various constraints.

Biomass theoretical energy potential: maximum amount of energy contained in biomass that can be used for energy purposes, explicitly excluding biomass used for food, fiber (e.g. round wood) and feedstock for the industry (e.g. co-products)

Biomethane: methane sourced from renewable biomass such as organic waste, sewage, agricultural residues or energy crops or from woody biomass through production of syngas (Strauch, 2013).

Capacity factor: ratio of the actual output of a power plant (or energy production process) over a period of time, to its potential output if running at its full rated capacity over the same period of time (Heaps, 2012).

Combined heat and power: simultaneous generation of both electricity and heat from the same fuel for useful purposes (IEA, 2011a).

Current biomass energy utilization: amount of biomass currently used in traditional applications (wood fuel for cooking and heating) and modern applications (use of bagasse and residues for heating, power generation and combined heat and power (CHP), biofuel production, etc.).

Energy carrier: substance or phenomenon that can be used to produce mechanical work or heat or to operate chemical or physical processes. It is any system or substance that contains energy for conversion as usable energy later or somewhere else. Examples include: electrical batteries, pressurized air, springs, biofuels, etc. (ISO, 1997).

First generation biofuels: biofuels produced from feedstocks that are used for human consumption, e.g. cane-based bioethanol, palm-based biodiesel, etc.

Primary energy: energy resource found in nature, which has not been transformed or converted.

Renewable diesel (hydrotreated vegetable oil –HVO–): mixture of straight chain and branched paraffinic hydrocarbons free from sulphur and aromatics, produced from vegetable oil via hydrocracking or hydrogenation (Neste Oil, 2014).

Renewable energy: energy from natural resources (e.g. sunlight and wind) that are replenished at a faster rate than they are consumed. Solar, wind, geothermal, hydro and some forms of biomass are common sources of renewable energy (IEA, 2014b).

Renewable resource: natural resource that is replenished at a faster rate than it is consumed. Examples include biomass harvested sustainably, i.e. certified wood. Tropical forests, native rain forests, protected forests and highly diverse ecosystems (wetlands, swamps, páramos, biodiverse savannah, etc.) are not considered renewable resources in this study, as they do not renew themselves at a sufficient rate for sustainable economic extraction.

Secondary energy: energy forms which have been transformed from primary energy, e.g. electricity, gasoline, diesel fuel, etc.

Second generation biofuels: biofuels produced from feedstocks (biomass/organic matter) that are not used for human consumption.

Sustainability: +meeting the needs of the current generation without compromising the ability of future generations to meet their own needs (UN, 1987). This definition, however, is not complete. In addition, it must include equity and justice and the whole instead of the specific (Center for Sustainable Communities, 2014; Leonard, 2010).

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# Appendix for Chapter C

***Table 29.*** *Dataset for agricultural residues in 2010*

| Crops | $P_i$ (t, w)[a] | $\sigma_{P_i}/P_i$ | Residue | $k_{i,j}$ | | | | $M_{i,j}$ | | | | $LHV_{i,j}$ (kJ/kg, d) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Min | Max | N | References | Min | Max | N | References | Min | Max | N | References |
| Cotton | 103257 | 0.117[b] | Husk | 1.77 | 2.76 | 3 | [m q r] | 0.07 | 0.10 | 3 | [y] | 14790 | 17492 | 5 | [y z] |
| Palm Oil | 5367541[c] | 0.050[d] | Stone | 0.06 | 0.17 | 5 | [n q r s] | 0.07 | 0.10 | 5 | [q r y] | 16483 | 20020 | 3 | [n y] |
| | | | Fiber | 0.14 | 0.22 | 5 | [n q r s] | 0.31 | 0.36 | 3 | [n y] | 17856 | 17882 | 2 | [n y] |
| | | | Rachis[e] | 0.23 | 0.50 | 5 | [m n q r s] | 0.50 | 0.58 | 5 | [m n o q r] | 16824 | 18502 | 2 | [n y] |
| Cane (large-scale) | 20060074[f] | 0.030[g] | Leaves & top | 0.25 | 0.47 | 5 | [m n p q r] | 0.30 | 0.75 | 5 | [m n o q] | 14800 | 21429 | 4 | [m n r y] |
| | | | Bagasse | 0.28 | 0.39 | 7 | [m n o p q r t] | 0.41 | 0.52 | 5 | [m n o z] | 16240 | 18644 | 8 | [m n y z] |
| Cane (small-scale) | 16797074[f] | 0.066[h] | Bagasse | 0.28 | 0.34 | 6 | [m n p q r t] | 0.41 | 0.52 | 5[i] | [m n o z] | 16240 | 18644 | 8[h] | [m n y z] |
| | | | Leaves & top | 0.25 | 0.46 | 5 | [m n p q r t] | 0.30 | 0.75 | 5[h] | [m n o q] | 14800 | 21429 | 4[h] | [m n y z] |
| Coffee | 779137[j] | 0.034[h] | Pulp | 2.10 | 2.67 | 4 | [n r u v] | 0.60 | 0.80 | 4 | [m n y ø] | 15880 | 17820 | 2 | [n v] |
| | | | Husk | 0.21 | 0.23 | 3 | [n r u] | 0.07 | 0.12 | 4 | [n y ø] | 13611 | 18535 | 5 | [n v y δ] |
| | | | Stem | 3.02 | 3.33 | 2 | [n v] | 0.14 | 0.26 | 2 | [n ø] | 18343 | 19750 | 2 | [n v] |
| Corn | 1099512 | 0.072[h] | Stem & leaves | 0.93 | 2.00 | 3 | [n q] | 0.15 | 0.15 | 2 | [q r] | 14347 | 16520 | 4 | [n y z] |
| | | | Cob | 0.27 | 0.27 | 3 | [n q r] | 0.16 | 0.27 | 2 | [n o] | 14184 | 17580 | 3 | [n r z] |
| | | | Skin | 0.20 | 0.21 | 3 | [n q r] | 0.05 | 0.09 | 3 | [n y] | 15962 | 17690 | 3 | [n λ] |
| Rice | 2449776[k] | 0.044[h] | Stem | 1.76 | 2.35 | 4 | [n q r] | 0.73 | 0.88 | 3 | [n y] | 13025 | 15340 | 3 | [n y z] |
| | | | Husk | 0.20 | 0.27 | 4 | [m n q r] | 0.04 | 0.14 | 6 | [m n q r y] | 13760 | 17818 | 7 | [m n y z] |
| Banana | 2016992 | 0.102[h] | Rachis | 1.00 | 1.08 | 2 | [n w] | 0.94 | 0.94 | 2 | [n β] | 7569 | 15530 | 2 | [n w] |
| | | | Stem | 3.00 | 6.51 | 3 | [n x] | 0.92 | 0.94 | 3 | [n β γ] | 8502 | 16130 | 5 | [n w x β τ] |
| | | | Rejected fruit | 0.15 | 0.67 | 3 | [n w] | 0.79 | 0.83 | 2 | [n β] | 10410 | 15748 | 2 | [n β] |
| Plantain | 2970435 | 0.048[h] | Rachis | 1.00 | 1.08 | 2[l] | [n w] | 0.94 | 0.94 | 2[l] | [n β] | 7565 | 15530 | 2[l] | [n w] |
| | | | Stem | 3.00 | 6.51 | 3[l] | [n x] | 0.92 | 0.94 | 3[l] | [n β γ] | 8502 | 16130 | 5[l] | [n w x β τ] |
| | | | Rejected fruit | 0.15 | 0.67 | 3[l] | [n w] | 0.79 | 0.83 | 2[l] | [n β] | 10410 | 15748 | 2[l] | [n β] |

**References and notes:**

[a] Ministerio de Agricultura y Desarrollo Rural (MADR, 2012).
[b] Encuesta Nacional Agropecuaria 2000 (DANE, 2000).
[c] Fresh fruit bunch (FFB).
[d] Encuesta Nacional Agropecuaria 1997 (DANE, 1997).
[e] Also known as Empty fruit bunches (EFB).
[f] Cane stalk excluding leaves and tops.
[g] UNFCCC, CDM form for submission of request for deviation (UNFCCC, 2009).
[h] Encuesta Nacional Agropecuaria 2009 (DANE, 2009).
[i] Assumed to be the same than for large-scale sugar cane.
[j] Green coffee bean (unroasted).
[k] Paddy rice (unmilled).
[l] Assumed to be the same than for banana
[m] (AENE, 2003)
[n] (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011)
[o] (Arias Chalico, et al., 2009)
[p] (Kline, Oladosu, Wolfe, Perlack, Dale, & McMahon, 2008)
[q] (Koopmans & Koppejan, 1997)
[r] (Bingh, 2004)
[s] (CORPODIB, 2003)
[t] (JIE, 2008)
[u] (Federación Nacional de Cafeteros, 2005)
[v] (Rodriguez Valencia & Zambrano Franco, Los subproductos del café: fuente de energía renovable, 2010)
[w] (DIBANET, 2012)
[x] (Garcia, Machimura, & Matsui, 2013)
[y] (Phyllis, 2012)
[z] (Bain, 2007)
[ø] (Rodriguez Valencia, 2011)
[β] (Velásquez Arrendondo, Ruiz Colorado, & Oliveira, 2010)
[γ] (FAO, 2012c)
[δ] (FAO, 2004)
[λ] (ORNL, 2012)
[τ] (Milbrandt, 2009)

## ***Table 30.*** *Dataset for animal waste in 2010*

| Type | Subtype | $H_{m,n}$ (heads)[h] | $\sigma_{w_{m,n}}/H_{m,n}$ [i] | $f_{m,n}$ (t/head, w) | | | | $b_{m,n}$ ($m^3$/t, w) | | | | $LHV_{m,n}$ ($MJ/m^3$)[j] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Min | Max | N | References | Min | Max | N | References | Min | Max | N | References |
| Cattle | <12 months | 5377345 | 0.023 | 1.46 | 1.49 | 2 | b d | 23 | 40 | 4[k] | a c e | 16.99 | 25.46 | 4 | e g |
| | 12-24 months | 6277827 | 0.023 | 3.29 | 4.30 | 3 | b d | | | | | | | | |
| | 24-36 months | 6526156 | 0.023 | 3.48 | 5.11 | 3 | b d | | | | | | | | |
| | > 36 months | 9572673 | 0.023 | 6.57 | 15.23 | 10 | b c d e | | | | | | | | |
| Swine | Nursey | 633895 | 0.028 | 0.10 | 0.22 | 2 | b d | 40 | 70 | 4[l] | a c e | | | | |
| | Grow | 1426360 | 0.028 | 0.38 | 0.45 | 3 | b d f | | | | | | | | |
| | Grow-finish | 1609263 | 0.028 | 0.70 | 0.80 | 3 | b e f | | | | | | | | |
| | Boar | 39397 | 0.028 | 1.19 | 2.05 | 5 | b c d f | | | | | | | | |
| | Lactating sow | 314392 | 0.028 | 2.69 | 5.46 | 3 | b d f | | | | | | | | |
| | Gestating | 76691 | 0.028 | 1.24 | 1.97 | 4 | b c d f | | | | | | | | |
| Poultry | Meat | 571000000 | 0.067 | 0.02 | 0.03 | 3 | b c d | 55 | 91 | 3[m] | a c e | | | | |
| | Eggs | 30049000 | 0.067 | 0.04 | 0.04 | 3 | b c d | | | | | | | | |
| Equine | | 2505580 | 0.054 | 7.45 | 9.22 | 3 | c d | 32 | 48 | 3 | a c e | | | | |

**References and notes:**

[a] (FAO, 1996).

[b] (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011).

[c] (Arias Chalico, et al., 2009).

[d] (Ohio State University, 2012).

[e] (Farret & Godoz Simoes, 2006).

[f] (Whitney, Shurson, Spiehs, Knott, & Mold, 2002).

[g] (Al Seadi, Rutz, Prassl, Köttner, & Finsterwalder, 2008).

[h] Ministerio de Agricultura y Desarrollo Rural (MADR, 2012).

[i] Encuesta Nacional Agropecuaria 2009 (DANE, 2009).

[j] It is assumed that the lower heating value ($MJ/m^3$) of biogas is the same for all animal types and subtypes. It is calculated using Aspen Hysys® at 1 bar and 15°C, based on the biogas composition reported in (Farret & Godoz Simoes, 2006; Al Seadi, Rutz, Prassl, Köttner, & Finsterwalder, 2008).

[k] It is assumed that the biogas yield from manure ($m^3$/t, w) is the same for all cattle subtypes.

[l] It is assumed that the biogas yield from manure ($m^3$/t, w) is the same for all swine subtypes.

[m] It is assumed that the biogas yield from manure ($m^3$/t, w) is the same for all poultry subtypes.

## ***Table 31.*** *Dataset for forestry and wood industry in 2010*

| Sub-category | $P_r$ ($m^3$)[j] | $\sigma_{P_r}/P_r$ [k] | Residue | $c_r$ | | | | $\rho_r$ ($t/m^3$, d) | | | | $LHV_r$ (kJ/kg, d) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Min | Max | N | References | Min | Max | N | References | Min | Max | N | References |
| Wood fuel | 8826000 | 0.035 | - | | | | | 0.33 | 0.87 | 60[l] | b i | 16734 | 19384 | 8 | a b f g |
| Total round wood | 11216000 | 0.035 | Forestry residues | 0.30 | 1.00 | 17 | a b c d e | 0.33 | 0.87 | 60[m] | b i | 16791 | 20768 | 9 | a b f g |
| Industrial round wood | 2390000 | 0.035 | Ind. residual wood | 0.30 | 0.55 | 19 | b c h | 0.39 | 0.75 | 21 | b c d e h | 16791 | 20768 | 9[n] | a b f g |

**References and notes:**

[a] (Rosillo-Calle, de Groot, Hemstock, & Woods, 2007)

[b] (AENE, 2003)

[c] (Arias Chalico, et al., 2009)

[d] (Kline, Oladosu, Wolfe, Perlack, Dale, & McMahon, 2008)

[e] (Koopmans & Koppejan, 1997)

[f] (Phyllis, 2012)

[g] (Bain, 2007)

[h] (Jölli & Giljum, 2005)

[i] (IPCC, 2006a)

[j] Taken from FAOSTAT (FAO, 2012b).

[k] The sampling error is not available in FAOSTAT. It is assumed to be equal to the sampling error of the current land used for forestry in Colombia available in Encuesta Nacional Agropecuaria 2009 (DANE, 2009).

[l] 60 different species of trees producing wood in Colombia were taken from (AENE, 2003), and then the corresponding density was taken from (IPCC, 2006a).

[m] It is assumed that the density of forestry residues is equal to the density of wood fuel.

[n] It is assumed that the lower heating value of industrial residual fuel is equal to that of forestry residues.

***Table 32.** Dataset for calculating the above-ground biomass forestry in 2010*

| Sub-category | $P_r$ (t, d) | $\sigma_{P_r}/P_r$ | Products and residues | $c_r$ | | | | $\rho_r$ (t/m$^3$, d) | | | | $LHV_r$ (kJ/kg, d) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Min | Max | N | References | Min | Max | N | References | Min | Max | N | References |
| Above-ground biomass[i] | 14289723630 | 0.1910[j] | - | | | | | | | | | | | | |
| Biomass in protected forest[k] | 2321106032 | 0.1950[l] | - | | | | | | | | | | | | |
| Biomass exc. Protected forest | 11968617598 | 0.2315[m] | Round wood[n] | 0.500 | 0.769 | 17 | a b c d e | 0.33 | 0.87 | 60 | b h | 16734 | 19384 | 8 | a b f g |
| | | | Forestry residues | 0.230 | 0.5 | 17 | a b c d e | 0.33 | 0.87 | 60 | b h | 16791 | 20768 | 9 | a b f g |

**References and notes:**

[a] (Rosillo-Calle, de Groot, Hemstock, & Woods, 2007)
[b] (AENE, 2003)
[c] (Arias Chalico, et al., 2009)
[d] (Kline, Oladosu, Wolfe, Perlack, Dale, & McMahon, 2008)
[e] (Koopmans & Koppejan, 1997)
[f] (Phyllis, 2012)
[g] (Bain, 2007)
[h] (IPCC, 2006a)

[i] Taken from the national estimation of carbon reserves in forests in Colombia (Phillips, et al., 2011).

[j] Calculated with areas and biomass yields from the estimation of carbon reserves in forests in Colombia (Phillips, et al., 2011) using Oracle® Crystal Ball 11.1.2.1.

[k] Taken from the estimation of biomass in protected forests in Colombia (Corredor, 2011).

[l] Calculated with areas and biomass yields from estimation of biomass in protected forests in Colombia (Corredor, 2011) using Oracle® Crystal Ball 11.1.2.1.

[m] Calculated from the above-ground biomass minus the biomass in protected forests using Oracle® Crystal Ball 11.1.2.1.

[n] Calculated based on the production ratio of forestry residues to round wood shown in Table 31.

***Table 33.** Dataset for urban waste in 2010*

| Sub-category | $P_x$ ([a] t, w; [b] m$^3$) | | | | $LHV_x$ ([a] kJ/kg, w; [b] MJ/m$^3$) | | | |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | N | References | Min | Max | N | References |
| Municipal solid waste per capita (t/inhab.) | 0.1707 | 0.2284 | 6 | e f g | - | - | - | - |
| Municipal solid waste (MSW)[n] [a] | 7906667 | 10578147 | | h | - | - | - | - |
| Landfill from MSW[o] [b] | 537041180 | 718495025 | | i | 10.20 | 20.38 | 3[p] | d j k |
| Residues of wholesale food market[q] [a] | 102179 | 138242 | 1 | c | 700 | 3900 | 5 | c l |
| Pruning[q] [a] | 38089 | 51533 | 1 | c | 1627 | 8457 | 7 | c m |

**References:**

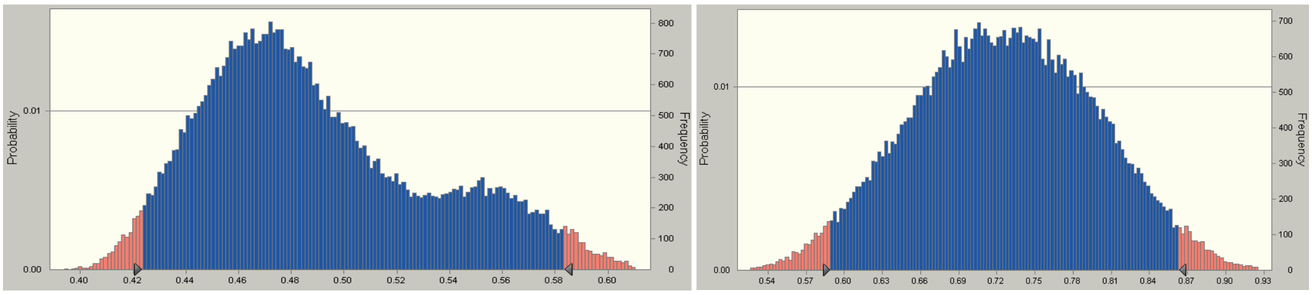
[c] (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011)
[d] (Al Seadi, Rutz, Prassl, Köttner, & Finsterwalder, 2008)
[e] (Superservicios, 2009)
[f] (Superservicios, 2011)
[g] (Superservicios, 2012)
[h] (DANE, 2005)
[i] (SCS Engineers, 2010)
[j] (CREDP, 2010)
[k] (Dudek, Klimek, Kolodziejak, Niemczewska, & Zaleska Bartosz, 2010)
[l] (Asquer, Pistis, & Scano, 2013)
[m] (Colomber Mendoza, Herrera Prats, Robles Martinez, Gallardo Izquierdo, & Piña Guzmán, 2013)

[n] Calculated by multiplying the municipal solid waste per capita (t, w) by the total population taken from (DANE, 2005).

[o] Calculated using the Colombia Landfill Gas Model V.1.0 (SCS Engineers, 2010), assuming that the type of landfill is engineered or sanitary, has started in 2005 and will be closed down in 2030.

[p] Lower heating value for landfill gas is calculated using Aspen Hysys® at 1 bar and 15°C, based on the composition reported in (Al Seadi, Rutz, Prassl, Köttner, & Finsterwalder, 2008; CREDP, 2010; Dudek, Klimek, Kolodziejak, Niemczewska, & Zaleska Bartosz, 2010).

[q] Ranges are not found in literature. After consulting experts on waste disposal, it was assumed to use the data reported by (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011) ± 15%.



Mean = 0.49, C.I. = 0.42-0.58 (95% probability)

Mean = 0.73, C.I. = 0.59-0.86 (95% probability)

***Figure 99.*** *Results of the weighted mean of density (left) and residue to product ratio (right) for forestry residues*

***Table 34.*** *Data to estimate weighted mean of forestry residues*

| Type of forest | Species of trees | Potential wood production (mio $m^3$)[a] | Weight factor | Residue to product ratio | |
|---|---|---|---|---|---|
| | | | | Min[b] | Max[c] |
| Montano bajo | Eucaliptus globulus, Acacia melanoxylon, Cupresus sp., Pinus radiata, Pinus patula | 5.85 | 0.042 | 0.4 | 1 |
| Premontano | Eucalitus (grandis, camandulensis, saligna), Pinus (tenuifolia, patula, oocarpa) | 4.8 | 0.034 | 0.3 | 1 |
| Tropical zona Caribe | Teca sp., Roble, Bombacopsis quinata, Melina Melina, Eucaliptus (tereticornis, pellita, urophylla), Cordia gerascanthus | 3.3 | 0.023 | 0.4 | 1 |
| Tropical Orinoquia | Eucaliptus (pellita, urophylla, tereticornis), Pinus (caribaea, oocarpa), Schizolobium | 0.9 | 0.006 | 0.4 | 1 |
| Bosque guandal | Camnosperma panamensis, Dialyanthera parvifolia | 8.4 | 0.060 | 0.45 | 1 |
| Bosque de terraza | Virola reidii, Humiriastrum porocera, Dacryodes can., Brosimun utile, Goupia glabra | 8 | 0.057 | 0.5 | 1 |
| Bosque de colina | Prioria copaifera, Cedrela spp., Tabebuia rosae, Carapa guianensis, Cariniana pyriformis, Brosimun utile, Pouteria caimito, Lecythis spp., Dacryodes canalensis, Anacardium rhinocarpus, Virola surinamensis, Coumarouna oleifera | 7.65 | 0.054 | 0.5 | 1 |
| Catival | Prioria copaifera, Cariniana pyriformis | 44 | 0.313 | 0.4 | 1 |
| Zona andina | Nectandra spp., Talauma sambuensis, Cedrela spp., Dacryodes canalensis, Abarema jupumba, Brosimun utile, Tabebuia rosae, Cordial gerascanthus, Clathrotropis brachypetala, Schizolobium parahyba, Himatanthus articulata | 37.5 | 0.266 | 0.52 | 1 |
| Serranía San Lucas | Cariniana pyriformis, Bombacopsis quinata, Nectandra spp., Jacaranda copaia, Clathrotropis brachypetakla, Humiriastrum colombianum, Couma macocarpa, Couratari guianensis | 10.2 | 0.072 | 0.45 | 1 |
| Bosques de galería | Bombacopsis quinata, Nectandra spp., Cordia alliodora, Jacaranda copaia, Dacryodes canalensis | 4.8 | 0.034 | 0.5 | 1 |
| Pied. Amazónico | Tabebuia rosae, Cedrela spp., Cedrelinga catenaeformis, Dacryodes canalensis, Catostemma alstonii, Cordia alliodora, Aniba sp., Jacaranda copaia, Platymiscium pinnatum, Nectandra spp. | 5.4 | 0.038 | 0.45 | 1 |

**References and notes:**

[a] Potential to produce wood fuel calculated by (AENE, 2003).

[b] According to AENE, the reported residue to product ratio is conservative as it takes into account losses. As the reported values by AENE lie in the lower end of the range shown in Table 31 in the Appendix, they are considered the minimum bound.

[c] The maximum value is not reported in the AENE report. Therefore, it is taken the maximum value reported in literature, e.g. 1.

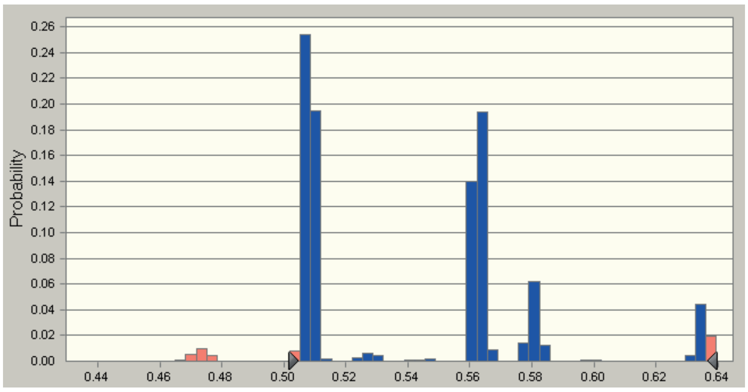
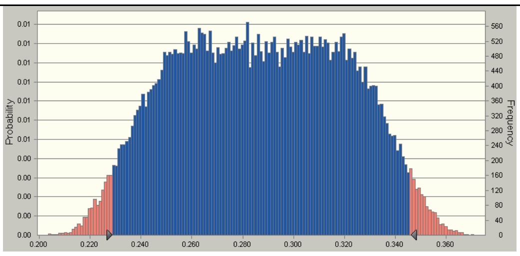


***Figure 100.*** *Special constraint factor for forestry residues*

<table>
<tr><th rowspan="2">Cane variety</th><th rowspan="2">Harvested area (%) [a]</th><th colspan="2">By-product to crop ratio [b c d]</th><td rowspan="8"> <br>Mean = 0.287, C.I. = 0.229-0.345 (95% probability)</td></tr>
<tr><th>Min</th><th>Max</th></tr>
<tr><td>CC 85-92</td><td>0.746</td><td>0.205</td><td>0.350</td></tr>
<tr><td>CC 84-75</td><td>0.097</td><td>0.205</td><td>0.350</td></tr>
<tr><td>CC 93-4418</td><td>0.039</td><td>0.213</td><td>0.401</td></tr>
<tr><td>V 71-51</td><td>0.022</td><td>0.500</td><td>0.800</td></tr>
<tr><td>PR 61-632</td><td>0.016</td><td>0.300</td><td>0.350</td></tr>
<tr><td>Others</td><td>0.08</td><td>0.190</td><td>0.350</td></tr>
</table>

**References and notes:**

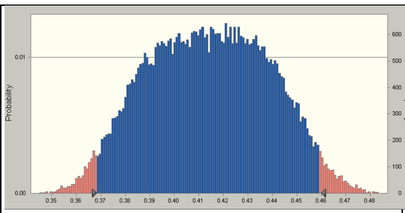
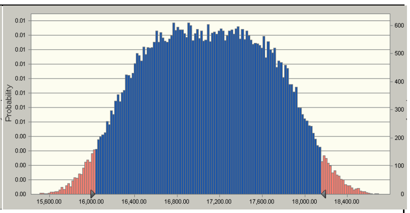
[a] (Cenicaña, 2012)

[b] (Cenicaña, 2006a)

[c] (Cenicaña, 2002)

[d] (Cenicaña, 2006b)

***Figure 101.*** *Weighted mean of by-product to crop ratio of cane leaves and tops*

<table>
<tr><th rowspan="2">Type of residue</th><th colspan="2">Fraction of residue [c]</th><th colspan="2">Moisture [d]</th><th colspan="2">LHV (kJ/kg, d) [a b]</th><td rowspan="5"> <br>Weighted mean of moisture<br>Mean = 0.41, C.I. = 0.37-0.46 (95% probability)</td><td rowspan="5"> <br>Weighted mean of LHV<br>Mean = 17089, C.I. = 16037-18140 (95% prob.)</td></tr>
<tr><th>Min</th><th>Max</th><th>Min</th><th>Max</th><th>Min</th><th>Max</th></tr>
<tr><td>Dry leaves</td><td>0.44</td><td>0.55</td><td>0.10</td><td>0.15</td><td>16730</td><td>17399</td></tr>
<tr><td>Green leaves</td><td>0.13</td><td>0.14</td><td>0.60</td><td>0.75</td><td>16848</td><td>17399</td></tr>
<tr><td>Tops</td><td>0.44[e]</td><td>0.32[e]</td><td>0.60</td><td>0.80</td><td>16399</td><td>17820</td></tr>
</table>

**References and notes:**

[a] (Cenicaña, 2006a)

[b] (Hassuani, Leal, & Macedo, 2005)

[c] Cenicaña concludes that the mass fraction of the different type of residues do not vary significantly after comparing their results to similar studies in other countries (Cenicaña, 2006a).

[d] According to Cenicaña the moisture of cane residues varies widely because of various reasons: cane burning, rain, climate, etc. For instance for green leaves the moisture might vary from 75% before field burning to 60% right after (Cenicaña, 2006a).

[e] Calculated by subtracting from 100% the compositional fraction of dry leaves and green leaves.

***Figure 102.*** *Weighted mean of moisture and LHV of cane leaves and tops*

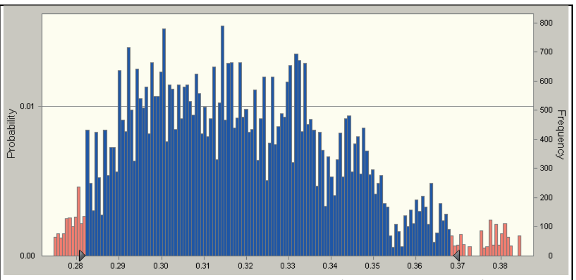
<table>
<tr><th></th><th>Jaggery production (t) [a]</th><th>Weighting factor</th><th>Varieties</th><th>By-product to crop ratio [b c]</th><td rowspan="13"> <br>Mean = 0.32, C.I. = 0.28-0.37 (95% probability)</td></tr>
<tr><td>Suarez River</td><td>518964</td><td>0.336</td><td>RD75-11</td><td>0.396</td></tr>
<tr><td></td><td></td><td></td><td>PR61-632</td><td>0.310</td></tr>
<tr><td></td><td></td><td></td><td>POJ28-78</td><td>0.287</td></tr>
<tr><td>Cundinamarca and N. Santander</td><td>232235</td><td>0.150</td><td>MY54-65</td><td>0.303</td></tr>
<tr><td></td><td></td><td></td><td>RD75-11</td><td>0.396</td></tr>
<tr><td></td><td></td><td></td><td>POJ28-78</td><td>0.287</td></tr>
<tr><td>Antioquia</td><td>172026</td><td>0.111</td><td>RD75-11</td><td>0.396</td></tr>
<tr><td></td><td></td><td></td><td>PR11-41</td><td>0.262</td></tr>
<tr><td></td><td></td><td></td><td>SP701284</td><td>0.303</td></tr>
<tr><td>Llanos orientales</td><td>15544</td><td>0.010</td><td>MY54-65</td><td>0.303</td></tr>
<tr><td></td><td></td><td></td><td>MZC74-275</td><td>0.500</td></tr>
<tr><td></td><td></td><td></td><td>PR62-88</td><td>0.350</td></tr>
<tr><td></td><td></td><td></td><td>RD75-11</td><td>0.396</td><td rowspan="2"><b>References and notes:</b><br>[a] (MADR, 2012)<br>[b] (Cenicaña, 2006a)<br>[c] (Universidad de Pamplona & Corpoica, 2012)</td></tr>
<tr><td>Others</td><td>605802</td><td>0.392</td><td>POJ 2878, PR 61-632, PR 11-41, RD 75-11, CC 84-75, POJ 2714, CO 421, CO 419, CP 57-603, CC 86-45, CC 85-47, CC 85-57, CC 85-92</td><td>0.262-0.396</td></tr>
</table>

***Figure 103.*** *Weighted mean of moisture and LHV of cane leaves and tops (small-scale)*

*Table 35. Availability of resources for energy production*

| | Resource | Current use | Availability | Preliminary availability factor | Improved availability factors | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Geographical constraint factor | Market constraint factor | Technical constraint factor | Environm. constraint factor | Special constraint factor |
| **Agricultural residues** | Cotton | Animal feed | ✗ | | | | | | |
| | Palm Oil | Heat | ✓ Rachis | 0-1[a] | 0.93 ± 0.01 | 1 | 1 | 1 | 0-1 (discrete) |
| | Cane (large) | CHP | ✓ Leaves, tops | 0-0.5[b] | 1 | 1 | 0.333-0.980 | 0-0.3 | 0.947-0.978 |
| | Cane (small) | Heat, animal feed | ✗ | | | | | | |
| | Coffee | Fertilizer | ✗ | | | | | | |
| | Corn | Animal feed | ✗ | | | | | | |
| | Rice | Waste, fertilizer | ✓ Husk | 0-0.44[c] | 1 | 1 | 0-0.44[d] | 1 | 1 |
| | Banana | Fertilizer, animal feed | ✗ | | | | | | |
| | Plantain | Fertilizer, animal feed | ✗ | | | | | | |
| **Animal waste** | Cattle | Waste | ✓ | 0.12-0.24[e] | 1 | 1 | 0.13 ± 0.01 | 1 | 0.91 (mean)[f] |
| | Pork | Waste | ✓ | 0.07-0.14[e] | 1 | 1 | 0.60 ± 0.04 | 1 | 0.97 ± 0.01 |
| | Poultry | Fertilizer | ✗ | | | | | | |
| | Equine | Waste | ✗ | | | | | | |
| **Forestry** | Wood fuel | Heat | ✗ | | | | | | |
| | Forestry residues | Soil replenishment | ✓ | 0-0.5[g] | 0.91-1[h] | 1 | 0.47 ± 0.06 | 1 | 0.51-0.64[i] |
| | Ind. residual wood | Marketable by-product | ✗ | | | | | | |
| **Urban waste** | Landfill gas | Waste | ✓ | 0.5-0.9[j] | 1 | 1 | 0.5-0.9[k] | 1 | 1 |
| | W. market residues | Animal feed | ✗ | | | | | | |
| | Pruning | Animal feed | ✗ | | | | | | |

**References and notes:**

[a] Uniform distribution, Refs. (BID-MME, Consorcio CUE, 2012; Panapanaan, Helin, Kujanpää, Soukka, Heinimö, & Linnannen, 2009; Schmidt, 2007).

[b] EUD distribution, Refs (Hassuani, Leal, & Macedo, 2005; BID-MME, Consorcio CUE, 2012; Pankhurst, 2005).

[c] EUD distribution, Refs. (AENE, 2003).

[d] It is used the preliminary availability factor, e.g. an EUD distribution, Refs. (AENE, 2003).

[e] EUD distribution, Refs. (Gonzalez-Salazar, et al., 2013).

[f] Beta probability distribution with a mean of 0.91, a minimum of 0.73, a maximum of 0.99, α = 12.14 and β = 5.352.

[g] EUD distribution, Refs. (AENE, 2003; Arias Chalico, et al., 2009; Kline, Oladosu, Wolfe, Perlack, Dale, & McMahon, 2008).

[h] Trapezoidal probability distribution with a min = 0.91, max = 1, and modes 0.94 and 0.97.

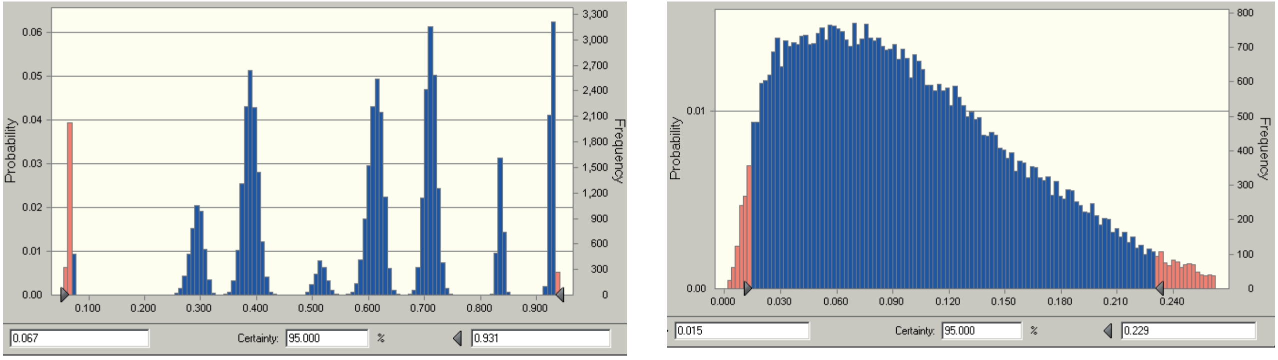
[i] Non-uniform distribution.

[j] EUD distribution, Refs. (SCS Engineers, 2010).

[k] It is used the preliminary availability factor, e.g. an EUD distribution, Refs. (SCS Engineers, 2010).

Total availability factor of rachis

Total availability factor of cane leaves and tops



Total availability factor of cattle manure

Total availability factor of forestry residues

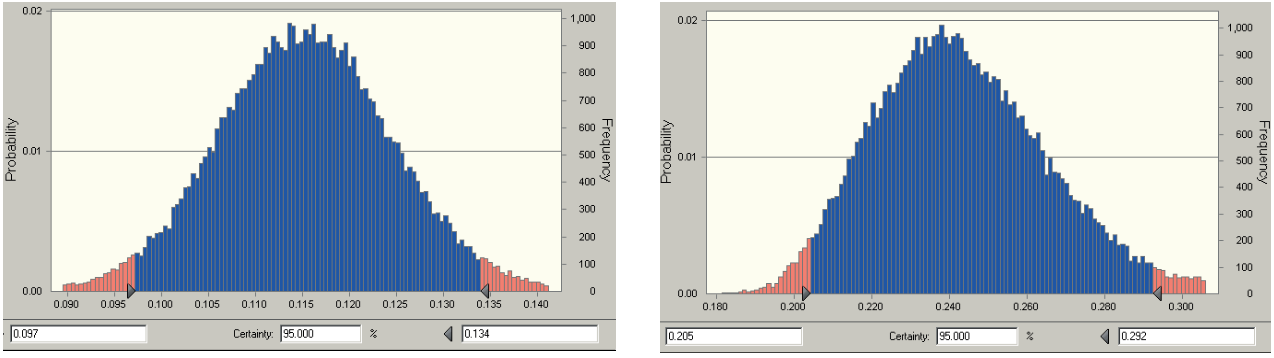


*Figure 104. Results of the improved availability factors for key variables*

*Table 36. Comparison of assumptions used by different studies*

| **Study** | | **Escalante** | **AENE** | **Arias et al** | **Kline et al** | **UPME** | **Escalante** | **AENE** | **Arias et al** | **Kline et al** | **UPME** | **Escalante** | **AENE** | **Arias et al** | **Kline et al** | **UPME** | **Escalante** | **AENE** | **Arias et al** | **Kline et al** | **UPME** | **Escalante** | **AENE** | **Arias et al** | **Kline et al** | **UPME** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Agricultural residues** | | **Type of residue (mio tons, dry)** | | | | | **Lower heating value (kJ/kg, dry)** | | | | | **Moisture (wet base)** | | | | | **Technical availability for biomass energy production** | | | | | **By-product to crop ratio** | | | | |
| Cotton | Husk | | 0.07 | | | | | 16747 | | | | | 0.73 | | | | | | 0.50 | | | | 2.00 | | | |
| Palm Oil | Stone | 0.15 | | | | | 17340 | | | | | 0.20 | | | | | | 1.00 | 1.00 | 1.00 | 1.00 | 0.07 | | | | |
| | Fiber | 0.36 | | | | | 18584 | | | | | 0.33 | | | | | | 1.00 | 1.00 | 1.00 | 1.00 | 0.22 | | | | |
| | Rachis | 0.38 | 0.47 | 0.05 | 0.93 | | 17485 | 20515 | | | | 0.59 | 0.59 | 0.50 | | | | 1.00 | 1.00 | 1.00 | 1.00 | 0.37 | 0.50 | 0.15 | 2.30 | |
| Cane (large) | Leaves, top | 2.60 | 7.05 | 2.19 | | | 16018 | 15000 | | | | 0.69 | 0.30 | 0.30 | | | | 1.00 | 0.50 | 0.56 | | 0.47 | 0.46 | 0.15 | 0.25 | |
| | Bagasse | 3.97 | 3.20 | 3.14 | 6.43 | | 19374 | 8895 | | | | 0.43 | 0.50 | 0.50 | | | | 1.00 | 1.00 | 1.00 | 0.67 | 0.39 | 0.29 | 0.30 | 0.34 | |
| Cane (small) | Bagasse | 3.22 | 1.99 | | | | 19374 | 8895 | | | | 0.43 | 0.50 | 0.50 | | | | 1.00 | 1.00 | 1.00 | | 0.52 | 0.29 | 0.30 | 0.34 | |
| | Leaves, top | 1.17 | 4.38 | | | | 16018 | 15000 | | | | 0.69 | 0.30 | 0.30 | | | | | 0.50 | 0.56 | | 0.35 | 0.46 | 0.15 | 0.25 | |
| Coffee | Pulp | 0.39 | 0.09 | | | | 18518 | | | | | 0.81 | 0.64 | | | | | | | | | 2.13 | 0.50 | | | |
| | Husk | 0.17 | | | | | 19265 | | | | | 0.10 | | | | | | | | | | 0.21 | | | | |
| | Stem | 2.02 | | | | | 19062 | | | | | 0.29 | | | | | | | | | | 3.02 | | | | |
| Corn | Stem, leaves | 0.84 | | | | | 14912 | | | | | 0.34 | | | | | | | 0.80 | | | 0.93 | | | | |
| | Cob | 0.26 | | 1.54 | | | 14740 | | | | | 0.29 | | 0.16 | | | | | 0.80 | | | 0.27 | | 1.00 | | |
| | Skin | 0.26 | | | | | 16590 | | | | | 0.09 | | | | | | | | | | 0.21 | | | | |
| Rice | Stem | 1.53 | | | | | 13537 | | | | | 0.74 | | | | | | | 0.50 | | | 2.35 | | | | |
| | Husk | 0.46 | 0.54 | | | | 15666 | 13900 | | | | 0.08 | 0.14 | | | | | 0.44 | 0.90 | | | 0.20 | 0.25 | | | |
| Banana | Rachis | 0.10 | | | | | 7863 | | | | | 0.95 | | | | | | | | | | 1.00 | | | | |
| | Stem | 0.60 | | | | | 8836 | | | | | 0.94 | | | | | | | | | | 5.00 | | | | |
| | Rejected fruit | 0.05 | | | | | 10820 | | | | | 0.84 | | | | | | | | | | 0.15 | | | | |
| Plantain | Rachis | 0.19 | | | | | 7570 | | | | | 0.94 | | | | | | | | | | 1.00 | | | | |
| | Stem | 1.10 | | | | | 8508 | | | | | 0.93 | | | | | | | | | | 5.00 | | | | |
| | Rejected fruit | 0.08 | | | | | 10417 | | | | | 0.83 | | | | | | | | | | 0.15 | | | | |
| **Animal waste** | | **Animal waste (mio tons, wet)** | | | | | **Fresh manure (ton/head/year)** | | | | | **Biogas conversion ($m^3$/ton of fresh matter)** | | | | | **Technical availability for biomass energy production** | | | | | **Lower heating value biogas ($MJ/m^3$)** | | | | |
| Cattle | | 99.17 | | 210.0 | | | 4.42 | | 8.69 | | | | | 32.0 | | | | | 1.00 | | | | | 20.0 | | |
| Pork | | 2.80 | | | | | 0.75 | | 1.68 | | | | | 50.0 | | | | | 1.00 | | | | | 20.0 | | |
| Poultry | | 3.45 | | | | | 0.03 | | 0.02 | | | | | 91.0 | | | | | 1.00 | | | | | 20.0 | | |
| Equine | | | | 13.66 | | | | | 7.45 | | | | | 32.0 | | | | | 1.00 | | | | | 20.0 | | |
| **Forestry** | | **Production (mio tons, dry)** | | | | | **Lower heating value (kJ/kg, dry)** | | | | | **Moisture (wet base)** | | | | | **Technical availability for biomass energy production** | | | | | **By-product to product ratio** | | | | |
| Wood fuel | | | | | 2.80 | | | | | | | | | | | | | 1.00 | 1.00 | 1.00 | 1.00 | | | | | |
| Short rotation woody crops | | | | 0.70 | | | | 18517 | | | | | | | | | | 0.90 | 1.00 | 0.50 | | | | | | |
| Biomass from forest mgmt. | | | | 1.90 | | | | 18517 | | | | | | | | | | 0.90 | 1.00 | 0.50 | | | | | | |
| Not harvested forest growth | | | | | | | | 18517 | | | | | | | | | | | 1.00 | 0.50 | | | | | | |
| Forest residues | | | | 4.80 | 0.60 | | | 18517 | | | | | | | | | | 0.50 | 1.00 | 0.50 | | | 0.47 | 0.46 | 0.50 | |
| **Urban waste** | | **Overall potential (TJ/year)** | | | | | **Technical availability for biomass energy production** | | | | | | | | | | | | | | | | | | | |
| Residues from food market | | 91.7 | | | | | | | | | | | | | | | | | | | | | | | | |
| Pruning | | 318.1 | | | | | | | | | | | | | | | | | | | | | | | | |
| Landfill | | | | | | | | | | | | | | | | | | | | | | | | | | |

# Appendix for Chapter D

***Table 37.*** *Commodities considered in the model*

| Category | Type | Commodities | | Type of market | Compete for land | Price prediction by global scenarios and datasets | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | IIASA-FAO | World Bank | FAPRI |
| **Crops** | Permanent | Banana | | Domestic, imports and exports | ✓ | ✓ | ✓ | ✗ |
| | | Coffee | | Domestic, imports and exports | ✓ | ✓ | ✓ | ✗ |
| | | Plantain | | Domestic only | ✓ | ✓ | ✗ | ✗ |
| | | Palm oil | Oil | Domestic, imports and exports | ✓ | ✓ | ✓ | ✓ |
| | | | Biodiesel | Domestic and exports | ✓ | ✗ | ✗ | ✓ |
| | | Cane large | Sugar | Domestic, imports and exports | ✓ | ✓ | ✓ | ✓ |
| | | | Bioethanol | Domestic and exports | ✓ | ✗ | ✗ | ✓ |
| | Temporary | Cotton | | Domestic, imports and exports | ✓ | ✓ | ✓ | ✗ |
| | | Maize | | Domestic, imports and exports | ✓ | ✓ | ✓ | ✓ |
| | | Rice | | Domestic, imports and exports | ✓ | ✓ | ✓ | ✗ |
| | | Cane small (jaggery) | | Domestic only | ✓ | ✓ | ✗ | ✗ |
| **Livestock** | Cattle | Cattle meat | | Domestic, imports and exports | ✓ | ✓ | ✓ | ✓ |
| | | Milk | | Domestic only | ✓ | ✓ | ✗ | ✗ |
| | Chicken | Chicken meat | | Domestic, imports and exports | ✗ | ✓ | ✓ | ✓ |
| | | Eggs | | Domestic only | ✗ | ✓ | ✗ | ✗ |
| | Pigs | Pig meat | | Domestic, imports and exports | ✗ | ✓ | ✗ | ✓ |
| | Horse | Horse meat | | Domestic only | ✗ | ✓ | ✗ | ✗ |
| **Forestry** | Wood | Wood logs | | Domestic, imports and exports | ✓ | ✓ | ✓ | ✗ |

***Table 38.*** *Comparison of international FOB price of commodities for selected global scenarios and datasets (US$2005)*

| Constant US$2005 | Year | Bananas, US (US$/ton) | Bananas, EU (US$/ton) | Meat, beef (US c/kg) | Meat, chicken (US c/kg) | Coffee, Arabica (US c/kg) | Cotton (US c/kg) | Maize (US$/ton) | Palm oil (US$/ton) | Meat, pork (US$/ton) | Rice, Thailand, 5% (US$/ton) | Sugar, world (US c/kg) | Sugar, US (US c/kg) | Logs, Malaysia (US$/m3) | Anhydrous ethanol, Brazil (US$/gallon) | Biodiesel, Europe (US$/gallon) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **FAO-REF-00** | **2010** | 769 | 888 | 297 | 168 | 383 | 202 | 165 | 798 | 1079 | 433 | 42 | 70 | 246 | 1.93 | 3.73 |
| | **2015** | 675 | 988 | 290 | 144 | 287 | 186 | 141 | 595 | 1113 | 362 | 34 | 60 | 213 | 1.65 | 3.97 |
| | **2020** | 582 | 1089 | 284 | 120 | 192 | 169 | 118 | 392 | 1192 | 291 | 27 | 50 | 180 | 1.27 | 3.33 |
| | **2025** | 587 | 1100 | 288 | 121 | 197 | 174 | 119 | 395 | 1188 | 294 | 28 | 51 | 183 | 1.49 | 3.25 |
| | **2030** | 593 | 1110 | 292 | 123 | 202 | 179 | 120 | 399 | 1269 | 297 | 28 | 52 | 187 | 1.82 | 3.55 |
| **FAO-REF-01** | **2010** | 769 | 888 | 297 | 168 | 383 | 202 | 165 | 798 | 1079 | 433 | 42 | 70 | 246 | 1.93 | 3.73 |
| | **2015** | 694 | 1024 | 294 | 145 | 291 | 189 | 145 | 607 | 1113 | 372 | 35 | 61 | 215 | 1.69 | 4.01 |
| | **2020** | 620 | 1160 | 291 | 123 | 199 | 176 | 125 | 417 | 1192 | 310 | 28 | 52 | 184 | 1.35 | 3.44 |
| | **2025** | 628 | 1177 | 296 | 125 | 205 | 181 | 127 | 423 | 1188 | 315 | 29 | 53 | 188 | 1.59 | 3.39 |
| | **2030** | 637 | 1193 | 300 | 127 | 211 | 187 | 129 | 429 | 1269 | 319 | 30 | 55 | 193 | 1.94 | 3.71 |
| **WEO-V2** | **2010** | 769 | 888 | 297 | 168 | 383 | 202 | 165 | 798 | 1079 | 433 | 42 | 70 | 246 | 1.93 | 3.73 |
| | **2015** | 736 | 1103 | 307 | 151 | 302 | 199 | 153 | 636 | 1113 | 393 | 36 | 64 | 223 | 1.81 | 4.10 |
| | **2020** | 704 | 1318 | 316 | 134 | 222 | 196 | 142 | 474 | 1192 | 352 | 31 | 58 | 200 | 1.59 | 3.67 |
| | **2025** | 709 | 1328 | 319 | 135 | 227 | 201 | 143 | 477 | 1188 | 355 | 32 | 59 | 203 | 1.84 | 3.65 |
| | **2030** | 714 | 1338 | 322 | 136 | 231 | 205 | 144 | 481 | 1269 | 358 | 32 | 60 | 207 | 2.23 | 3.98 |
| **TAR-V1** | **2010** | 769 | 888 | 297 | 168 | 383 | 202 | 165 | 798 | 1079 | 433 | 42 | 70 | 246 | 1.93 | 3.73 |
| | **2015** | 808 | 1236 | 332 | 161 | 325 | 219 | 168 | 684 | 1113 | 428 | 39 | 70 | 239 | 2.04 | 4.24 |
| | **2020** | 846 | 1585 | 367 | 155 | 266 | 235 | 171 | 570 | 1192 | 424 | 37 | 69 | 233 | 2.08 | 4.04 |
| | **2025** | 853 | 1597 | 370 | 156 | 272 | 241 | 172 | 574 | 1188 | 427 | 38 | 71 | 235 | 2.41 | 4.08 |
| | **2030** | 860 | 1609 | 372 | 157 | 278 | 246 | 174 | 579 | 1269 | 431 | 39 | 72 | 238 | 2.92 | 4.45 |
| **FAPRI** | **2010** | 769 | 888 | 185 | 163 | 383 | 202 | 182 | 837 | 1079 | 433 | 50 | 69 | 246 | 1.93 | 3.73 |
| | **2015** | 694 | 1024 | 202 | 171 | 291 | 189 | 169 | 770 | 1113 | 372 | 42 | 53 | 215 | 1.80 | 4.16 |
| | **2020** | 620 | 1160 | 209 | 183 | 199 | 176 | 169 | 866 | 1192 | 310 | 46 | 52 | 184 | 2.15 | 4.61 |
| | **2025** | 628 | 1177 | 206 | 186 | 205 | 181 | 156 | 946 | 1188 | 315 | 42 | 49 | 188 | 2.03 | 4.86 |
| | **2030** | 637 | 1193 | 215 | 198 | 211 | 187 | 154 | 1055 | 1269 | 319 | 42 | 49 | 193 | 1.92 | 5.35 |
| **World Bank** | **2010** | 769 | 888 | 297 | 168 | 383 | 202 | 165 | 798 | 1079 | 433 | 42 | 70 | 246 | 1.93 | 3.73 |
| | **2015** | 749 | 864 | 254 | 167 | 308 | 183 | 175 | 665 | 1113 | 391 | 32 | 53 | 250 | 1.43 | 4.18 |
| | **2020** | 742 | 856 | 272 | 171 | 297 | 176 | 174 | 627 | 1192 | 377 | 31 | 52 | 277 | 1.50 | 4.25 |
| | **2025** | 708 | 817 | 285 | 175 | 277 | 163 | 167 | 569 | 1188 | 350 | 28 | 48 | 305 | 1.52 | 4.16 |
| | **2030** | 702 | 811 | 285 | 179 | 280 | 150 | 167 | 567 | 1269 | 353 | 29 | 49 | 278 | 1.85 | 4.44 |

***Table 39.*** *Minimum and maximum yearly growth for commodities*

| Commodities | Min. yearly growth | Max. yearly growth |
|---|---|---|
| Bananas (ha) [a,b] | 5500 | 6500 |
| Cattle meat (slaughtered animals) [b] | | 379620 |
| Area for cattle (ha) [b] | | 741000 |
| Chicken meat (animals) [b] | | 52458000 |
| Coffee (ha) [b] | 107658 | 67000 |
| Cotton (ha) [a,b] | | 17593 |
| Milk (animals) [b] | | 500000 |
| Hen (animals) [b] | | 3000000 |
| Horse (animals) [b] | | 10000 |
| Maize (ha) [a,b] | | 97267 |
| Palm oil (ha) [a,b] | 2500 | 24985 |
| Pig meat (animal) [b] | | 303420 |
| Plantain (ha) [a,b] | 27497 | 46200 |
| Rice (ha) [a,b] | | 82624 |
| Cane large (ha) [c] | 27371 | 35249 |
| Cane small (ha) [a,b] | | 13406 |
| Wood (ha) [b] | | 8712 |

**References:**

[a] (MinAgricultura, 2012), [b] (FAO, 2012b), [c] (Asocaña, 2011)

***Table 40.*** *Yields for different commodities*

| Yields | 2010 | 2015 | 2020 | 2025 | 2030 | Refs. on historical yields | Refs. on yield growth |
|---|---|---|---|---|---|---|---|
| Bananas (ton/ha) | 27.62 | 27.62 | 27.62 | 27.62 | 27.62 | 1961-1991 [d], 1992-2009 [c] | Time-series method |
| Cattle meat (kg/animal) | 215.82 | 218.94 | 222.11 | 225.33 | 228.59 | 1961-2009 [d] | [e] |
| Cattle density (animals/ha) | 0.78 | 0.80 | 0.83 | 0.86 | 0.89 | 1961-2009 [d] | Time-series method |
| Chicken meat, carcass weight (kg/animal) | 1.77 | 1.84 | 1.92 | 2.00 | 2.08 | 1961-2009 [d] | [e] |
| Coffee (ton/ha) | 0.96 | 1.00 | 1.03 | 1.07 | 1.10 | 1961-2009 [d] | Time-series method |
| Cotton (ton/ha) | 0.79 | 0.86 | 0.93 | 1.01 | 1.09 | 2006-2009 [c] | [e] |
| Cow milk, fresh (ton/animal) | 1.43 | 1.45 | 1.47 | 1.49 | 1.51 | 1961-2009 [d] | [e] |
| Hen eggs, in shell (kg/animal) | 19.67 | 19.89 | 20.11 | 20.33 | 20.55 | 1961-2009 [d] | [e] |
| Horse meat, carcass weight (kg/animal) | 125.00 | 125.00 | 125.00 | 125.00 | 125.00 | 1961-2009 [d] | [e] |
| Maize (ton/ha) | 2.24 | 2.38 | 2.52 | 2.68 | 2.84 | 1961-1986 [d], 1987-2009 [c] | [e] |
| Palm oil, oil (ton/ha) | 3.58 | 3.73 | 3.89 | 4.05 | 4.20 | 1961-1986 [d], 1987-2009 [c] | Time-series method |
| Pig meat, carcass weight (kg/animal) | 80.18 | 82.10 | 84.07 | 86.09 | 88.15 | 1961-2009 [d] | [e] |
| Plantain (ton/ha) | 7.96 | 8.32 | 8.67 | 9.02 | 9.37 | 1961-1986 [d], 1987-2009 [c] | Time-series method |
| Rice, milled (ton/ha)[a] | 4.04 | 4.24 | 4.44 | 4.65 | 4.87 | 1961-1986 [d], 1987-2009 [c] | [e] |
| Sugar (ton/ha) | 13.60 | 14.18 | 14.76 | 15.34 | 15.92 | 1986-2009 [f] | Time-series method |
| Jaggery (ton/ha) | 6.09 | 6.09 | 6.09 | 6.09 | 6.09 | 1987-2009 [c] | Time-series method |
| Palm oil, fresh fruit (ton/ha) | 19.61 | 20.20 | 20.80 | 21.39 | 21.98 | 1961-2009 [d] | Time-series method |
| Cane large (ton/ha) | 117.33 | 117.51 | 117.51 | 117.51 | 117.51 | 1986-2009 [f] | [e] |
| Cane small (ton/ha) | 83.84 | 88.93 | 94.33 | 100.06 | 106.14 | 2009 [g] | [e] |
| Wood ($m^3$/ha) | 36.04 | 36.95 | 37.88 | 38.84 | 39.82 | 2009 [h] | Assumed |
| Anhydrous Ethanol (liters/ton-cane) | 83.82 | 85.59 | 87.54 | 89.53 | 91.56 | 2006-2009 [i,j] | Calculated |
| Anhydrous Ethanol (liters/ha) | 9835 | 10058 | 10286 | 10520 | 10759 | Calculated | [b] |
| Biodiesel (liters/ton fresh fruit) | 185.22 | 188.96 | 192.95 | 197.19 | 201.67 | 2009 [i,j] | Calculated |
| Biodiesel (liters/ha) | 3633 | 3818 | 4013 | 4217 | 4432 | Calculated | [b] |
| Bioethanol from molasses (liters/ton-cane) | 12.62 | 13.14 | 13.68 | 14.22 | 14.75 | [k,l] | [b] |

**References and notes:**

[a] Assumed to be 75% of paddy yield according to (Fedearroz, 2012).

[b] (Eisentraut, 2010).

[c] (MinAgricultura, 2012).

[d] (FAO, 2012b)

[e] (FAO, 2003)

[f] (Asocaña, 2011)

[g] (Osorio Cadavid, 2007)

[h] (UPME, 2005)

[i] (UPME, 2011b)

[j] (Fedebiocombustibles, 2012)

[k] (Masera Cerutti, et al., 2006)

[l] (Nguyen & Gheewala, 2008)

## *Table 41. Demand per capita for different commodities*

| | Year | Bananas (kg/person/year) | Bovine Meat (kg/person/year) | Chicken Meat (kg/person/year) | Coffee, green (kg/person/year) | Cotton (kg/person/year) | Milk, Whole (kg/person/year) | Eggs (kg/person/year) | Horse meat (kg/person/year) | Maize (kg/person/year) | Palm oil (kg/person/year) | Pig meat (kg/person/year) | Plantains (kg/person/year) | Rice, milled (kg/person/year) | Sugar (kg/person/year) | Jaggery (kg/person/year) | Ind. round wood ($m^3$/person/year) | Wood fuel ($m^3$/person/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **FAO-REF-00** | **2010** | 2.64 | 19.52 | 23.06 | 1.29 | 1.99 | 163.85 | 12.93 | 0.15 | 100.11 | 12.53 | 4.19 | 58.81 | 51.90 | 39.47 | 26.91 | 0.052 | 0.191 |
| | **2015** | 2.75 | 21.76 | 27.26 | 1.29 | 1.99 | 179.14 | 14.13 | 0.15 | 109.09 | 14.24 | 4.56 | 60.71 | 56.56 | 40.68 | 27.74 | 0.052 | 0.185 |
| | **2020** | 2.83 | 24.26 | 32.22 | 1.39 | 1.99 | 195.85 | 15.45 | 0.15 | 118.88 | 16.19 | 4.96 | 62.67 | 61.63 | 41.83 | 28.53 | 0.052 | 0.186 |
| | **2025** | 2.90 | 27.05 | 38.08 | 1.50 | 1.99 | 214.13 | 16.89 | 0.15 | 127.93 | 18.41 | 5.40 | 64.70 | 66.33 | 43.01 | 29.33 | 0.052 | 0.186 |
| | **2030** | 2.98 | 30.16 | 45.01 | 1.62 | 1.99 | 234.10 | 18.47 | 0.15 | 137.68 | 20.93 | 5.88 | 66.79 | 71.38 | 44.22 | 30.16 | 0.052 | 0.186 |
| **FAO-REF-01** | **2010** | 2.64 | 19.52 | 23.06 | 1.29 | 1.99 | 163.85 | 12.93 | 0.15 | 99.66 | 12.53 | 4.19 | 58.81 | 51.67 | 39.47 | 26.91 | 0.052 | 0.191 |
| | **2015** | 2.75 | 21.76 | 27.26 | 1.29 | 1.99 | 179.14 | 14.13 | 0.15 | 106.16 | 14.24 | 4.56 | 60.71 | 55.04 | 40.68 | 27.74 | 0.052 | 0.185 |
| | **2020** | 2.83 | 24.26 | 32.22 | 1.39 | 1.99 | 195.85 | 15.45 | 0.15 | 113.09 | 16.19 | 4.96 | 62.67 | 58.63 | 41.83 | 28.53 | 0.052 | 0.186 |
| | **2025** | 2.90 | 27.05 | 38.08 | 1.50 | 1.99 | 214.13 | 16.89 | 0.15 | 118.79 | 18.41 | 5.40 | 64.70 | 61.59 | 43.01 | 29.33 | 0.052 | 0.186 |
| | **2030** | 2.98 | 30.16 | 45.01 | 1.62 | 1.99 | 234.10 | 18.47 | 0.15 | 124.78 | 20.93 | 5.88 | 66.79 | 64.69 | 44.22 | 30.16 | 0.052 | 0.186 |
| **WEO-V2** | **2010** | 2.64 | 19.52 | 23.06 | 1.29 | 1.99 | 163.85 | 12.93 | 0.15 | 98.65 | 12.53 | 4.19 | 58.81 | 51.14 | 39.47 | 26.91 | 0.052 | 0.191 |
| | **2015** | 2.75 | 21.76 | 27.26 | 1.29 | 1.99 | 179.14 | 14.13 | 0.15 | 99.86 | 14.24 | 4.56 | 60.71 | 51.78 | 40.68 | 27.74 | 0.052 | 0.185 |
| | **2020** | 2.83 | 24.26 | 32.22 | 1.39 | 1.99 | 195.85 | 15.45 | 0.15 | 101.10 | 16.19 | 4.96 | 62.67 | 52.42 | 41.83 | 28.53 | 0.052 | 0.186 |
| | **2025** | 2.90 | 27.05 | 38.08 | 1.50 | 1.99 | 214.13 | 16.89 | 0.15 | 104.67 | 18.41 | 5.40 | 64.70 | 54.27 | 43.01 | 29.33 | 0.052 | 0.186 |
| | **2030** | 2.98 | 30.16 | 45.01 | 1.62 | 1.99 | 234.10 | 18.47 | 0.15 | 108.37 | 20.93 | 5.88 | 66.79 | 56.19 | 44.22 | 30.16 | 0.052 | 0.186 |
| **TAR-V1** | **2010** | 2.64 | 19.52 | 23.06 | 1.29 | 1.99 | 163.85 | 12.93 | 0.15 | 96.84 | 12.53 | 4.19 | 58.81 | 50.21 | 39.47 | 26.91 | 0.052 | 0.191 |
| | **2015** | 2.75 | 21.76 | 27.26 | 1.29 | 1.99 | 179.14 | 14.13 | 0.15 | 89.41 | 14.24 | 4.56 | 60.71 | 46.36 | 40.68 | 27.74 | 0.052 | 0.185 |
| | **2020** | 2.83 | 24.26 | 32.22 | 1.39 | 1.99 | 195.85 | 15.45 | 0.15 | 82.55 | 16.19 | 4.96 | 62.67 | 42.80 | 41.83 | 28.53 | 0.052 | 0.186 |
| | **2025** | 2.90 | 27.05 | 38.08 | 1.50 | 1.99 | 214.13 | 16.89 | 0.15 | 80.06 | 18.41 | 5.40 | 64.70 | 41.51 | 43.01 | 29.33 | 0.052 | 0.186 |
| | **2030** | 2.98 | 30.16 | 45.01 | 1.62 | 1.99 | 234.10 | 18.47 | 0.15 | 77.65 | 20.93 | 5.88 | 66.79 | 40.26 | 44.22 | 30.16 | 0.052 | 0.186 |
| **World Bank** | **2010** | 2.64 | 19.52 | 23.06 | 1.29 | 1.99 | 163.85 | 12.93 | 0.15 | 99.66 | 12.53 | 4.19 | 58.81 | 51.67 | 39.47 | 26.91 | 0.052 | 0.191 |
| | **2015** | 2.75 | 21.76 | 27.26 | 1.29 | 1.99 | 179.14 | 14.13 | 0.15 | 106.16 | 14.24 | 4.56 | 60.71 | 55.04 | 40.68 | 27.74 | 0.052 | 0.185 |
| | **2020** | 2.83 | 24.26 | 32.22 | 1.39 | 1.99 | 195.85 | 15.45 | 0.15 | 113.09 | 16.19 | 4.96 | 62.67 | 58.63 | 41.83 | 28.53 | 0.052 | 0.186 |
| | **2025** | 2.90 | 27.05 | 38.08 | 1.50 | 1.99 | 214.13 | 16.89 | 0.15 | 118.79 | 18.41 | 5.40 | 64.70 | 61.59 | 43.01 | 29.33 | 0.052 | 0.186 |
| | **2030** | 2.98 | 30.16 | 45.01 | 1.62 | 1.99 | 234.10 | 18.47 | 0.15 | 124.78 | 20.93 | 5.88 | 66.79 | 64.69 | 44.22 | 30.16 | 0.052 | 0.186 |
| **References on historical data** | | [b c] | [c] | [c] | [c] | [b] | [c] | [c] | [c] | [b c] | [b c] | [c] | [b c] | [b c] | [e] | [b] | [c] | [c] |
| **References on growth** | | [d] | [f] | [f] | [d] | Time-series | [f] | [f] | Time-series | [a] | [f] | [f] | [f] | [a] | [d] | [d] | Time-series | Time-series |

**References and notes:**

[a] (Fischer, 2011)
[b] (MinAgricultura, 2012)
[c] (FAO, 2012b)
[d] (FAO, 2003)
[e] (Asocaña, 2011)
[f] (FAO, 2006)

***Table 42.*** *Production cost in current prices (non-discounted)*

| | **Production cost in 2009 (US$, current prices)** | | | | | | | | | **Predicted production costs (US$, current prices)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Labor** | **Seed** | **Fertilizers** | **Fixed** | **Extraction and transport** | **Cost per animal** | **Consumables** | **Other op. costs** | **Total** | **2010** | **2015** | **2020** | **2025** | **2030** |
| Bananas (US$/ton) [b] | 146 | 26 | 34 | 88 | 0 | 0 | 0 | 0 | 294 | 339 | 394 | 404 | 422 | 466 |
| Bovine meat (US$/ton) [b o] | 151 | 0 | 0 | 123 | 0 | 669 | 63 | 525 | 1531 | 1817 | 2207 | 2287 | 2358 | 2575 |
| Chicken meat (US$/ton) [b q] | 59 | 0 | 0 | 144 | 0 | 214 | 980 | 378 | 1775 | 2098 | 2493 | 2519 | 2533 | 2698 |
| Coffee, green (US$/ton) [b j] | 1246 | 84 | 568 | 426 | 0 | 0 | 0 | 0 | 2325 | 2564 | 2744 | 2622 | 2652 | 2821 |
| Cotton (US$/ton) [b c] | 594 | 292 | 223 | 826 | 0 | 0 | 0 | 0 | 1935 | 2202 | 2393 | 2265 | 2189 | 2233 |
| Milk (US$/ton) [b] | 57 | 36 | 0 | 90 | 0 | 0 | 114 | 0 | 297 | 353 | 426 | 442 | 455 | 497 |
| Eggs (US$/ton) [b] | 104 | 0 | 0 | 179 | 0 | 137 | 1298 | 0 | 1719 | 2043 | 2493 | 2593 | 2682 | 2940 |
| Horse meat (US$/ton) [d] | 0 | 0 | 0 | 0 | 0 | 460 | 0 | 0 | 460 | 548 | 678 | 713 | 746 | 826 |
| Maize (US$/ton) [b] | 50 | 24 | 50 | 95 | 0 | 0 | 0 | 0 | 219 | 244 | 261 | 245 | 241 | 250 |
| Palm oil (US$/ton) [b f k l] | 213 | 12 | 139 | 162 | 70 | 0 | 0 | 0 | 596 | 623 | 672 | 641 | 645 | 683 |
| Pig meat (US$/ton) [b p] | 191 | 0 | 0 | 168 | 0 | 367 | 971 | 1189 | 2886 | 3421 | 4122 | 4232 | 4322 | 4676 |
| Plantains (US$/ton) [b] | 55 | 17 | 31 | 67 | 0 | 0 | 0 | 0 | 171 | 191 | 210 | 203 | 204 | 217 |
| Rice, milled (US$/ton) [b e] | 33 | 55 | 79 | 203 | 0 | 0 | 0 | 0 | 370 | 415 | 456 | 435 | 434 | 456 |
| Sugar (US$/ton) [b g m] | 15 | 10 | 21 | 71 | 96 | 0 | 0 | 229 | 442 | 516 | 603 | 603 | 606 | 647 |
| Jaggery (US$/ton) [b n] | 107 | 22 | 41 | 64 | 0 | 0 | 0 | 224 | 458 | 534 | 635 | 655 | 685 | 757 |
| Wood (US$/$m^3$) [h] | 23 | 0 | 0 | 11 | 0 | 0 | 4 | 0 | 37 | 44 | 51 | 53 | 54 | 58 |
| Ethanol (US$/liter) [b g l m] | 0.02 | 0.01 | 0.03 | 0.14 | 0.13 | 0.00 | 0.02 | 0.10 | 0.45 | 0.50 | 0.59 | 0.60 | 0.61 | 0.66 |
| Ethanol from molasses (US$/liter)[a] | 0.01 | 0.01 | 0.01 | 0.07 | 0.06 | 0.00 | 0.02 | 0.10 | 0.27 | 0.30 | 0.35 | 0.35 | 0.36 | 0.38 |
| Biodiesel (US$/liter) [b f k l] | 0.24 | 0.01 | 0.13 | 0.15 | 0.06 | 0.00 | 0.02 | 0.01 | 0.63 | 0.71 | 0.79 | 0.77 | 0.79 | 0.85 |

**References and notes:**

[a] Calculated assuming yield of 12 liter ethanol/ton-cane
[b] (CCI, 2012)
[c] (MinAgricultura, 2012)
[d] (FAO, 2012b)
[e] (Fedearroz, 2012)
[f] (Fedepalma, 2012)
[g] (Asocaña, 2011)
[h] (UPME, 2005)
[i] (DNP, 2008)
[j] (Federación Nacional de Cafeteros, 2005)
[k] (FAO, 2010)
[l] (CORPODIB, 2003)
[m] (Montoya Rodríguez & Quintero Suárez, 2005)
[n] (Rodríguez, García, Roa Diaz, & Santacoloma, 2004)
[o] (Fedegan, 2012)
[p] (Castellanos, et al., 2011)
[q] (Finagro, 2012)

***Table 43.*** *Domestic price of commodities (current prices, non-discounted)*

| | Min. margin (% prod. cost) | Correlation between historical prices and intl. prices or price index (in current US$) | R$^2$ | Ref. | Future domestic price $\left(\pi_{i,j}^{D}\right)_{Final}$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **2009** | **2010** | **2015** | **2020** | **2025** | **2030** |
| Bananas (US$/ton) | 10.9% | $\pi_i^D = 35.91 + \left(0.29 \cdot \pi_i^{FOB,Europe}\right)\ [US\$/ton]$ | 0.7 | b c | 370 | 376 | 438 | 448 | 468 | 517 |
| Meat, beef (US$/ton) | 69.8% | $\pi_i^D = \pi_{i-1}^D \cdot (PIC_i/PIC_{i-1})\ [US\$/ton]$ | 0.95 | b c | 3,029 | 3,611 | 4,469 | 4,698 | 4,914 | 5,444 |
| Meat, chicken (US$/ton) | 18.8% | $\pi_i^D = \pi_{i-1}^D \cdot (PIC_i/PIC_{i-1})\ [US\$/ton]$ | 0.98 | b c | 2,121 | 2,528 | 3,129 | 3,289 | 3,440 | 3,811 |
| Coffee, arabica (US$/ton) | 9.4% | $\pi_i^D = 258.32 + \left(0.68 \cdot \pi_i^{FOB}\right)\ [US\$/ton]$ | 0.87 | b | 2,542 | 3,214 | 3,001 | 2,868 | 2,901 | 3,086 |
| Cotton (US$/ton) | 12.8% | $\pi_i^D = 121.13 + \left(0.97 \cdot \pi_i^{FOB}\right)\ [US\$/ton]$ | 0.87 | b g | 2,184 | 2,485 | 2,700 | 2,557 | 2,470 | 2,520 |
| Milk (US$/ton) | 79.6% | $\pi_i^D = \pi_{i-1}^D \cdot (PIC_i/PIC_{i-1})\ [US\$/ton]$ | 0.97 | b c | 732 | 872 | 1,079 | 1,135 | 1,187 | 1,315 |
| Eggs (US$/ton) | 7.0% | $\pi_i^D = \pi_{i-1}^D \cdot (PIC_i/PIC_{i-1})\ [US\$/ton]$ | 0.98 | b c | 1,862 | 2,219 | 2,747 | 2,888 | 3,020 | 3,346 |
| Horse (US$/ton) | 0.0% | $\pi_i^D = \pi_{i-1}^D \cdot (PIC_i/PIC_{i-1})\ [US\$/ton]$ | N.A. | b c | 460 | 548 | 678 | 713 | 746 | 826 |
| Maize (US$/ton) | 44.0% | $\pi_i^D = 93.51 + \left(1.70 \cdot \pi_i^{FOB}\right)\ [US\$/ton]$ | 0.86 | b c | 376 | 410 | 383 | 353 | 348 | 360 |
| Palm oil (US$/ton) | 18.2% | $\pi_i^D = \pi_i^{FOB} \cdot (1 + tariff_i)\ [US\$/ton]$ | N.A. | b e | 730 | 901 | 795 | 758 | 762 | 807 |
| Pork meat (US$/ton) | 5.0% | $\pi_i^D = \pi_{i-1}^D \cdot (PIC_i/PIC_{i-1})\ [US\$/ton]$ | 0.96 | b c | 3,030 | 3,592 | 4,328 | 4,443 | 4,587 | 5,082 |
| Plantains (US$/ton) | 124.6% | $\pi_i^D = \pi_{i-1}^D \cdot (PIC_i/PIC_{i-1})\ [US\$/ton]$ | 0.96 | b c | 408 | 487 | 602 | 633 | 662 | 734 |
| Rice, Thailand, 5% (US$/ton) | 101.5% | $\pi_i^D = \pi_i^{FOB} \cdot (1 + tariff_i)\ [US\$/ton]$ | N.A. | b d | 932 | 877 | 919 | 877 | 875 | 919 |
| Sugar, world (US$/ton) | 41.2% | $\pi_i^D = 202.24 + \left(1.94 \cdot \pi_{i-1}^{FOB,world}\right)\ [US\$/ton]$ | 0.93 | b c | 800 | 982 | 1,034 | 866 | 857 | 913 |
| Panela (US$/ton) | 8.2% | $\pi_i^D = 22.64 + \left(2.05 \cdot \pi_{i-1}^{FOB,sugar\ w.}\right)\ [US\$/ton]$ | 0.74 | b c | 496 | 845 | 899 | 722 | 742 | 819 |
| Wood (US$/m$^3$) | 20.0% | $\pi_i^D = \pi_{i-1}^D \cdot (PIC_i/PIC_{i-1})\ [US\$/ton]$ | - | b c | 62 | 73 | 91 | 96 | 100 | 111 |
| Ethanol (US$/liter) | [a] | $\pi_i^D = 0.16 + \left(0.002 \cdot \pi_{i-1}^{FOB,sugar\ w.}\right)\ [US\$/ton]$ | 0.91 | b f | 0.806 | 0.959 | 1.012 | 0.840 | 0.843 | 0.915 |
| Biodiesel (US$/liter) | [a] | $\pi_i^D = 0.41 + \left(0.0008 \cdot \pi_i^{FOB,palm\ oil}\right)\ [US\$/ton]$ | 0.92 | b f | 0.940 | 1.133 | 1.140 | 1.185 | 1.228 | 1.332 |

**References and notes:**

[a] The minimum margin for the producer of biofuels in Colombia is regulated by the Ministry of Mines and Energy. The method used to calculate the minimum margin is explained in (DNP, 2008). Basically, a minimum price of 1187 COL/liter for ethanol and 1729 COL/liter for biodiesel in 2008 prices should be updated according to the price index for Colombia (using a 70% factor) and the exchange rate (using a 30% factor).

[b] (World Bank, 2012)

[c] (MinAgricultura, 2012)

[d] (Fedearroz, 2012)

[e] (Fedepalma, 2012)

[f] (UPME, 2012a)

[g] (BVC, 2012)

***Table 44.*** *Price sensitivity coefficient*

| | Price sensitivity coefficient |
|---|---|
| Bananas | 3.0 |
| Cattle Meat | 2.0 |
| Chicken meat | 2.0 |
| Coffee | 3.0 |
| Cotton | 1.2 |
| Maize | 3.0 |
| Palm oil | 3.0 |
| Pig meat | 2.0 |
| Rice | 2.0 |
| Sugar | 4.0 |
| Wood | 3.0 |

***Table 45.** Assumptions about trade and estimated price of imported commodities*

| **Commodities** | **Assumptions about international trade** | | | | | | **Calculated price of imported commodities ($\pi_{i,j}^{I1}$ in current prices, non-discounted)** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Transport cost in 2009 (US$/ton)[f]** | **Tariff in 2009 (% of CIF)[e]** | **Assumption about model import tariffs** | **Year for phase-out tariffs[d]** | **TRQ in 2012 (ton)[d]** | **TRQ yearly increase (%)[d]** | **2010** | **2015** | **2020** | **2025** | **2030** | **Units** |
| Banana | 186.5 | | No tariff | | | | 1522 | 1458 | 1286 | 1335 | 1339 | US$/ton |
| Coffee | 251.9 | | No tariff | | | | 6594 | 5366 | 3683 | 3885 | 3939 | US$/ton |
| Plantain | 132.6 | | No tariff | | | | 0 | 0 | 0 | 0 | 0 | - |
| Palm oil | 109.0 | 7%[a] | Depends on intl. price of palm oil[a] | | | | 1457 | 1268 | 967 | 998 | 1030 | US$/ton |
| Biodiesel | 25.8 | 100%[c] | Constant | | | | 3 | 4 | 3 | 3 | 3 | US$/liter |
| Sugar | 85.0 | 100% | Constant | | | | 1599 | 1449 | 1185 | 1246 | 1266 | US$/ton |
| Bioethanol | 25.8 | 100%[c] | Constant | | | | 2 | 2 | 1 | 1 | 2 | US$/liter |
| Cotton | 78.7 | 10% | Gradually decrease until phase-out | 2013 | | | 3747 | 3342 | 3033 | 3209 | 3253 | US$/ton |
| Maize | 35.9 | 3% | Gradually decrease until phase-out | 2012 | 2100000 | 5 | 325 | 300 | 257 | 267 | 268 | US$/ton |
| Rice | 35.9 | 68%[b] | Depends on intl. price of rice[b] | 2030 | 79000 | 4.5 | 1357 | 1288 | 1006 | 812 | 577 | US$/ton |
| Jaggery | 85.0 | | No tariff | | | | 0 | 0 | 0 | 0 | 0 | - |
| Cattle meat | 142.4 | 80% | Gradually decrease until phase-out | 2022 | 2100 | 5 | 9070 | 6986 | 5578 | 5322 | 5329 | US$/ton |
| Milk | 139.6 | 20% | Gradually decrease until phase-out | 2028 | 5500 | 10 | 0 | 0 | 0 | 0 | 0 | - |
| Chicken meat | 142.4 | 164% | Gradually decrease until phase-out | 2030 | 27040 | 4 | 7759 | 7164 | 5397 | 4004 | 2383 | US$/ton |
| Eggs | 139.6 | | No tariff | | | | 0 | 0 | 0 | 0 | 0 | - |
| Pig meat | 142.4 | 200% | Gradually decrease until phase-out | 2022 | | | 5891 | 5156 | 3176 | 2331 | 2451 | US$/ton |
| Horse meat | 142.4 | | No tariff | | | | 0 | 0 | 0 | 0 | 0 | - |
| Wood logs | 139.0 | | No tariff | | | | 580 | 560 | 498 | 520 | 528 | US$/m$^3$ |

**References and notes**

[a] Regression used: if Int. palm oil price ≥ 867 $/ton then tariff (%) = 0, otherwise tariff (%) = 32.79 - (0.03*Int. palm oil price [$/ton]). Based on statistics from (World Bank, 2012; CCI, 2012; Finagro, 2012).

[b] Regression used in period 2010-2018: tariff (%) = 163.06 - (0.17*intl. price of rice [$/ton]). A linear decrease is used in period 2018-2030. Based on statistics from (World Bank, 2012; CCI, 2012; Finagro, 2012).[c] No information is found on tariffs for biofuels. A constant tariff of 100% is assumed.

[d] (USDA, 2012)

[e] (Finagro, 2012)

[f] (OECD, 2012)

# Appendix for Chapter E

***Table 46.** Questions formulated in the first survey and responses from experts*

| **Questions** | | **Possible answers** | **Response** |
|---|---|---|---|
| 1 | Country of origin | | Colombia (91%), Ecuador (4.5%), Portugal (4.5%) |
| 2 | Field of expertise | a) Biofuels, b) power generation, c) biofuels and power generation, d) other | Biofuels and/or power generation (82%), other (18%) |
| 3 | Affiliation | a) University or R&D, b) industry, c) government, d) international organization or non-governmental organization, e) other | University and R&D (62%), industry (24%), government (10%), IO/NGO (5%) |
| 4 | Would you like to participate on behalf of your institution or on your own behalf? | a) Institution, b) own behalf | Institution (40%), own behalf (60%) |
| 5 | Do you work or have worked on the design of energy policies? | a) Yes, b) no | Yes (59%), no (41%) |
| 6 | How would you describe the current market conditions to: | a) Very good/good, b) neither good nor poor, c) poor/very poor | |
| | a. Produce bioethanol? | | Very good/good (68%), neither good nor poor (32%), poor/very poor (0%) |
| | b. Produce biodiesel? | | Very good/good (68%), neither good nor poor (23%), poor/very poor (9%) |
| | c. Generate biomass-based power and combined heat and power (CHP)? | | Very good/good (19%), neither good nor poor (32%), poor/very poor (50%) |
| 7 | How would you describe the current technologies used in Colombia to: | a) Very good/good, b) neither good nor poor, c) poor/very poor | |
| | a. Produce bioethanol? | | Very good/good (64%), neither good nor poor (32%), poor/very poor (5%) |
| | b. Produce biodiesel? | | Very good/good (64%), neither good nor poor (32%), poor/very poor (5%) |
| | c. Generate biomass-based power and CHP? | | Very good/good (10%), neither good nor poor (41%), poor/very poor (50%) |
| 8 | How would you describe the effectiveness of the current policy framework to: | a) Very good/good, b) neither good nor poor, c) poor/very poor | |
| | a. Produce bioethanol? | | Very good/good (55%), neither good nor poor (23%), poor/very poor (23%) |
| | b. Produce biodiesel? | | Very good/good (54%), neither good nor poor (18%), poor/very poor (28%) |
| | c. Generate biomass-based power and CHP? | | Very good/good (5%), neither good nor poor (23%), poor/very poor (73%) |
| 9 | Do you think bioenergy should be promoted in the future? | a) Yes, b) no | Yes (100%) |
| 10 | Please select the top-3 reasons why bioenergy should be supported | a) Reduce GHG emissions, b) enhance energy security, c) create jobs, d) promote rural development, e) other. | |
| | a. 1st reason | | Promote rural development (30.3%) |
| | b. 2nd reason | | Enhance energy security (25.8%) |
| | c. 3rd reason | | Reduce GHG emissions (21.2%) |
| 11 | Please select the top-3 national energy targets that you expect will be implemented over 2014-2030 in Colombia. | a) Reduce GHG emissions below 1990 levels, b) increase share of renewable power generation (exc. Large hydro), c) increase share of biofuels of road transport fuel, d) reduce the volume of imported fossil fuels, e) increase energy efficiency, f) increase access to electricity in non-interconnected zones, g) other | |
| | a. 1st national energy target | | Increase energy efficiency nationwide (22.8%) |
| | b. 2nd national energy target | | Increase share of biofuels in road transport fuel (19.7%) |
| | c. 3rd national energy target | | Increase share of renewable power generation, exc. large hydro (16.7%) |

*Questions formulated in the first survey and responses from experts (continuation)*

| **Questions** | | **Possible answers** | **Response** |
|---|---|---|---|
| 12 | Please select the top-3 key barriers to further deploy bioethanol | a) Low price of bioethanol, b) lack of political support, c) potential market threat from imported duty-free ethanol, d) limitations in technology, e) limited production capacity, f) limited infrastructure for expansion, g) limited infrastructure for transporting ethanol, h) limited success of current policy framework, i) lack of clear targets and strategic planning, j) lack of public acceptance, k) other | |
| | a. 1st key barrier | | Lack of clear targets and strategic planning (21.7%) |
| | b. 2nd key barrier | | Limitations in technologies to produce bioethanol (11.7%) |
| | c. 3rd key barrier | | Others (11.7%) |
| 13 | Please select the top-3 key barriers to further deploy biodiesel | a) Low price of biodiesel, b) lack of political support, c) potential market threat from imported duty-free biodiesel, d) limitations in technology, e) limited production capacity, f) limited infrastructure for expansion, g) limited infrastructure for transporting biodiesel, h) limited success of current policy framework, i) lack of clear targets and strategic planning, j) lack of public acceptance, k) other | |
| | a. 1st key barrier | | Lack of clear targets and strategic planning (17%) |
| | b. 2nd key barrier | | Limited production capacity that covers only domestic market (17%) |
| | c. 3rd key barrier | | Others (15.2%) |
| 14 | Please select the top-3 key barriers to further deploy biomass-based power generation | a) Low price of electricity, b) lack of political support, c) competition with subsidized diesel-based generation in NIZ, d) limitations in technology, e) high cost of technologies, f) limited infrastructure for transporting biomass, g) perception that hydro power is the best solution, h) limited success of current policies, i) lack of clear targets and strategic planning, j) lack of public acceptance, k) other. | |
| | a. 1st key barrier | | Lack of clear targets and strategic planning (19.3%) |
| | b. 2nd key barrier | | High cost of power generation equipment (17.5%) |
| | c. 3rd key barrier | | Competition with subsidized diesel-based generation in NIZ (15.8%) |

***Table 47.*** *Questions formulated in the second survey*

**Part 1: Information about the participant**

This part intends to collect information about the expertise of the survey's participant

| | **Question** | **Possible answers** |
|---|---|---|
| 1 | Please select your level of expertise on biomass-based power generation | a) excellent, b) above average, c) average, d) below average, e) poor |
| 2 | Please select your level of expertise on biofuels | a) excellent, b) above average, c) average, d) below average, e) poor |
| 3 | Please select your level of expertise on energy policy | a) excellent, b) above average, c) average, d) below average, e) poor |

**Part 2: Increase share of renewable power generation**

This part intends to identify concrete goals and specific pathways for the target of increasing share of renewable power generation (excluding hydro power >10 MW)

| | **Question** | **Possible answers** |
|---|---|---|
| 4 | Please select the percentage of total electricity that you think should be generated from renewable energy sources (excluding hydro power > 10 MW) | a) 2.5%, b) 5%, c) 7.5%, d) 10%, e) other |
| 5 | Please select the year at which you expect this target to be accomplished | a) 2015, b) 2020, c) 2025, d) 2030 |
| 6 | Please select the top-3 technology scenarios to generate biomass-based power and CHP that you expect to be implemented to achieve this target | a) Biomass fired CHP plants using condensing-extraction steam turbines, b) Biomass fired organic Rankine cycle (ORC) power plants, c) Biomass gasification and syngas combustion in reciprocating gas engines, d) Biomass gasification and syngas combustion in gas turbines, e) Biomass co-firing (up to 10% by volume) in existing coal power plants, f) Combustion of landfill gas in reciprocating engines, g) Anaerobic digestion and biogas combustion in reciprocating engines, h) other |
| | a. 1st scenario | |
| | b. 2nd scenario | |
| | c. 3rd scenario | |
| 7 | Do you think a new policy framework is necessary to support renewable power generation (excluding hydro power > 10 MW)? | a) yes, b) no |
| 8 | If the answer to the previous question is positive, please select the option that you consider most appropriate for Colombia | a) feed-in-tariff, b) Renewable Energy Portfolio Standard, c) National Renewable Energy Auction, d) Net metering, e) Renewable Energy Certificates, f) Other, g) Do not know |

**Part 3: Increase share of biofuels in road transport fuel (bioethanol)**

This part intends to identify concrete goals and specific pathways for the target of increasing share of bioethanol in the road transport fuel

| | **Question** | **Possible answers** |
|---|---|---|
| 9 | Please select the percentage quota mandate of bioethanol in gasohol (volume basis) | a) E12, b) E15, c) E20, d) E25, e) hE15 (15% hydrous ethanol), f) he100 (pure hydrous ethanol), g) other |
| 10 | Please select the year at which you expect this target to be accomplished | a) 2015, b) 2020, c) 2025, d) 2030 |
| 11 | Please select the top-3 technology scenarios to produce bioethanol that you expect to be implemented to achieve this target | a) cane-based bioethanol with standard fermentation and distillation,<br>b) cane-based bioethanol with improved fermentation and distillation,<br>c) small-scale cane-based bioethanol with batch fermentation and distillation,<br>d) bioethanol from alternative feedstock (cassava, beet, etc.),<br>e) lignocellulosic bioethanol, f) other |
| | a. 1st scenario | |
| | b. 2nd scenario | |
| | c. 3rd scenario | |
| 12 | Do you think the existing policy framework to support bioethanol production should be modified? | a) yes, b) no |
| 13 | If the answer to the previous question is positive, please describe the reasons for doing so | |

*Questions formulated in the second survey (continuation)*

| | | |
|---|---|---|
| **Part 4: Increase share of biofuels in road transport fuel (biodiesel)** | | |
| This part intends to identify concrete goals and specific pathways for the target of increasing share of biodiesel in the road transport fuel | | |
| | **Question** | **Possible answers** |
| 14 | Please select the percentage quota mandate of biodiesel in diesel fuel (volume basis) | a) B12, b) B15, c) B20, d) B25, e) other |
| 15 | Please select the year at which you expect this target to be accomplished | a) 2015, b) 2020, c) 2025, d) 2030 |
| 16 | Please select the top-3 technology scenarios to produce biodiesel that you expect to be implemented to achieve this target | a) palm-oil biodiesel via transesterification, b) palm-oil biodiesel vial alternative methods, c) biodiesel from alternative feedstock (jatropha, soy, etc.), d) biodiesel via hydrotreated vegetable oil, e) biodiesel via gasification and Fischer-Tropsch, f) biodiesel via algae, g) other |
| | a. 1st scenario | |
| | b. 2nd scenario | |
| | c. 3rd scenario | |
| 17 | Do you think the existing policy framework to support biodiesel production should be modified? | a) yes, b) no |
| 18 | If the answer to the previous question is positive, please describe the reasons for doing so | |

| | | |
|---|---|---|
| **Part 5: Alternative biofuels and additives** | | |
| This part intends to capture the participant's perception of the use of alternative biofuels and additives | | |
| | **Question** | **Possible answers** |
| 19 | Do you think alternative biofuels and additives should be promoted? | a) yes, b) no |
| 20 | If the answer to the previous question is positive, please select the most appropriate option for Colombia | a) Bio-methane for injection into natural gas grid, b) pyrolysis-based fuels, c) Dimethyl ether (DME), d) methanol, e) hydrogen, f) other |
| 21 | Do you think there should be a target for your selected option? Please describe it. | a) yes, b) no |

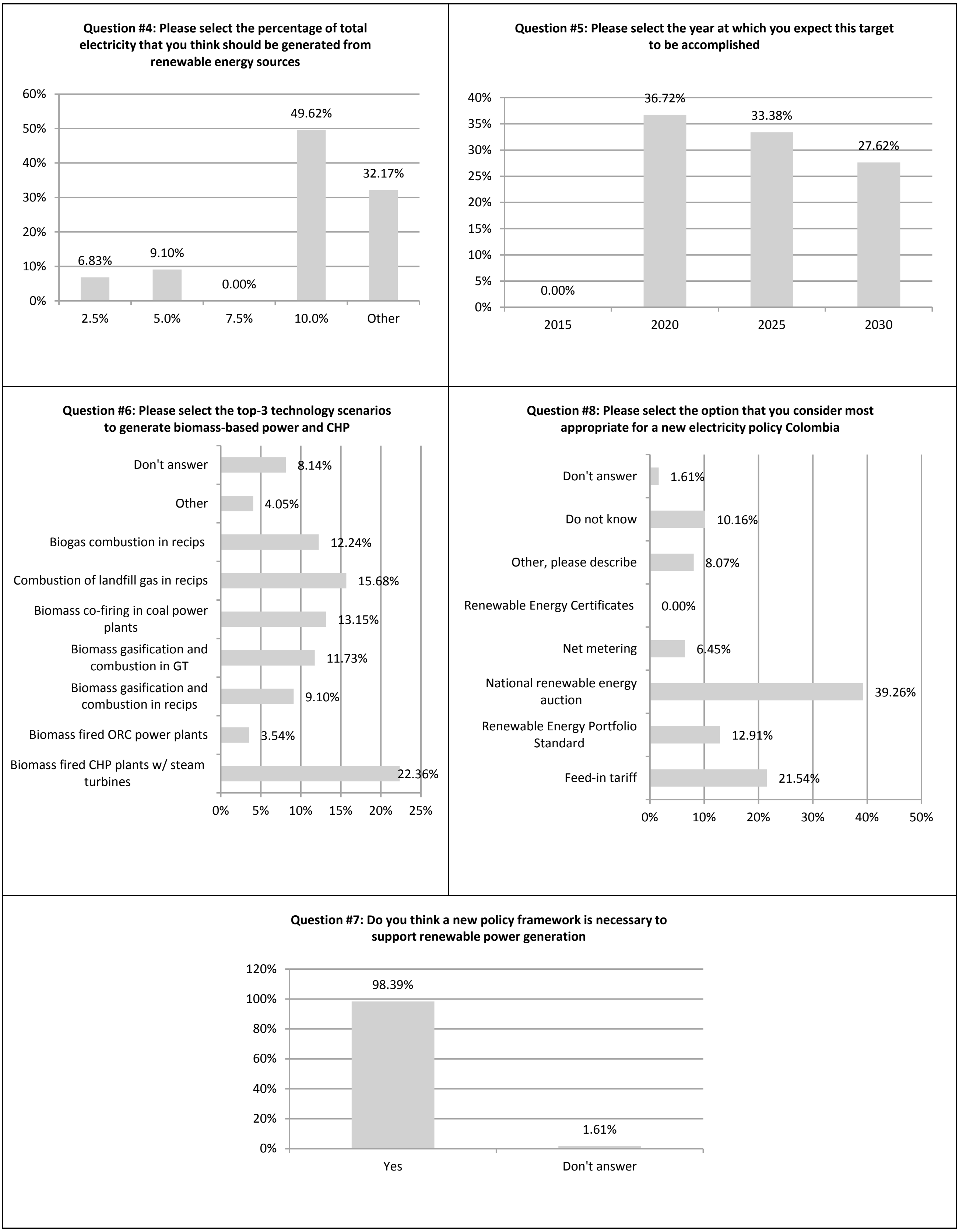


***Figure 105.*** *Answers from experts regarding Part 2 of the second survey (increase share of renewable power generation)*

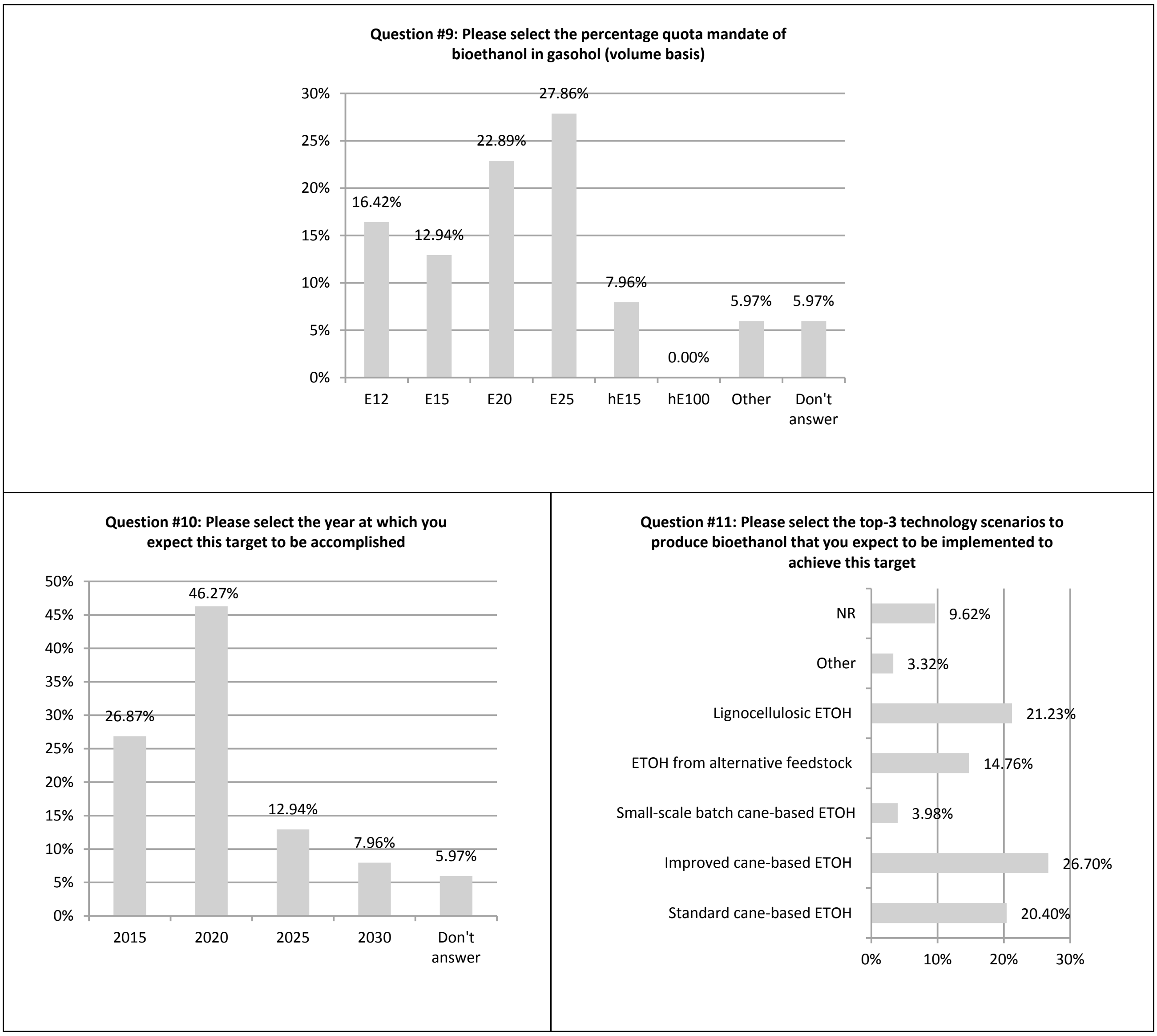


***Figure 106.*** *Answers from experts regarding Part 3 of the second survey (increase share of bioethanol in road transport fuel)*

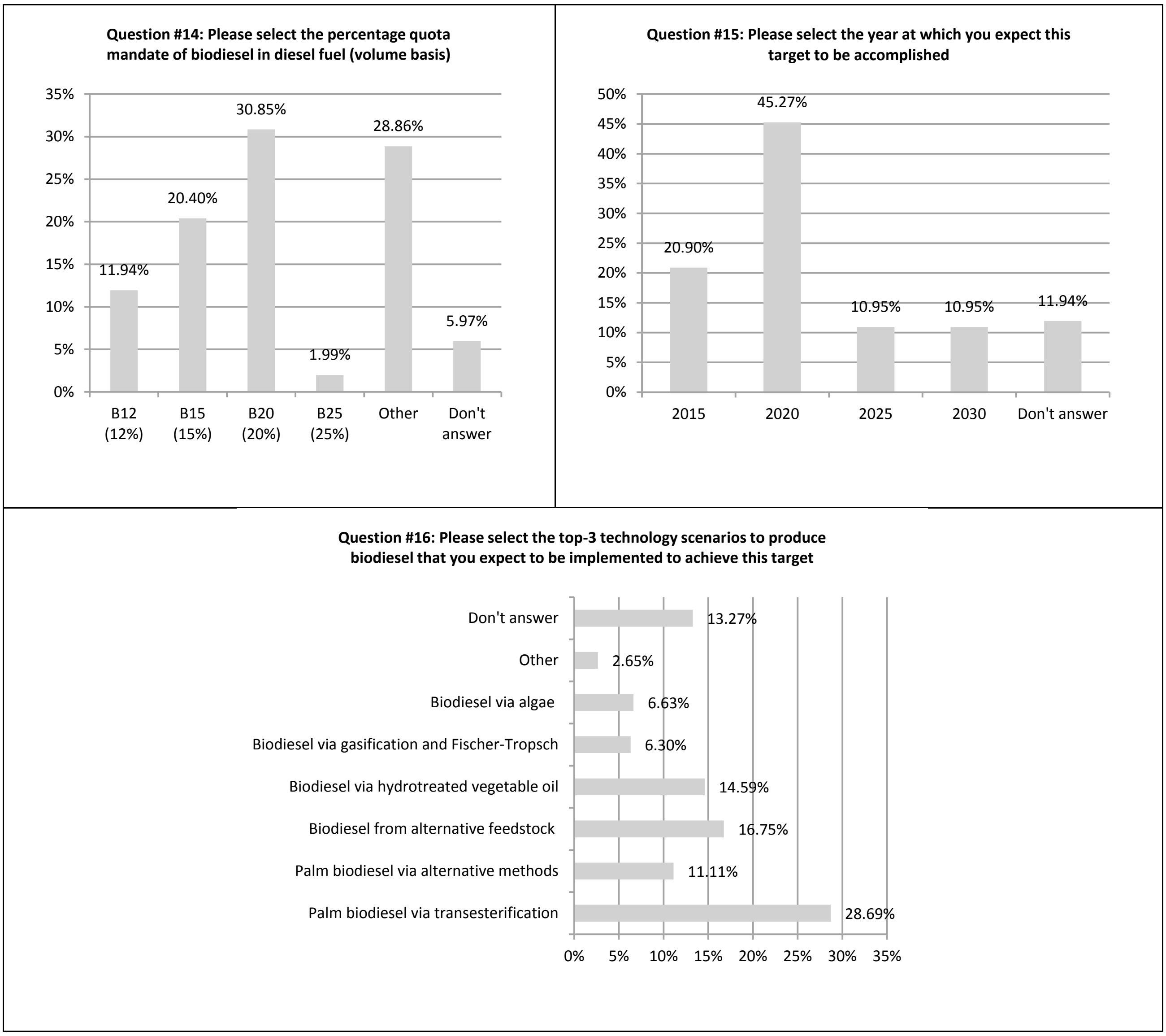


***Figure 107.*** *Answers from experts regarding Part 4 of the second survey (increase share of biodiesel in road transport fuel)*

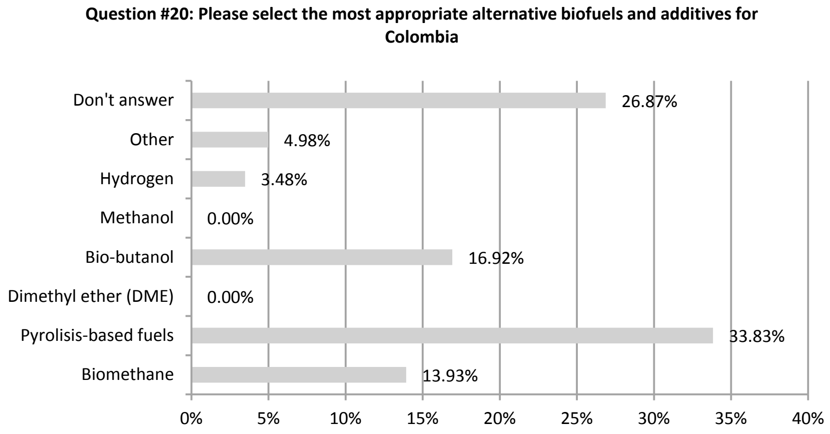


***Figure 108.*** *Answers from experts regarding Part 5 of the second survey (alternative biofuels and additives)*

# Appendix for Chapter F

*Table 48.* *Assumed energy prices (US$2005)*

| US$2005 | Unit | 1975 | 1980 | 1985 | 1990 | 1995 | 2000 | 2005 | 2009 | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **International prices** | | | | | | | | | | | | | | |
| Aviation gasoline | MMBtu | 10.27 | 18.87 | 16.21 | 12.90 | 10.24 | 12.25 | 18.56 | 18.52 | 22.69 | 27.98 | 32.41 | 34.66 | 36.33 |
| Coke | MMBtu | 10.33 | 6.67 | 4.85 | 5.26 | 4.20 | 3.00 | 8.92 | 9.86 | 12.04 | 10.86 | 11.44 | 11.67 | 11.77 |
| Coal | MMBtu | 3.07 | 3.05 | 2.74 | 2.06 | 1.68 | 1.40 | 1.62 | 2.12 | 2.18 | 2.40 | 2.52 | 2.69 | 2.87 |
| Jet fuel | MMBtu | 6.10 | 13.31 | 9.59 | 7.86 | 4.90 | 7.48 | 12.86 | 11.49 | 14.67 | 17.36 | 20.11 | 21.51 | 22.54 |
| Kerosene | MMBtu | 8.13 | 14.58 | 12.56 | 10.13 | 6.79 | 10.07 | 14.44 | 19.30 | 21.16 | 23.99 | 26.43 | 28.15 | 29.23 |
| LPG | MMBtu | 8.81 | 11.80 | 10.76 | 9.45 | 7.98 | 10.76 | 14.58 | 14.93 | 17.67 | 18.56 | 20.44 | 21.77 | 22.61 |
| Oil | Barrel | 21.36 | 48.37 | 38.98 | 23.66 | 15.95 | 31.60 | 53.39 | 56.50 | 69.99 | 100.48 | 105.07 | 109.75 | 114.69 |
| **Domestic prices** | | | | | | | | | | | | | | |
| Fuel oil | MMBtu | 3.48 | 4.60 | 4.10 | 2.13 | 1.78 | 3.26 | 5.22 | 6.91 | 9.93 | 9.37 | 10.21 | 10.66 | 11.07 |
| Natural gas | MMBtu | 0.54 | 2.25 | 3.09 | 1.19 | 1.02 | 1.64 | 1.86 | 2.78 | 3.49 | 4.54 | 5.82 | 6.65 | 7.29 |
| Electricity | MMBtu | 1.70 | 3.04 | 4.56 | 3.28 | 4.38 | 7.07 | 9.42 | 17.46 | 17.82 | 11.29 | 12.43 | 13.71 | 15.16 |
| Gasoline | MMBtu | 4.21 | 9.18 | 7.61 | 5.13 | 7.00 | 10.96 | 19.39 | 26.86 | 29.63 | 33.46 | 34.44 | 34.35 | 34.65 |
| Diesel | MMBtu | 4.63 | 8.22 | 6.81 | 4.61 | 6.27 | 8.01 | 12.22 | 20.11 | 21.77 | 31.07 | 32.83 | 33.52 | 34.21 |
| Wood fuel[1] | MMBtu | 3.15 | 3.14 | 2.82 | 2.12 | 1.73 | 1.44 | 1.67 | 2.18 | 2.24 | 2.46 | 2.59 | 2.77 | 2.95 |
| Anhydrous ethanol[2] | Gallon | | | | | | | | 2.79 | 3.21 | 3.22 | 2.74 | 2.64 | 2.74 |
| Biodiesel[2] | Gallon | | | | | | | | 3.26 | 3.80 | 3.59 | 3.76 | 3.78 | 3.98 |
| **MUV index (2005 = 1)** | | | | | | | | | 1.09 | 1.13 | 1.20 | 1.19 | 1.23 | 1.27 |

[1] Prices for wood fuel are not available. It is assumed to be proportional to the international price of coal.

[2] Future prices for anhydrous ethanol and biodiesel are taken from (Gonzalez-Salazar, et al., 2014b), scenario FAO-REF-01

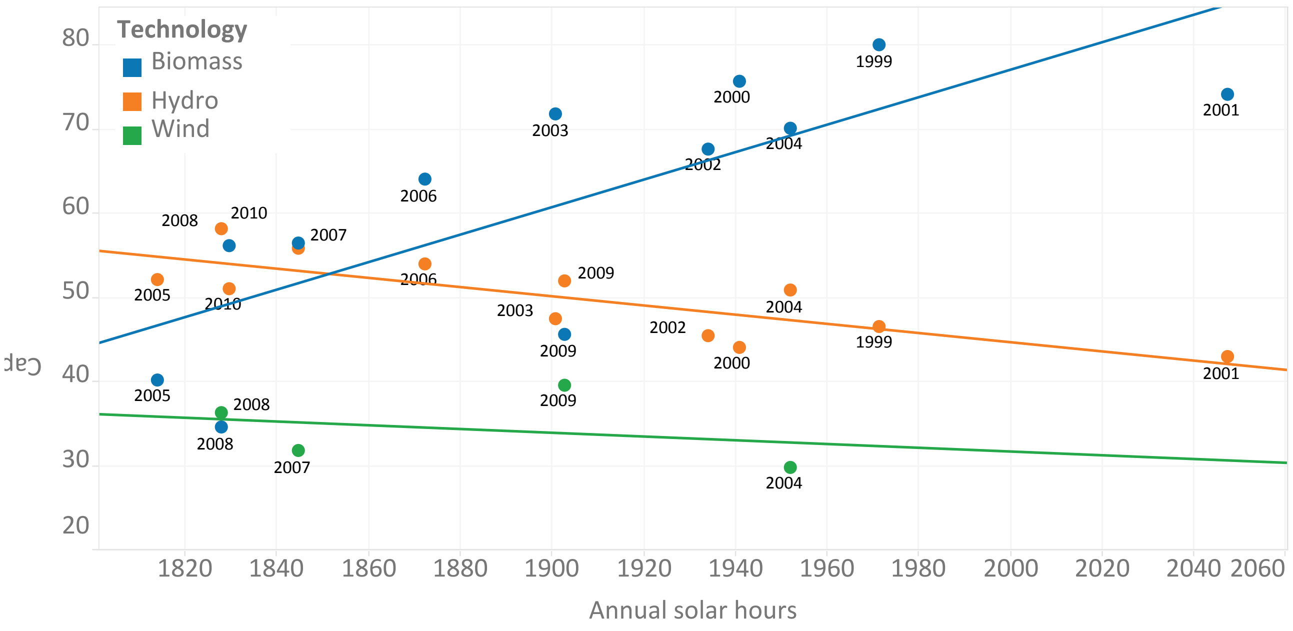


*Figure 109.* *Capacity factor of renewable energies as a function of solar radiance (XM, 2013)*

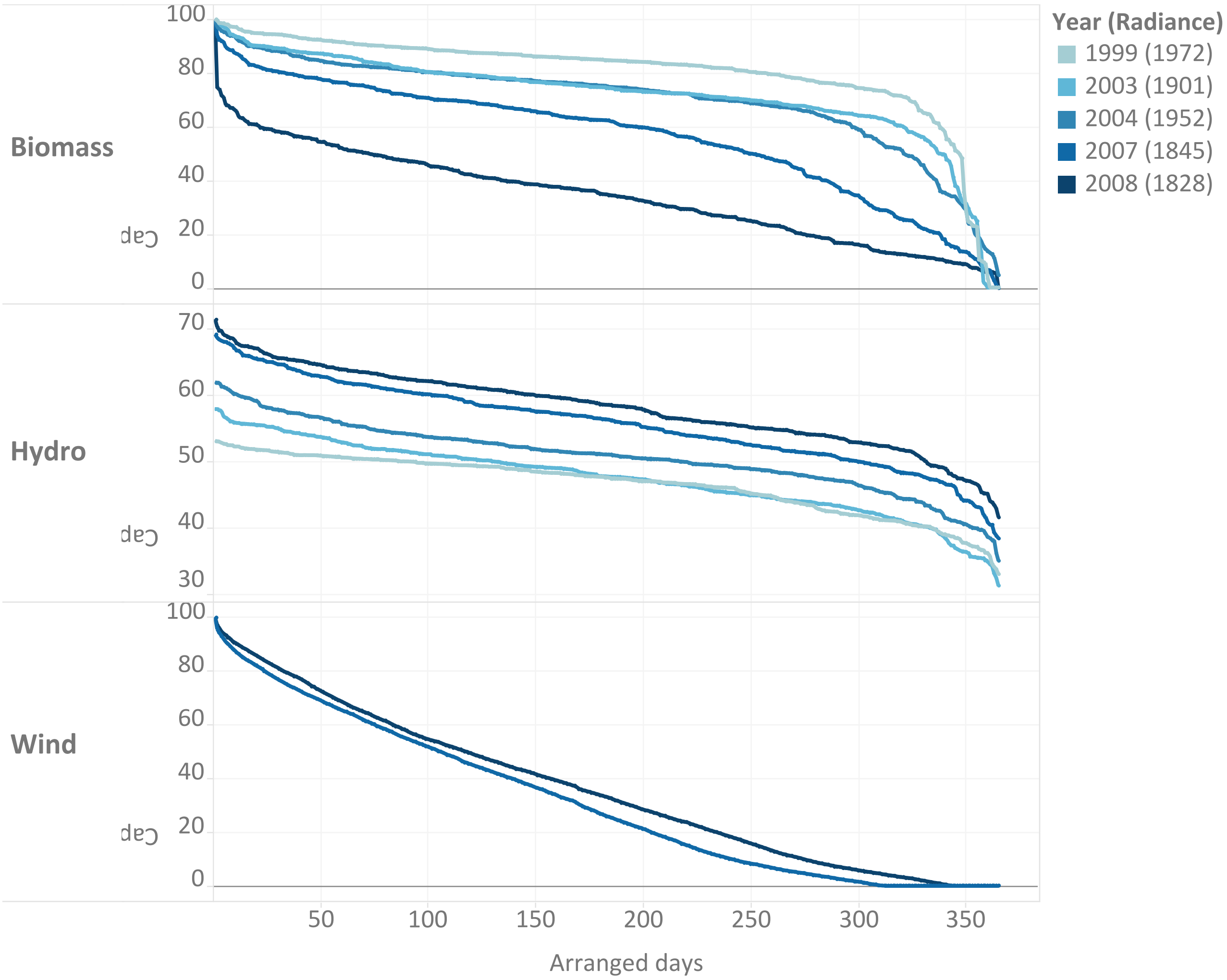


*Figure 110.* *Capacity factor of renewable energies for arranged days in different years (XM, 2013)*

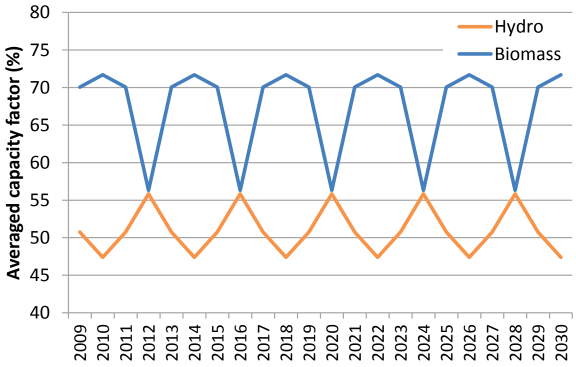


*Figure 111.* *Averaged assumed profiles for hydro and biomass-based power*

*Table 49.* *Assumed availability of land*

| **Availability of land (mio ha)** | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|
| Forest area | 60.50 | 60.00 | 59.50 | 59.00 | 58.50 |
| Other land | 8.00 | 8.00 | 8.00 | 8.00 | 8.00 |
| Area for commodities not included in model | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Area for commodities included in model (including area for cattle) | 41.45 | 41.95 | 42.45 | 42.95 | 43.45 |

***Table 50.*** *Produced volumes of biomass resources*

| **Biomass categories** | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|
| **Agricultural crops [1] (million tons)** | | | | | |
| Cotton | 0.04 | 0.06 | 0.06 | 0.08 | 0.06 |
| Palm oil (FFB) | 5.50 | 8.19 | 9.73 | 12.68 | 15.78 |
| Sugar cane without leaves (large-scale) | 25.67 | 28.50 | 28.17 | 28.50 | 28.50 |
| Sugar cane without leaves (small-scale) | 17.11 | 19.81 | 22.82 | 26.06 | 29.51 |
| Coffee (green) | 0.77 | 0.83 | 0.63 | 0.08 | 0.08 |
| Corn | 1.48 | 1.69 | 1.81 | 2.09 | 2.29 |
| Rice (paddy) | 3.42 | 2.39 | 2.39 | 2.18 | 1.49 |
| Banana | 2.09 | 2.35 | 2.68 | 3.06 | 3.45 |
| Plantain | 2.72 | 2.97 | 3.24 | 3.50 | 3.75 |
| **Animals (million stocks)** | | | | | |
| Cattle [1] | 29.74 | 31.05 | 32.61 | 34.41 | 35.94 |
| Pork [1] | 3.87 | 2.91 | 1.88 | 1.27 | 1.29 |
| Poultry [1] | 624.45 | 643.88 | 680.07 | 651.38 | 406.17 |
| Equine [1] | 2.14 | 2.27 | 2.40 | 2.51 | 2.61 |
| Buffalos [2] | 0.23 | 0.23 | 0.23 | 0.23 | 0.23 |
| Sheep [3] | 3.58 | 3.58 | 3.58 | 3.58 | 3.58 |
| Goats [3] | 2.69 | 2.69 | 2.69 | 2.69 | 2.69 |
| Mules and asses [3] | 0.71 | 0.71 | 0.71 | 0.71 | 0.71 |
| **Forest resources from forest plantations [1] (million $m^3$)** | | | | | |
| Roundwood | 11.59 | 13.49 | 15.48 | 17.56 | 19.74 |
| Woodfuel | 9.12 | 10.61 | 12.18 | 13.82 | 15.53 |
| Industrial roundwood | 2.47 | 2.87 | 3.30 | 3.74 | 4.21 |
| **Forest resources from deforestation [7] (million $m^3$)** | | | | | |
| Field residues | 13.44 | 13.44 | 13.44 | 13.44 | 13.44 |
| **Urban waste** | | | | | |
| Landfill gas [4] (kton) | 739.64 | 1021.80 | 1194.72 | 1333.10 | 1457.66 |
| Wastewater [5] (kton BOD) | 666.55 | 712.27 | 756.43 | 798.85 | 839.59 |
| Wastewater from biodiesel plants [6] (kton BOD), Baseline and Scenario I | 77.54 | 123.15 | 162.46 | 216.11 | 279.49 |
| Wastewater from biodiesel plants [6] (kton BOD), Scenarios II and II with expansion | 77.54 | 155.51 | 316.91 | 531.99 | 834.42 |

Notes:

[1] Produced volumes of agricultural crops, forestry resources and animal stocks are taken from the results of the LUTM model for the baseline scenario. These values are almost unchanged across scenarios and it is assumed that they are the same for all scenarios.

[2] Account of these animals is not included in LUTM. Values for 2014 are taken from (ICA, 2014) and assumed to maintain constant until 2030 given their low contribution.

[3] Account of these animals is not included in LUTM. Values for 2014 are taken from (FAO, 2012b) and assumed to maintain constant until 2030 given their low contribution.

[4] Volumes of landfill gas are estimated using the Colombia Landfill Gas Model Version 1.0 (SCS Engineers, 2010). The model calculates landfill gas generation by using a first order decay equation, specific data of climate, waste composition and disposal practices in each of the 33 departments in Colombia. It is assumed that the type of landfill is engineered or sanitary, that the start year of the landfill is 2005 and that the projected closure year is 2030. Current production of municipal solid waste (MSW) for the different departments is taken from various reports published by the Colombian Administration of Public Services (Superservicios, 2009; Superservicios, 2011; Superservicios, 2012). Future production of MSW is estimated by multiplying the current MSW per capita for the different departments by the population forecast taken from Table 21.

[5] Estimated using the Tier 1 methodology to estimate wastewater treatment and discharge in the IPCC guidelines for national greenhouse gas inventories (IPCC, 2006c). Specifically, a theoretical BOD generation per capita of 40 g BOD/person/day and population forecast from Table 21 are used.

[6] The volume of wastewater produced in biodiesel processing plants is estimated by multiplying a BOD emission factor by the production of biodiesel for the different scenarios. A BOD emission factor of 0.0523 kg-BOD/kg-FFB taken from (BID-MME, Consorcio CUE, 2012) is used. The biodiesel production for the different scenarios is taken from the results of the ESM model (see Figure 66 and Figure 67).

[7] It is assumed that forest residues left in the field are available from deforested areas, which amount to 100 kha annually until 2030. The amount of residues is estimated using an above-ground biomass yield of 259.7 ton-dry/ha taken from (Phillips, et al., 2011), a ratio of residues to total biomass of 0.31 ton-residues/ton-biomass taken from and a density of 0.6 dry-ton/$m^3$ taken from Table 31.

***Table 51.** Specific energy of biomass resources*

| **Agriculture** | **Residues** | **Residue to product ratio (RTP)** | **Moisture** | **LHV (kJ/kg, d)** | **References** |
|---|---|---|---|---|---|
| Cotton | Husk | 2.17 | 0.09 | 15815 | For all residues from agricultural crops the average values in Table 29 are taken. |
| Palm oil | Stone | 0.17 | 0.09 | 17948 | |
| | Fiber | 0.22 | 0.35 | 18220 | |
| | Rachis | 0.35 | 0.54 | 17993 | |
| Sugar cane (large-scale) | Leaves and top | 0.36 | 0.23 | 17394 | |
| | Bagasse | 0.31 | 0.48 | 17342 | |
| Sugar cane (small-scale) | Bagasse | 0.30 | 0.48 | 17342 | |
| | Leaves and top | 0.33 | 0.23 | 17394 | |
| Coffee | Pulp | 2.12 | 0.68 | 18518 | |
| | Husk | 0.21 | 0.11 | 16151 | |
| | Stem | 3.02 | 0.29 | 19062 | |
| Corn | Stem and leaves | 0.93 | 0.15 | 16108 | |
| | Cob | 0.27 | 0.29 | 16340 | |
| | Skin | 0.20 | 0.08 | 16590 | |
| Rice | Stem | 1.94 | 0.82 | 14599 | |
| | Husk | 0.25 | 0.10 | 15551 | |
| Banana | Rachis | 1.00 | 0.95 | 7863 | |
| | Stem | 5.00 | 0.94 | 8836 | |
| | Rejected fruit | 0.15 | 0.84 | 10820 | |
| Plantain | Rachis | 1.00 | 0.94 | 7570 | |
| | Stem | 5.00 | 0.93 | 8508 | |
| | Rejected fruit | 0.15 | 0.83 | 10417 | |

| **Animal waste** | **kg-CH4/head** | **Reference** |
|---|---|---|
| Cattle | 93.29 | Table 30 |
| Swine | 19.17 | Table 30 |
| Poultry | 0.84 | Table 30 |
| Equine | 149.48 | Table 30 |
| Buffalos | 56.92 | (IPCC, 2006b) |
| Sheep | 5.18 | (IPCC, 2006b) |
| Goats | 5.21 | (IPCC, 2006b) |
| Mules and asses | 11.08 | (IPCC, 2006b) |

| **Forestry residues** | **RTP** | **Specific weight (ton-d/m$^3$)** | **LHV (kJ/kg, d)** | **Reference** |
|---|---|---|---|---|
| Field residues | 0.45 | | 18548 | All values are taken from averages in Table 31 |
| Industrial residues | 0.24 | | 18548 | |
| Woodfuel | | 0.725 | 18098 | |

| **Urban waste** | **Value** | **Reference** |
|---|---|---|
| Landfill LHV (MJ/m$^3$) | 16.99 | Table 33 |
| Wastewater (kg-CH$_4$/kg-BOD) | 0.198 | Tier 1 method in (IPCC, 2006c) and using population from Table 21 |
| Wastewater in biodiesel plants (kg-CH$_4$/kg-BOD) | 0.197 | (BID-MME, Consorcio CUE, 2012) |

*Table 52. Availability of biomass resources*

| Categories | Residues | Availability factor |
|---|---|---|
| **Residues from agricultural crops** [1] | | |
| Cotton | Husk | 0.00 |
| Palm oil | Stone | 1.00 [3] |
| | Fiber | 1.00 [3] |
| | Rachis | 1.00 [3] |
| Sugarcane (large-scale) | Leaves and top | 0.43 |
| | Bagasse | 0.94 [3] |
| Sugarcane (medium, small-scale) | Bagasse | 1.00 [3] |
| | Leaves and top | 0.00 |
| Coffee | Pulp | 0.00 |
| | Husk | 0.00 |
| | Stem | 0.00 |
| Corn | Stem and leaves | 0.00 |
| | Cob | 0.00 |
| | Skin | 0.00 |
| Rice | Stem | 0.00 |
| | Husk | 0.75 |
| Banana | Rachis | 0.00 |
| | Stem | 0.00 |
| | Rejected fruit | 0.00 |
| Plantain | Rachis | 0.00 |
| | Stem | 0.00 |
| | Rejected fruit | 0.00 |
| **Animal waste** [1] | | |
| Cattle | Manure | 0.16 |
| Pork | Manure | 0.11 |
| Poultry | Manure | 0.00 |
| Equine | Manure | 0.00 |
| Other | Manure | 0.00 |
| **Forest resources from forest plantations** [1] | | |
| Woodfuel | | 1.00 [3] |
| Field residues | | 0.30 |
| Industrial residues | | 0.00 |
| **Forest resources from deforestation** [1] | | |
| Field residues | | 0.30 |
| **Urban waste** [1] | | |
| Landfill gas | | 0.57 |
| Methane from wastewater | | 0.03 |
| **Methane from wastewater in biodiesel processing plants** [2] | | |
| Scenario I | | 1.00 |
| Scenario II | | 1.00 |

Notes:

[1] For these categories the average values from Table 35 are taken.

[2] For methane from wastewater in biodiesel processing plants it is assumed a technical availability of 100% in 2030 based on recommendations of experts.

[3] For these sub-categories the availability factor considers two parts: a) the part of the resource already used for energy production and b) the part of the resource potentially available for energy production after considering competition and other constraints as described in Section C.4.4.

***Table 53.*** *Theoretical biomass energy potential used in roadmap*

| **Categories** | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|
| **Residues from agricultural crops (thousand TJ)** | | | | | |
| Cotton | 3.23 | 2.02 | 1.95 | 2.41 | 1.89 |
| Palm oil | 44.92 | 68.54 | 81.45 | 106.12 | 132.04 |
| Sugar cane (large-scale) | 152.15 | 216.17 | 213.64 | 216.17 | 216.17 |
| Sugar cane (small-scale) | 119.69 | 141.19 | 162.64 | 185.73 | 210.28 |
| Coffee | 43.90 | 47.03 | 35.42 | 4.27 | 4.41 |
| Corn | 20.92 | 32.22 | 34.39 | 39.69 | 43.48 |
| Rice | 21.25 | 20.72 | 20.77 | 18.89 | 12.96 |
| Banana | 7.08 | 8.25 | 9.41 | 10.74 | 12.10 |
| Plantain | 10.43 | 10.43 | 11.37 | 12.29 | 13.17 |
| Sub-total | 423.58 | 546.57 | 571.04 | 596.31 | 646.50 |
| **Animal waste (thousand TJ)** | | | | | |
| Cattle | 138.74 | 144.85 | 152.11 | 160.50 | 167.63 |
| Pork | 3.71 | 2.79 | 1.80 | 1.22 | 1.23 |
| Poultry | 26.16 | 26.97 | 28.49 | 27.29 | 17.01 |
| Equine | 16.03 | 16.98 | 17.93 | 18.78 | 19.49 |
| Other | 2.69 | 2.69 | 2.69 | 2.69 | 2.69 |
| Sub-total | 187.32 | 194.27 | 203.02 | 210.46 | 208.06 |
| **Forest resources from forest plantations (thousand TJ)** | | | | | |
| Woodfuel | 119.63 | 139.27 | 159.83 | 181.33 | 203.82 |
| Field residues | 96.75 | 112.64 | 129.26 | 146.66 | 164.84 |
| Industrial residues | 11.00 | 12.80 | 14.69 | 16.67 | 18.74 |
| Sub-total | 227.38 | 264.71 | 303.78 | 344.66 | 387.41 |
| **Forest resources from deforestation (thousand TJ)** | | | | | |
| Field residues | 149.54 | 149.54 | 149.54 | 149.54 | 149.54 |
| **Urban waste (thousand TJ)** | | | | | |
| Landfill gas | 9.89 | 13.66 | 15.97 | 17.82 | 19.49 |
| Methane from wastewater | 6.69 | 7.14 | 7.57 | 7.99 | 8.39 |
| Sub-total | 16.58 | 22.01 | 25.15 | 27.94 | 30.63 |
| **Methane from wastewater in biodiesel processing plants (thousand TJ)** | | | | | |
| Scenario I | 0.76 | 1.21 | 1.60 | 2.13 | 2.75 |
| Scenarios II and II with expansion | 0.76 | 1.53 | 3.12 | 5.24 | 8.22 |
| **Total (thousand TJ)** | | | | | |
| **Baseline and Scenario I** | 1005.16 | 1178.33 | 1254.12 | 1331.04 | 1424.90 |
| **Scenarios II and II with expansion** | 1005.16 | 1178.64 | 1255.65 | 1334.15 | 1430.36 |

***Table 54.*** *Technical biomass energy potential (including current uses) used in roadmap*

| | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| **Residues from agricultural crops (thousand TJ)** | | | | | |
| Cotton | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Palm oil | 44.92 | 68.54 | 81.45 | 106.12 | 132.04 |
| Sugar cane (large-scale) | 94.58 | 134.37 | 132.80 | 134.37 | 134.37 |
| Sugar cane (small-scale) | 45.04 | 53.12 | 61.19 | 69.88 | 79.12 |
| Coffee | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Corn | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Rice | 6.35 | 6.19 | 6.21 | 5.64 | 3.87 |
| Banana | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Plantain | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub-total | 190.88 | 262.22 | 281.65 | 316.02 | 349.40 |
| **Animal waste (thousand TJ)** | | | | | |
| Cattle | 22.34 | 23.33 | 24.50 | 25.85 | 27.00 |
| Pork | 0.41 | 0.31 | 0.20 | 0.13 | 0.14 |
| Poultry | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Equine | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Other | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub-total | 22.75 | 23.63 | 24.69 | 25.98 | 27.13 |
| **Forest resources from forest plantations (thousand TJ)** | | | | | |
| Woodfuel | 119.63 | 139.27 | 159.83 | 181.33 | 203.82 |
| Field residues | 29.26 | 34.06 | 39.09 | 44.35 | 49.85 |
| Industrial residues | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sub-total | 148.89 | 173.33 | 198.92 | 225.68 | 253.67 |
| **Forest resources from deforestation (thousand TJ)** | | | | | |
| Field residues | 45.22 | 45.22 | 45.22 | 45.22 | 45.22 |
| **Urban waste (thousand TJ)** | | | | | |
| Landfill gas | 5.59 | 7.72 | 9.03 | 10.07 | 11.02 |
| Methane from wastewater | 0.18 | 0.19 | 0.20 | 0.21 | 0.22 |
| Sub-total | 5.77 | 9.12 | 10.83 | 12.41 | 13.99 |
| **Methane from wastewater in biodiesel processing plants (thousand TJ)** | | | | | |
| Scenario I | 0.76 | 1.21 | 1.60 | 2.13 | 2.75 |
| Scenario II | 0.76 | 1.53 | 3.12 | 5.24 | 8.22 |
| **Total (thousand TJ)** | | | | | |
| **Baseline and Scenario I** | 414.27 | 514.75 | 562.91 | 627.45 | 692.17 |
| **Scenario II** | 414.27 | 515.06 | 564.43 | 630.56 | 697.63 |

***Table 55.*** *Primary energy targeted in long-term goals of biomethane and biomass-based power generation in Scenarios I and II*

| **Primary energy targeted** | **Scenario I** | | | | **Scenario II** | | | |
|---|---|---|---|---|---|---|---|---|
| | **2015** | **2020** | **2025** | **2030** | **2015** | **2020** | **2025** | **2030** |
| **Biomethane** | | | | | | | | |
| 5% biomass residues (TJ) | 2020 | 12122 | 22224 | 32325 | 2020 | 12122 | 22224 | 32325 |
| 1% animal waste (TJ) | 130 | 780 | 1430 | 2081 | 130 | 780 | 1430 | 2081 |
| **Power generation** | | | | | | | | |
| 5% animal waste (TJ) | 650 | 3901 | 7152 | 10403 | 650 | 3901 | 7152 | 10403 |
| 5% methane in wastewater (TJ) | 26 | 157 | 288 | 420 | 26 | 157 | 288 | 420 |
| 100% methane in wastewater from biodiesel plants (TJ) | 172 | 1032 | 1892 | 2752 | 514 | 3081 | 5649 | 8217 |
| 10% landfill gas (TJ) | 85 | 512 | 938 | 1364 | 85 | 512 | 938 | 1364 |

***Table 56.*** *Validation of the primary energy demand by fuel in the ESM model against official statistics*

| **Primary energy (mio TOE), taken from the national energy balances** | **1975** | **1980** | **1985** | **1990** | **1995** | **2000** | **2005** | **2009** |
|---|---|---|---|---|---|---|---|---|
| Bioenergy | 4.45 | 4.39 | 4.47 | 4.35 | 4.31 | 3.74 | 3.78 | 3.77 |
| Coal | 2.27 | 2.43 | 3.05 | 1.60 | 3.61 | 2.70 | 1.34 | 3.86 |
| Gas | 1.66 | 2.77 | 3.57 | 3.76 | 4.12 | 6.25 | 6.92 | 8.42 |
| Hydro | 1.00 | 1.48 | 1.89 | 2.81 | 3.27 | 3.15 | 4.01 | 4.20 |
| Oil | 8.07 | 8.49 | 10.56 | 13.66 | 15.21 | 15.00 | 15.99 | 16.95 |
| Other renewables | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.05 | 0.91 |
| Total | 17.44 | 19.56 | 23.53 | 26.18 | 30.52 | 30.85 | 32.09 | 38.10 |
| **Primary energy (mio TOE), modeled values** | | | | | | | | |
| Bioenergy | 4.50 | 4.25 | 4.12 | 4.17 | 4.91 | 4.50 | 4.73 | 4.60 |
| Coal | 2.35 | 2.52 | 3.14 | 1.69 | 3.70 | 2.75 | 1.38 | 3.89 |
| Gas | 1.67 | 2.86 | 3.66 | 3.87 | 4.20 | 6.25 | 6.94 | 8.48 |
| Hydro | 1.00 | 1.48 | 1.89 | 2.81 | 3.27 | 3.15 | 4.00 | 4.19 |
| Oil | 8.07 | 8.49 | 10.56 | 13.66 | 15.21 | 15.00 | 15.99 | 16.95 |
| Other renewables | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 |
| Total | 17.57 | 19.60 | 23.38 | 26.21 | 31.29 | 31.65 | 33.06 | 38.13 |

Notes:

1. Bioenergy in national energy balances includes bagasse from sugar cane on a large scale, wood and residues of palm oil, but excludes bagasse from jaggery cane. Bioenergy in the ESM model includes all these sub-categories. For the sake of comparison bagasse from jaggery cane is not accounted in the validation of the ESM model.
2. Imports of oil-based secondary fuels are converted into primary energy.
3. Accounting adjustments published in the national energy balances for all fuels are considered for validating the ESM model.

***Table 57.*** *Goodness of fit between primary energy modeled values and official statistics*

| **Goodness of fit** | **$R^2$** |
|---|---|
| Bioenergy | - |
| Coal | 98.4% |
| Gas | 99.9% |
| Hydro | 100% |
| Oil | 100% |
| Other renewables | - |
| Total | 99.2% |

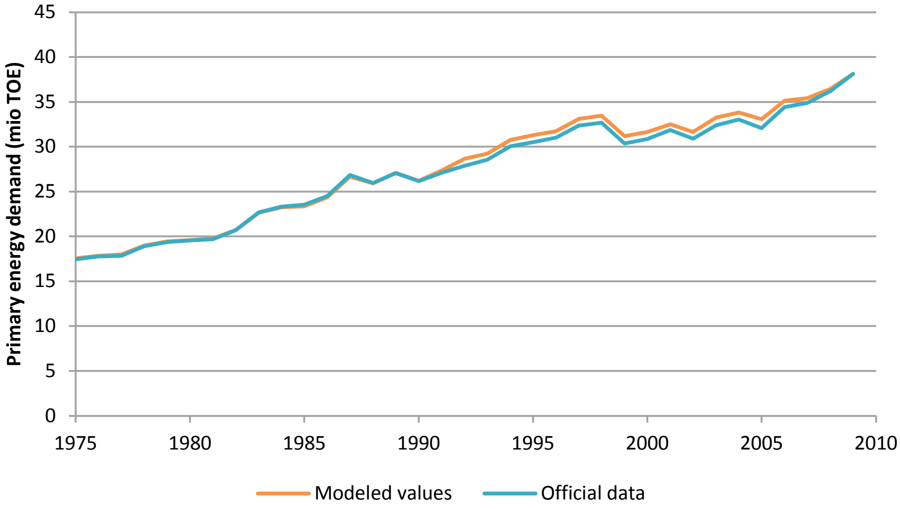


***Figure 112.*** *Modeled primary energy demand vs. official data*

*Table 58. Validation of the GHG emissions by branch in the ESM model against official statistics*

| **Energy related GHG emissions (mio ton $CO_2$-eq.), taken from the national energy balances** | **1975** | **1980** | **1985** | **1990** | **1995** | **2000** | **2005** | **2009** |
|---|---|---|---|---|---|---|---|---|
| Demand | 23.30 | 26.20 | 27.65 | 34.16 | 41.38 | 41.06 | 44.97 | 48.03 |
| Own use | 3.20 | 3.14 | 3.20 | 3.94 | 4.44 | 6.61 | 6.91 | 7.59 |
| Power generation | 4.70 | 6.53 | 7.91 | 7.05 | 9.28 | 8.71 | 8.49 | 12.40 |
| Other transformation processes | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Total | 31.20 | 35.87 | 38.76 | 45.16 | 55.11 | 56.38 | 60.36 | 68.01 |
| Total excluding other processes | 31.20 | 35.87 | 38.76 | 45.16 | 55.11 | 56.38 | 60.36 | 68.01 |
| **Energy related GHG emissions (mio ton $CO_2$-eq.), calculated values** | | | | | | | | |
| Demand | 22.86 | 25.86 | 27.04 | 33.66 | 41.09 | 40.87 | 44.70 | 47.54 |
| Own use | 2.09 | 2.09 | 1.93 | 2.36 | 2.68 | 4.72 | 4.97 | 5.62 |
| Power generation | 4.47 | 6.17 | 7.73 | 7.02 | 9.07 | 8.54 | 8.23 | 11.96 |
| Other transformation processes | 4.70 | 5.99 | 6.60 | 6.88 | 5.83 | 5.29 | 4.56 | 6.17 |
| Total | 34.12 | 40.12 | 43.30 | 49.92 | 58.66 | 59.42 | 62.47 | 71.28 |
| Total excluding other processes | 29.42 | 34.13 | 36.70 | 43.04 | 52.83 | 54.13 | 57.91 | 65.11 |

*Table 59. Goodness of fit between GHG emissions modeled values and official statistics*

| **Goodness of fit** | **$R^2$** |
|---|---|
| Demand | 99.8% |
| Own use | - |
| Power generation | 97.4% |
| Other transformation processes | - |
| Total | 87.9% |
| Total excluding other processes | 95.7% |

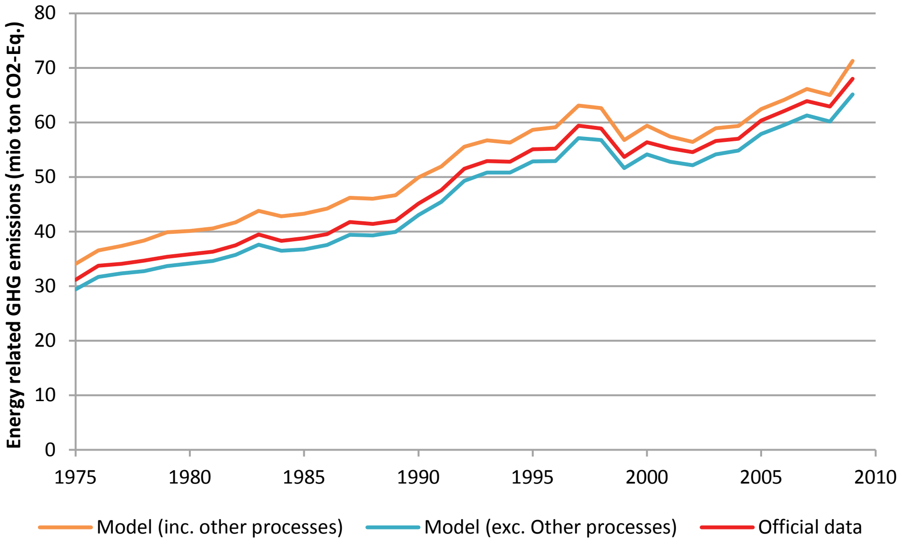


***Figure 113.*** *Modeled GHG emissions vs. official data*

*Table 60. Updated production costs of sugar, palm oil and biofuels in LUTM model*

| **Production cost (US$2005)** | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|
| Palm oil (US$2005/ton) | 623.3 | 673.0 | 642.4 | 646.1 | 684.1 |
| Biodiesel (US$2005/liter) | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 |
| Sugar (US$2005/ton), Route 1 in Valley of the Cauca River | 519.6 | 631.8 | 656.8 | 687.0 | 759.9 |
| Sugar (US$2005/ton), Route 2 in Valley of the Cauca River | 519.6 | 631.8 | 656.8 | 687.0 | 759.9 |
| Bioethanol (US$2005/liter), Route 2 in Valley of the Cauca River | 0.40 | 0.48 | 0.50 | 0.52 | 0.58 |
| Bioethanol (US$2005/liter), Route 3 in Valley of the Cauca River | 0.52 | 0.63 | 0.66 | 0.69 | 0.76 |
| Sugar (US$2005/ton), Route 1 in Llanos and Costa regions | 896.9 | 1026.3 | 1004.7 | 990.6 | 1033.0 |
| Sugar (US$2005/ton), Route 2 in Llanos and Costa regions | 896.9 | 1026.3 | 1004.7 | 990.6 | 1033.0 |
| Bioethanol (US$2005/liter), Route 2 in Llanos and Costa regions | 0.67 | 0.76 | 0.75 | 0.74 | 0.77 |
| Bioethanol (US$2005/liter), Route 3 in Llanos and Costa regions | 0.88 | 1.01 | 0.98 | 0.97 | 1.01 |

***Table 61.*** *Updated yields of sugar, palm oil and biofuels in LUTM model*

| **Yields** | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|
| **Palm oil and derivatives** | | | | | |
| Fresh fruit bunches -FFB- (Ton/Ha) - | 19.61 | 20.20 | 20.80 | 21.39 | 21.98 |
| Palm oil (Ton/Ha) | 3.58 | 3.73 | 3.89 | 4.05 | 4.20 |
| Biodiesel (liters/ton fresh fruit) | 233.61 | 233.61 | 233.61 | 233.61 | 233.61 |
| Biodiesel (liters/ha) | 4581.72 | 4719.94 | 4858.16 | 4996.38 | 5134.60 |
| Biodiesel yield (ton-oil/liter) | 0.00078 | 0.00079 | 0.00080 | 0.00081 | 0.00082 |
| **Sugar and derivatives in Valley of the Cauca River** | | | | | |
| Cane without leaves (Ton/Ha) | 114.00 | 114.00 | 114.00 | 114.00 | 114.00 |
| Sugar (ton/ha), Route 1 | 13.68 | 13.68 | 13.68 | 13.68 | 13.68 |
| Sugar (ton/ha), Route 2 | 10.60 | 10.60 | 10.60 | 10.60 | 10.60 |
| Bioethanol (ton bioethanol/ton sugar), Route 2 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 |
| Bioethanol (liters/ton cane), Route 3 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 |
| Bioethanol (liters/ha), Route 3 | 9120.00 | 9120.00 | 9120.00 | 9120.00 | 9120.00 |
| **Sugar and derivatives in expansion (i.e. Llanos and Costa regions)** | | | | | |
| Cane without leaves (Ton/Ha) | 70.83 | 75.13 | 79.69 | 84.53 | 89.67 |
| Sugar (ton/ha), Route 1 | 8.50 | 9.02 | 9.56 | 10.14 | 10.76 |
| Sugar (ton/ha), Route 2 | 5.42 | 5.94 | 6.49 | 7.07 | 7.68 |
| Bioethanol (ton bioethanol/ton sugar), Route 2 | 0.21 | 0.21 | 0.21 | 0.21 | 0.21 |
| Bioethanol (liters/ton cane), Route 3 | 80.00 | 80.00 | 80.00 | 80.00 | 80.00 |
| Bioethanol (liters/ha), Route 3 | 5666.42 | 6010.50 | 6375.48 | 6762.62 | 7173.27 |

Note: Data taken from (BID-MME, Consorcio CUE, 2012; Ferreira-Leitao, Fortes Gottschalk, Ferrara, Lima Nepomuceno, Correa Molinari, & Bon, 2010)

***Table 62.*** *Other assumptions about expansion of sugar cane in the Llanos and Costa regions*

| **Assumptions in Llanos and Costa regions** | **Value** | **References** |
|---|---|---|
| Maximum historical yearly growth (ha) | 35249 | Assumed to be the same as for sugar cane in Valley of the Cauca River taken from (Gonzalez-Salazar, et al., 2014b) |
| Available land area (ha) | 1518000 | Taken from (BID-MME, Consorcio CUE, 2012) |

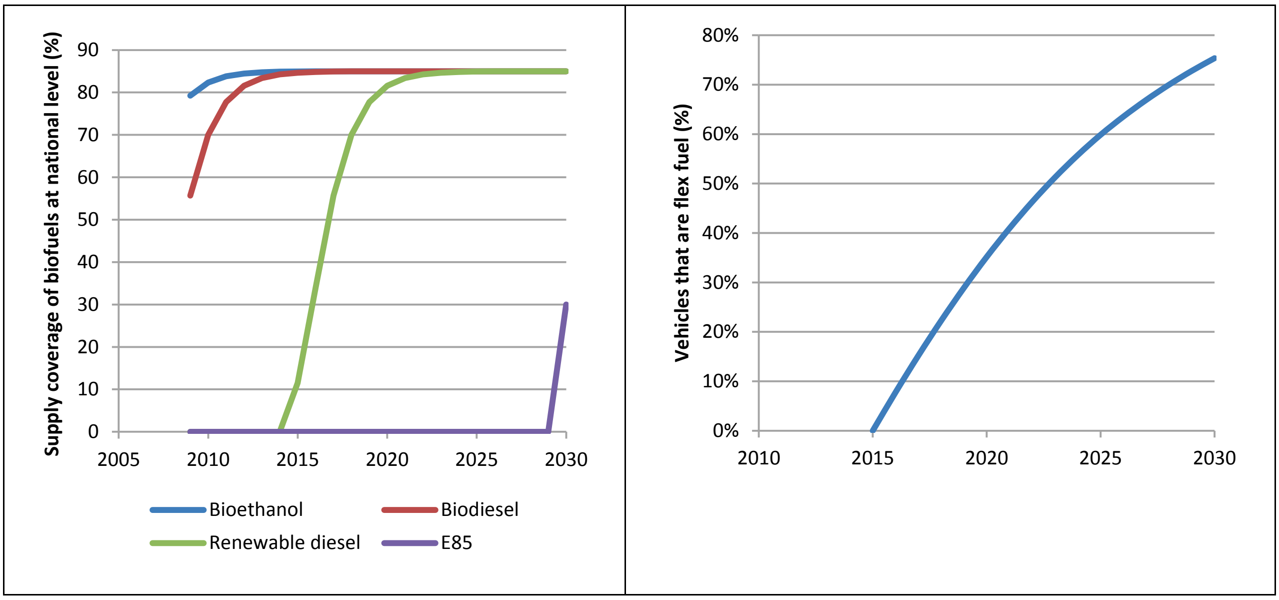


***Figure 114.*** *Supply coverage of biofuels at a national level (left) and percentage of vehicles that are flex fuel (right)*

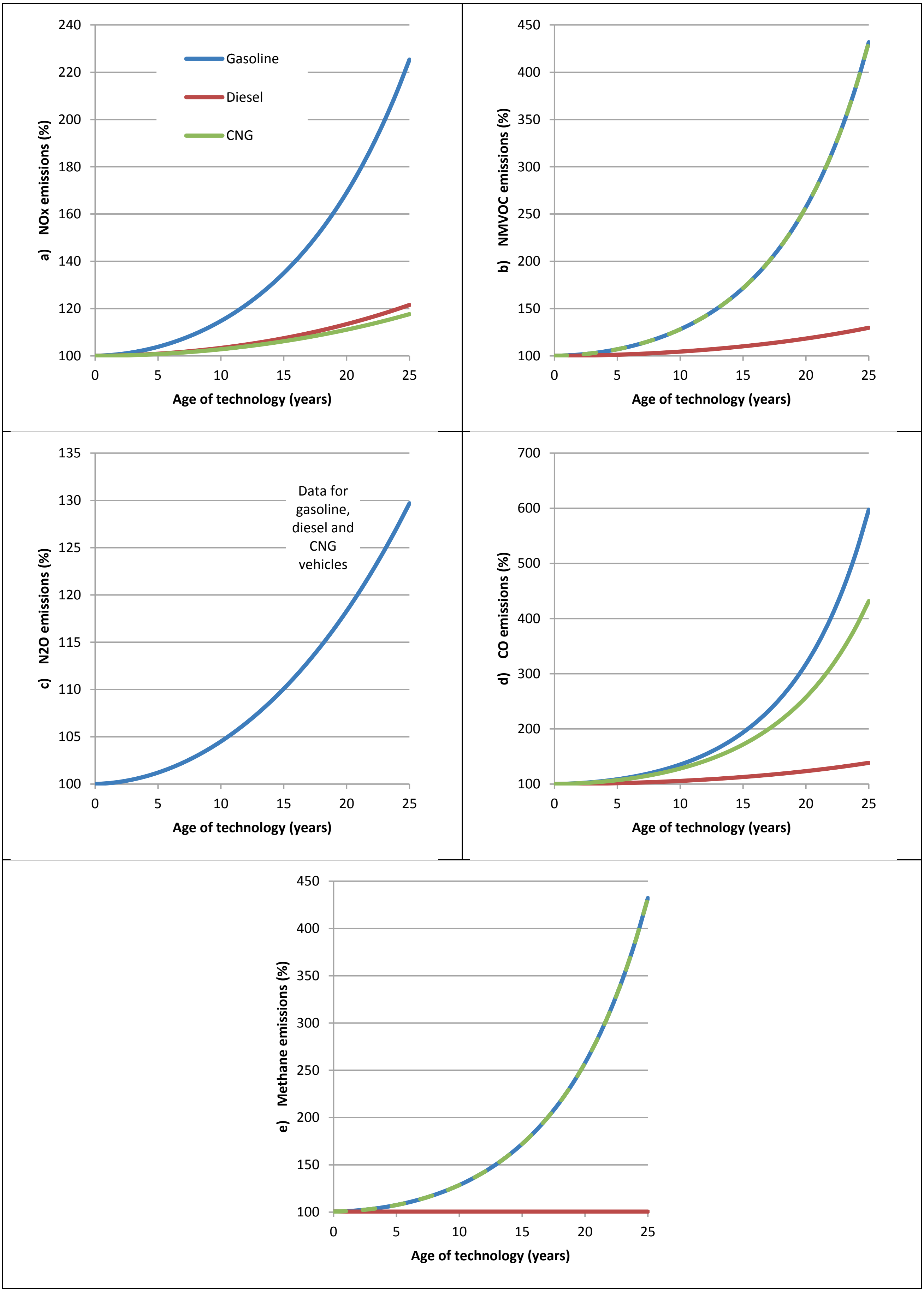


***Figure 115.*** *Degradation profiles for: a) NOx, b) NMVOC, c) $N_2O$, d) CO and e) methane emissions (Toro Gómez, Molina Vásquez, Londoño Largo, & Acevedo Cardona, 2012)*

***Table 63.*** *Income shares by quintile and region in 1999*

| **Quintile** | **Urban (%)** | **Rural (%)** |
|---|---|---|
| Income share by lowest 20% (Q1) | 33.98% | 66.02% |
| Income share by second 20% (Q2) | 51.00% | 49.00% |
| Income share by third 20% (Q3) | 63.14% | 36.86% |
| Income share by fourth 20% (Q4) | 74.11% | 25.89% |
| Income share by highest 20% (Q5) | 83.78% | 16.22% |

***Table 64.*** *Past and future income shares by quintile*

| | **1980** | **1985** | **1990** | **1995** | **2000** | **2005** | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Income shares by quintile** | | | | | | | | | | | |
| Income share by lowest 20% (Q1) | 2.60% | 3.06% | 3.57% | 2.75% | 1.90% | 2.79% | 2.79% | 3.31% | 3.18% | 2.75% | 2.62% |
| Income share by second 20% (Q2) | 5.97% | 6.75% | 7.38% | 7.38% | 6.76% | 7.11% | 6.70% | 6.70% | 6.70% | 6.70% | 6.70% |
| Income share by third 20% (Q3) | 10.52% | 11.52% | 12.21% | 11.43% | 10.97% | 11.24% | 11.12% | 11.21% | 11.24% | 11.26% | 11.27% |
| Income share by fourth 20% (Q4) | 18.20% | 19.33% | 19.95% | 18.70% | 18.13% | 18.54% | 18.84% | 18.78% | 18.68% | 18.70% | 18.78% |
| Income share by highest 20% (Q5) | 62.71% | 59.35% | 56.90% | 59.74% | 62.24% | 60.32% | 60.54% | 60.01% | 60.20% | 60.59% | 60.64% |

***Table 65.*** *Household expenditure per person by quintile and region*

| | **1980** | **1985** | **1990** | **1995** | **2000** | **2005** | **2010** | **2015** | **2020** | **2025** | **2030** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rural household expenditure per person-quintile (US$2005/person)** | | | | | | | | | | | |
| Lowest 20% (Q1) | 839 | 1069 | 1439 | 1343 | 919 | 1519 | 1854 | 2678 | 3176 | 3326 | 3769 |
| Second 20% (Q2) | 1430 | 1751 | 2210 | 2678 | 2428 | 2873 | 3303 | 4028 | 4966 | 6020 | 7166 |
| Third 20% (Q3) | 1895 | 2249 | 2752 | 3119 | 2963 | 3417 | 4125 | 5066 | 6268 | 7611 | 9068 |
| Fourth 20% (Q4) | 2303 | 2650 | 3158 | 3585 | 3440 | 3958 | 4908 | 5965 | 7314 | 8878 | 10610 |
| Highest 20% (Q5) | 4971 | 5099 | 5643 | 7174 | 7398 | 8068 | 9879 | 11938 | 14766 | 18015 | 21465 |
| Average | 2288 | 2564 | 3040 | 3580 | 3430 | 3967 | 4814 | 5935 | 7298 | 8770 | 10416 |
| **Urban household expenditure per person-quintile (US$2005/person)** | | | | | | | | | | | |
| Lowest 20% (Q1) | 263 | 289 | 344 | 289 | 183 | 281 | 319 | 436 | 493 | 496 | 544 |
| Second 20% (Q2) | 907 | 957 | 1069 | 1166 | 979 | 1074 | 1148 | 1327 | 1558 | 1814 | 2091 |
| Third 20% (Q3) | 1980 | 2023 | 2190 | 2234 | 1967 | 2102 | 2359 | 2747 | 3236 | 3774 | 4355 |
| Fourth 20% (Q4) | 4020 | 3983 | 4201 | 4291 | 3815 | 4069 | 4690 | 5405 | 6310 | 7357 | 8516 |
| Highest 20% (Q5) | 15659 | 13829 | 13545 | 15496 | 14807 | 14965 | 17036 | 19521 | 22988 | 26941 | 31089 |
| Average | 4566 | 4216 | 4270 | 4695 | 4350 | 4498 | 5110 | 5887 | 6917 | 8076 | 9319 |

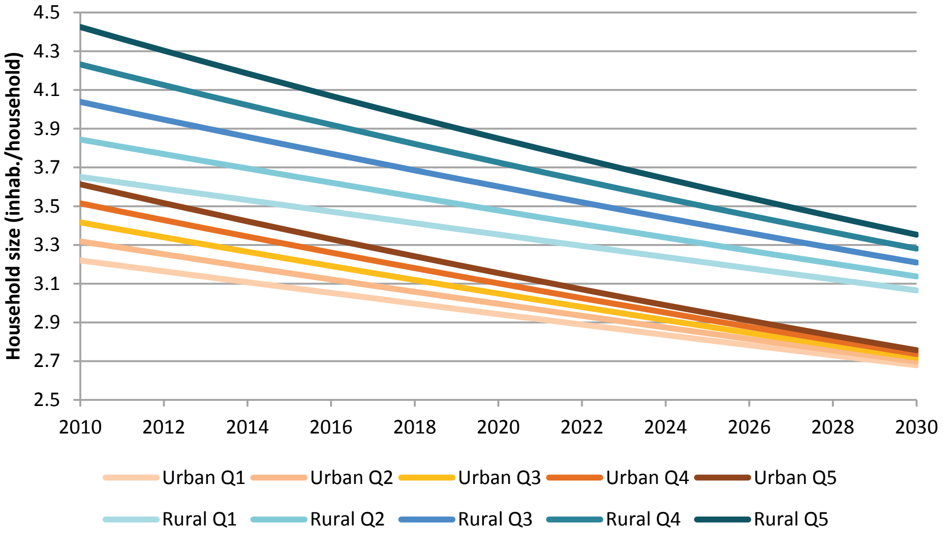


***Figure 116.*** *Household size by region and quintile*

***Table 66.*** *Floor space by region and quintile*

| Floorspace | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|
| **Rural ($m^2$/person)** | | | | | |
| Q1 | 21.85 | 23.53 | 25.61 | 27.80 | 30.01 |
| Q2 | 25.73 | 27.71 | 30.16 | 32.74 | 35.33 |
| Q3 | 29.61 | 31.89 | 34.71 | 37.67 | 40.66 |
| Q4 | 33.49 | 36.07 | 39.25 | 42.61 | 45.99 |
| Q5 | 37.37 | 40.24 | 43.80 | 47.54 | 51.31 |
| **Urban ($m^2$/person)** | | | | | |
| Q1 | 17.03 | 18.37 | 20.03 | 21.76 | 23.51 |
| Q2 | 20.06 | 21.64 | 23.58 | 25.63 | 27.68 |
| Q3 | 23.08 | 24.90 | 27.14 | 29.49 | 31.86 |
| Q4 | 26.11 | 28.16 | 30.69 | 33.35 | 36.03 |
| Q5 | 29.13 | 31.42 | 34.25 | 37.22 | 40.21 |

***Table 67.*** *Historical access to electricity and natural gas by region*

| | 1973 | 1985 | 1993 | 1997 | 2003 | 2008 | 2010 | 2011 |
|---|---|---|---|---|---|---|---|---|
| **Access to electricity** | | | | | | | | |
| Rural | 15.4 | 40.8 | 71 | 77.2 | 83.1 | 89.2 | 90.7 | 89.9 |
| Urban | 88.6 | 95.1 | 99.2 | 99.6 | 99.8 | 99.4 | 99.6 | 99.5 |
| Total | 61.9 | 78.2 | 91.2 | 93.8 | 95.6 | 97.2 | 97.7 | 97.4 |
| References | (Fresneda, Gonzalez, Cárdenas, & Sarmiento, 2009) | (Fresneda, Gonzalez, Cárdenas, & Sarmiento, 2009) | (Fresneda, Gonzalez, Cárdenas, & Sarmiento, 2009) | (Parra Torrado, 2011) | (Parra Torrado, 2011) | (Parra Torrado, 2011) | (DANE, 2010b) | (DANE, 2011) |
| **Access to natural gas** | | | | | | | | |
| Rural | 0 | 0 | N.A. | 0.8 | 2.4 | 3.6 | 5.1 | 4 |
| Urban | 0 | 0 | N.A. | 25.1 | 46.8 | 61.2 | 65.3 | 65.6 |
| Total | 0 | 0 | N.A. | 18.9 | 35.9 | 47.4 | 52.4 | 52.1 |
| References | | (Coronado Arango & Uribe Botero, 2005) | | (Parra Torrado, 2011) | (Parra Torrado, 2011) | (Parra Torrado, 2011) | (DANE, 2010b) | (DANE, 2011) |

***Table 68.*** *Gompertz parameters to model the access to electricity and natural gas*

| | **Electricity** | | **Natural gas** | |
|---|---|---|---|---|
| | **Rural** | **Urban** | **Rural** | **Urban** |
| Parameter $\kappa_1$ | 100 | 100 | 100 | 100 |
| Parameter $\kappa_2$ | 2.18446 | 0.13653 | 6.37273 | 5.99393 |
| Parameter $\kappa_3$ | 0.08488 | 0.10477 | 0.02833 | 0.08802 |
| Coefficient of determination $R^2$ | 99.05% | 97.49% | 93.31% | 99.75% |

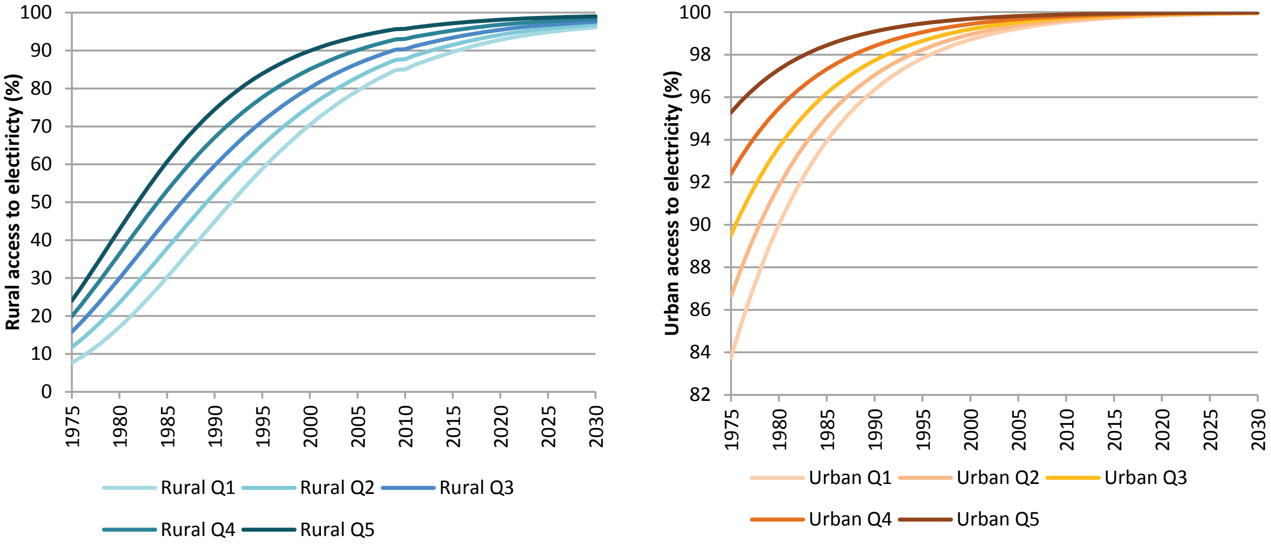


***Figure 117.*** *Estimated access to electricity by region and quintile*

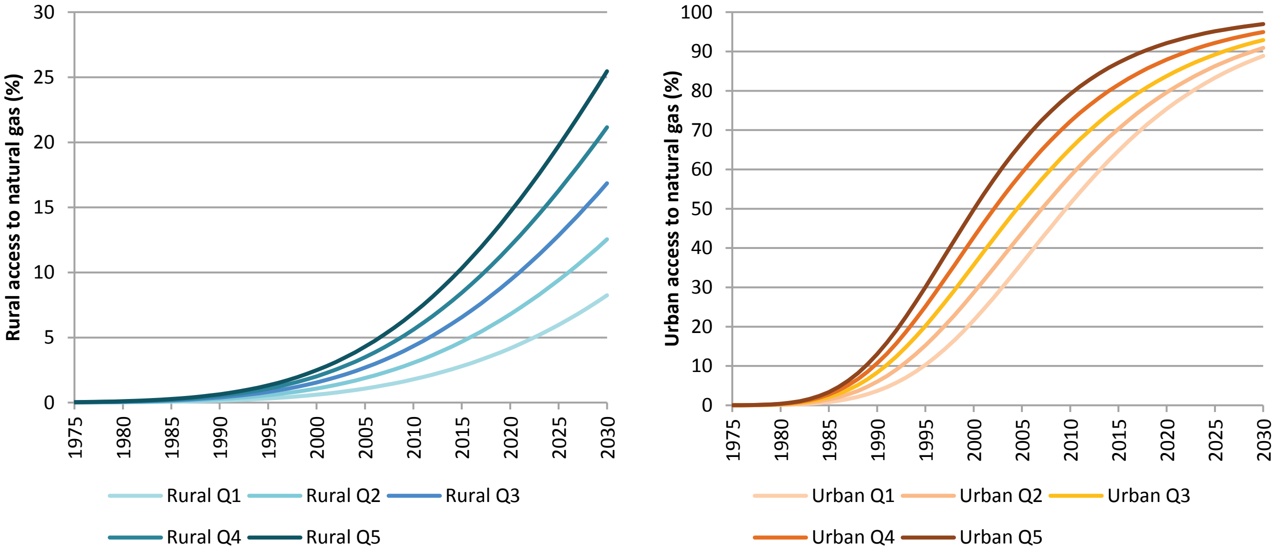


***Figure 118.*** *Estimated access to natural gas by region and quintile*

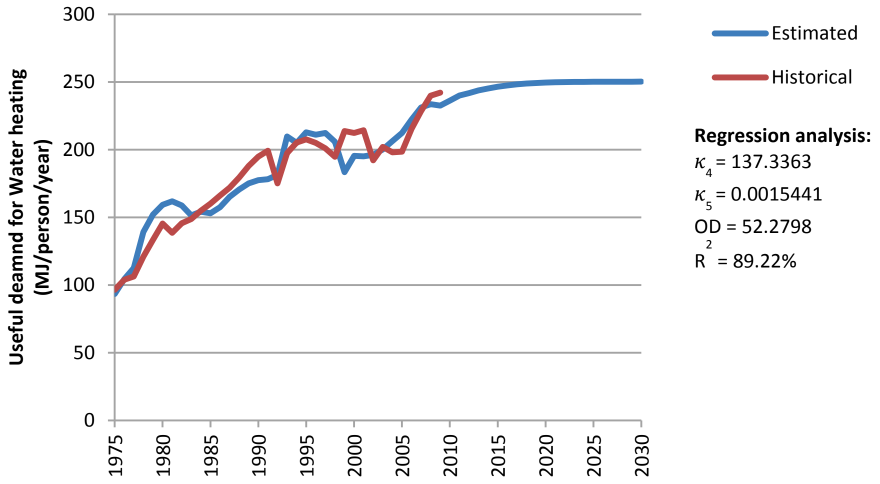


*Figure 119. Historical and estimated useful demand for water heating*

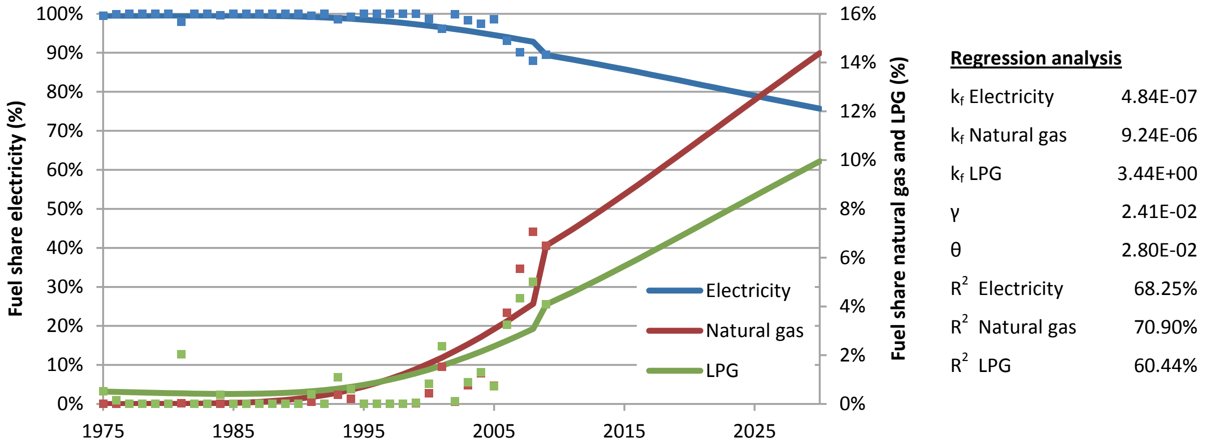


*Figure 120. Historical and estimated fuel shares for water heating*

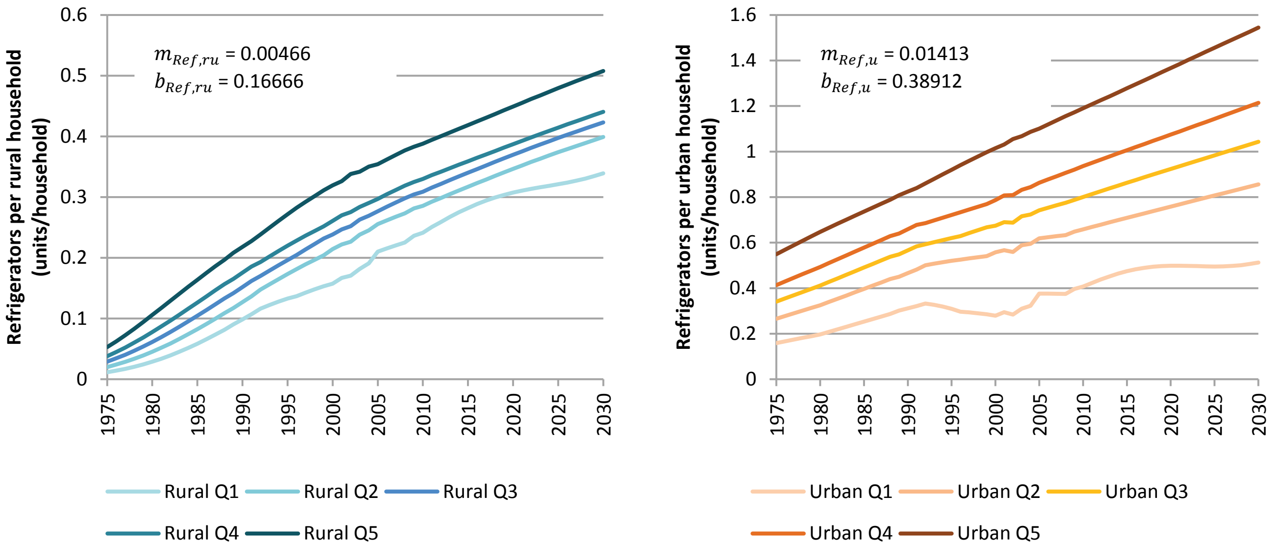
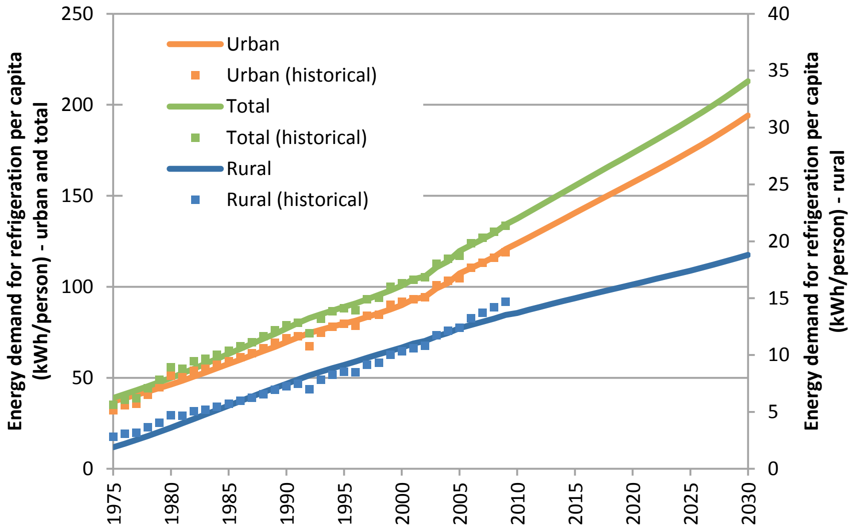


*Figure 121. Ownership of refrigerators by region and quintile*



**Regression analysis**

| | |
|---|---|
| $\vartheta_{Ref}$ | 501.4419 |
| $\zeta_{Ref}$ | 0.9639 |
| $UEC_{MAx,Ref}$ | 600 |

| **Gompertz** | **Rural** | **Urban** |
|---|---|---|
| $\kappa_6$ | 5 | 5 |
| $m_{Ref}$ | 0.0046 | 0.0141 |
| $b_{Ref}$ | 0.1666 | 0.3891 |
| $d_{Ref}$ | 27.9541 | 27.9560 |
| $e_{Ref}$ | 104.2357 | 104.2357 |
| $R^2$ | 96.38% | 98.92% |

***Figure 122.*** *Energy demand for refrigeration per capita (historical vs. estimations)*

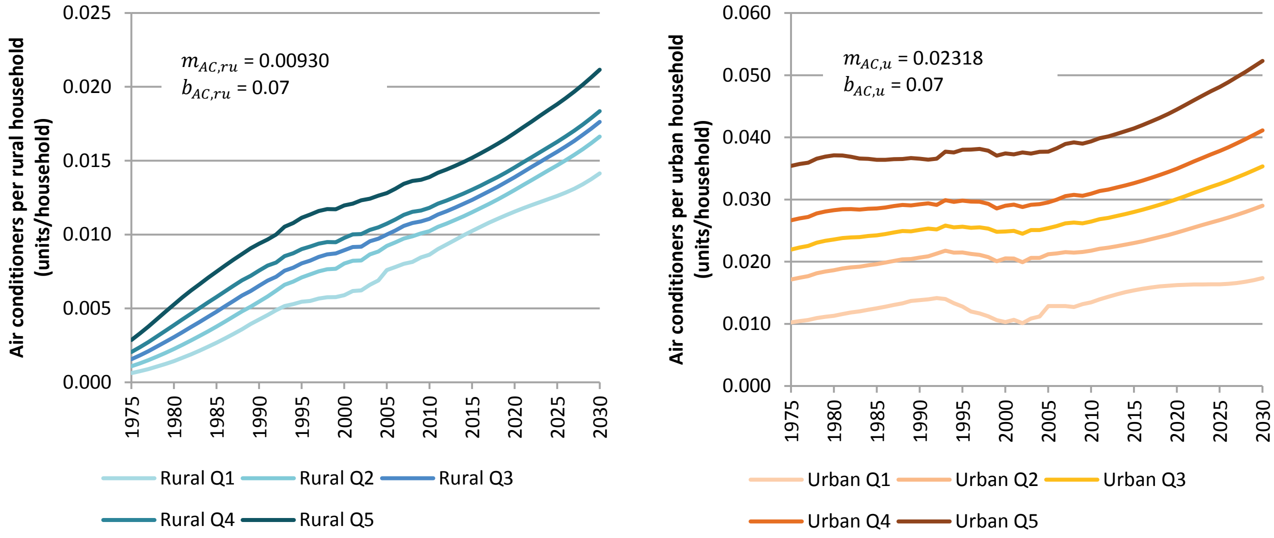
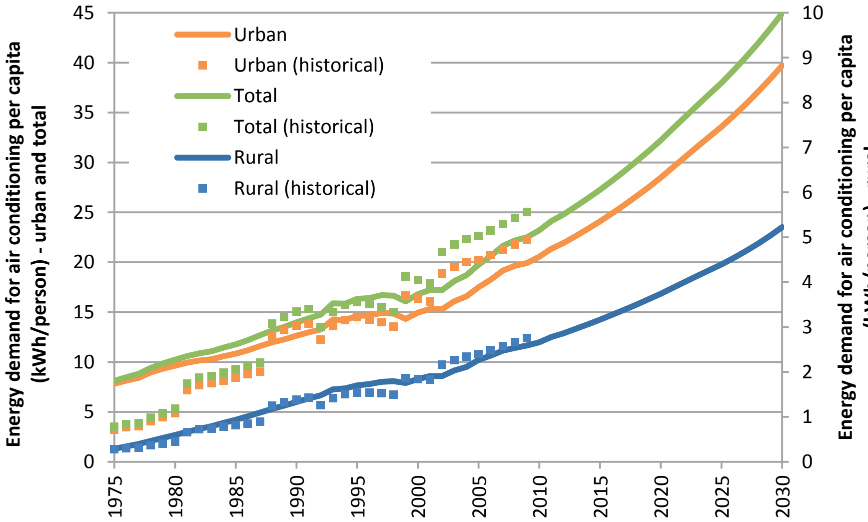


***Figure 123.*** *Ownership of air conditioners by region and quintile*



**Regression analysis**

| | |
|---|---|
| $COP$ | 3.5 (in 2050) |
| $COP_{Re}$ | 2.8 (in 2009) |

| **Parameters** | **Rural** | **Urban** |
|---|---|---|
| $\kappa_6, \kappa_7$ | 0 | 0 |
| $m_{AC}$ | 0.0093 | 0.02318 |
| $b_{AC}$ | 0.07 | 0.07 |
| $R^2$ | 96.06% | 77.80% |

***Figure 124.*** *Energy demand for air conditioning per capita (historical vs. estimations)*

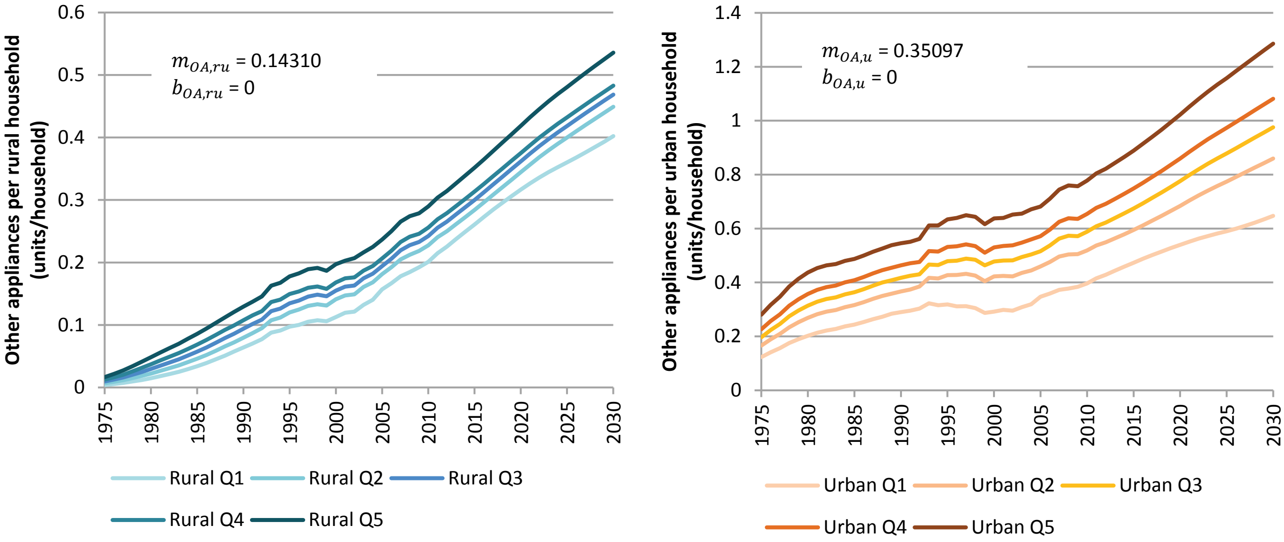
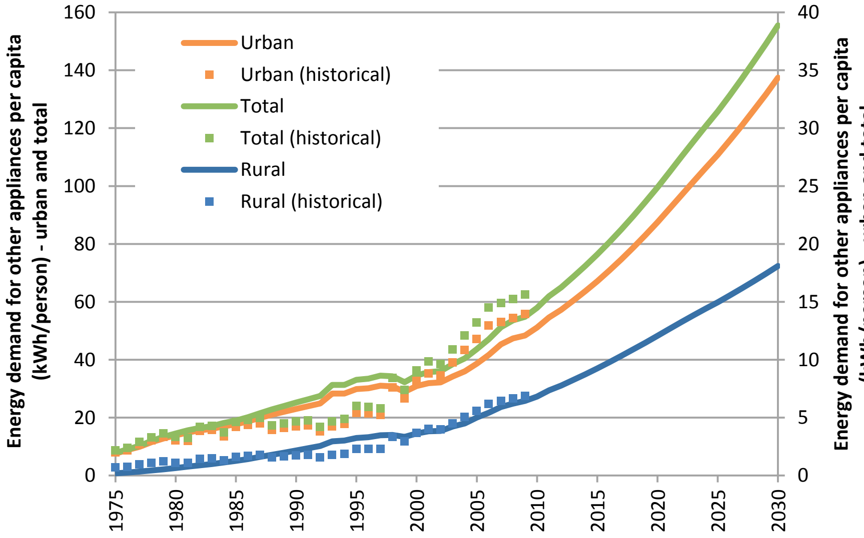


***Figure 125.*** *Ownership of other appliances by region and quintile*

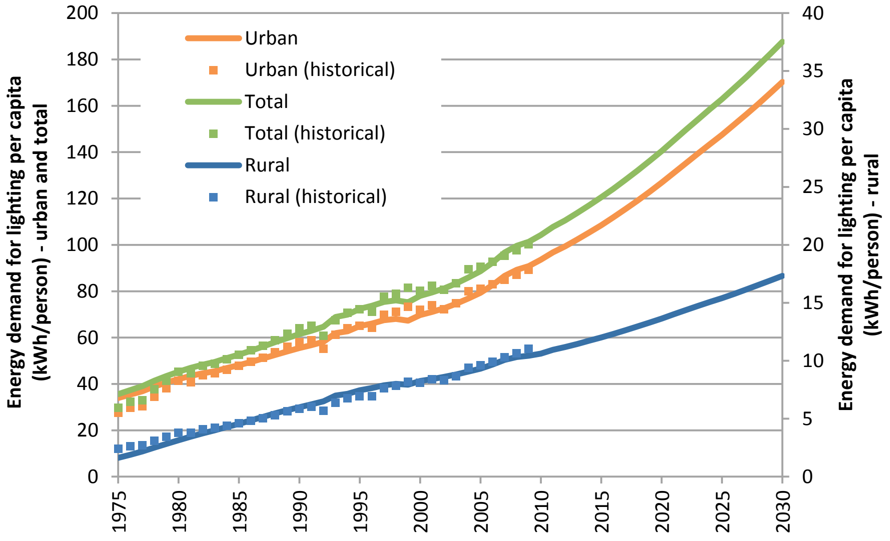


**Regression analysis**

| | |
|---|---|
| $C1_{OA}$ | 148.39815 |
| $C2_{OA}$ | 786.51005 |

| **Gompertz** | **Rural** | **Urban** |
|---|---|---|
| $\kappa_6$ | 2 | 2 |
| $\kappa_7$ | 0.23185 | 0.21444 |
| $m_{OA}$ | 0.14310 | 0.35097 |
| $b_{OA}$ | 0 | 0 |
| $R^2$ | 89.13% | 83.09% |

***Figure 126.*** *Energy demand for other appliances per capita (historical vs. estimations)*



**Regression analysis**

| | **Rural** | **Urban** |
|---|---|---|
| $LHF_r$ | 0.431292 | 1.251358 |
| $R^2$ | 97.25% | 97.4% |

***Figure 127.*** *Energy demand for lighting per capita (historical vs. estimations)*

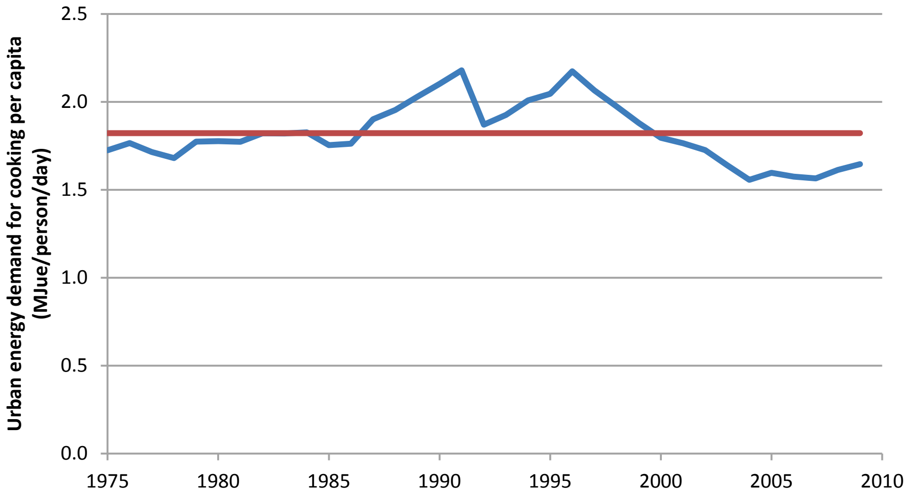
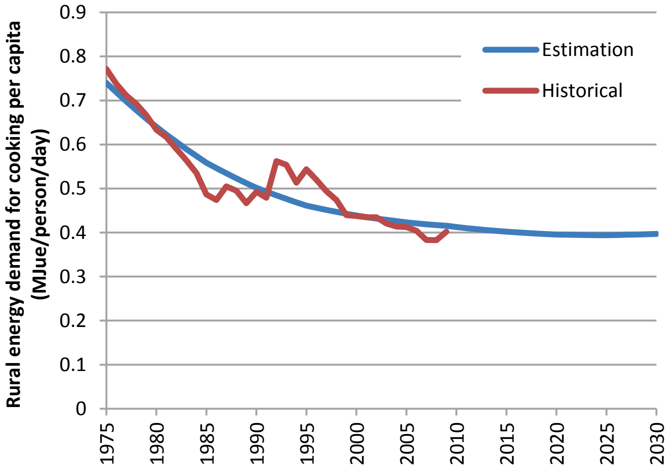


***Figure 128.*** *Historical urban energy demand for cooking per capita*



**Regression analysis**

$CK1$ = 0.06299
$CK2$ = 0.96123
$CK3$ = 0.00478
$R^2$ = 86.61%

***Figure 129.*** *Historical and estimated rural energy demand for cooking per capita*

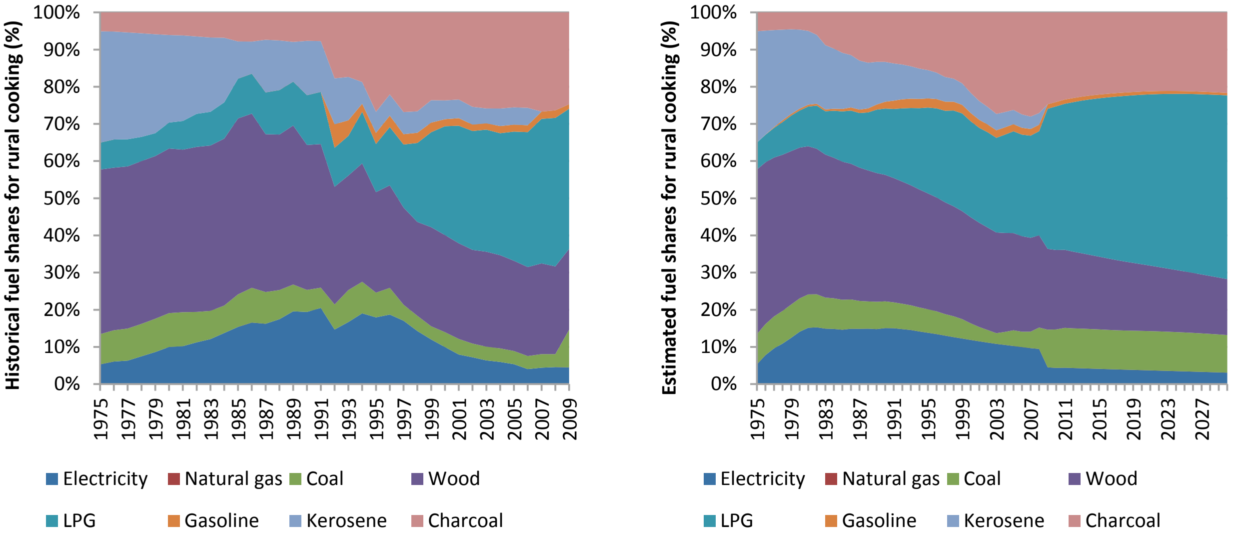


***Figure 130.*** *Historical and estimated fuel shares for rural cooking*

***Table 69.*** *Model parameters to estimate fuel shares for rural cooking*

| **Fuel** | $\gamma$ | $k_f$ | $\theta$ | **$R^2$** |
|---|---|---|---|---|
| Electricity | 5.28591 | 0.47499 | 0.03130 | 53.10% |
| Natural gas | 5.28591 | 2.22007 | 0.00000 | 100.00% |
| Coal | 5.28591 | 1.54585 | 0.50000 | 80.40% |
| Wood | 5.28591 | 1.61729 | 0.01740 | 76.23% |
| LPG | 5.28591 | 0.14489 | 0.02608 | 71.43% |
| Gasoline | 5.28591 | 0.32915 | 0.03300 | 55.65% |
| Kerosene | 5.28591 | 1.12338 | 0.06618 | 92.86% |
| Charcoal | 5.28591 | 0.32906 | 0.03610 | 78.65% |

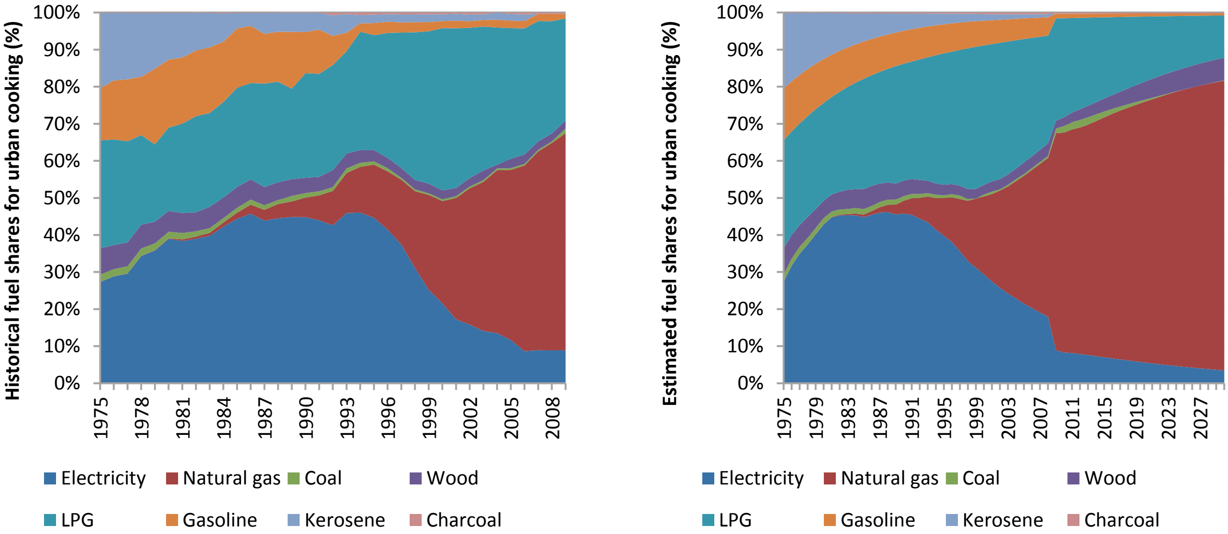


***Figure 131.*** *Historical and estimated fuel shares for urban cooking*

***Table 70.*** *Model parameters to estimate fuel shares for urban cooking*

| **Fuel** | $\gamma$ | $k_f$ | $\theta$ | **$R^2$** |
|---|---|---|---|---|
| Electricity | 2.84822 | 0.28248 | 0.07738 | 80.47% |
| Natural gas | 2.84822 | 0.11892 | 0.14616 | 89.44% |
| Coal | 2.84822 | 0.96167 | 0.51704 | 89.53% |
| Wood | 2.84822 | 0.13601 | 0.12188 | 86.21% |
| LPG | 2.84822 | 0.11630 | 0.07437 | 67.93% |
| Gasoline | 2.84822 | 0.42613 | 0.03736 | 53.86% |
| Kerosene | 2.84822 | 1.14088 | 0.09420 | 96.24% |
| Charcoal | 2.84822 | 1.09590 | 0.03696 | 30.53% |

***Table 71.** Results of the regression analysis of the energy demand by fuel for various sectors*

| | **Agriculture** | | | | **Commercial** | | | | **Industrial** | | | | **Transport by air** | | | | **Transport by rail** | | | | **Transport by river** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $\theta$ | $\xi_1$ | $\xi_2$ | $R^2$ | $\theta$ | $\xi_1$ | $\xi_2$ | $R^2$ | $\theta$ | $\xi_1$ | $\xi_2$ | $R^2$ | $\theta$ | $\xi_1$ | $\xi_2$ | $R^2$ | $\theta$ | $\xi_1$ | $\xi_2$ | $R^2$ | $\theta$ | $\xi_1$ | $\xi_2$ | $R^2$ |
| Bagasse | | | | | | | | | 0.01 | 0.00 | 0.11 | 0.77 | | | | | | | | | | | | |
| Biodiesel | | | | a | | | | | | | | | | | | | | | | | | | | |
| Bioethanol | | | | a | | | | | | | | | | | | | | | | | | | | |
| Charcoal | | | | | | | | | | | | b | | | | | | | | | | | | |
| Coal | | | | | | | | | 0.02 | 0.00 | 1.99 | 0.88 | | | | | 0.00 | 0.00 | -6.03 | 0.86 | | | | |
| Coke | | | | | | | | | 0.14 | 0.00 | 0.72 | 0.57 | | | | | | | | | | | | |
| Diesel | 0.02 | 0.00 | 2.15 | 0.88 | 0.15 | -3.17 | 1.06 | 0.78 | 0.18 | -0.21 | 1.34 | 0.86 | | | | | | | | b | | | | b |
| Electricity | 0.00 | -148.21 | 88.88 | 0.75 | 0.00 | -15.85 | 10.24 | 0.98 | 0.00 | -11.77 | 11.26 | 0.99 | | | | | | | | | 0.15 | 0.00 | 0.31 | 0.80 |
| Fuel Oil | | | | b | | | | b | 0.00 | 0.00 | -47.74 | 0.90 | | | | | | | | b | 0.05 | -2.15 | 0.94 | 0.79 |
| Gasoline | 0.09 | -0.88 | 0.52 | 0.67 | | | | | 0.09 | -1.68 | 0.93 | 0.82 | 0.00 | -5.99 | -5.08 | 0.90 | | | | b | 0.90 | -0.70 | 0.88 | 0.73 |
| Industrial gas | | | | | | | | | 0.69 | -0.10 | 0.93 | 0.64 | | | | | | | | | | | | |
| Kerosene | 0.01 | -38.93 | 22.14 | 0.95 | | | | b | | | | b | 0.00 | 0.00 | 65822.39 | 0.70 | | | | | | | | |
| LPG | | | | | 0.73 | -0.42 | 1.00 | 0.92 | 0.43 | -0.54 | 1.26 | 0.94 | | | | | | | | | | | | |
| NG | | | | | 0.09 | -0.70 | 1.36 | 0.98 | 1.00 | -0.06 | 1.59 | 0.87 | | | | | | | | | | | | |
| Non energy | | | | | | | | | | | | b | | | | | | | | | | | | |
| Oil | 0.24 | -1.22 | 1.48 | 0.91 | 0.00 | -0.24 | 5.19 | 0.98 | 0.77 | -1.83 | 2.63 | 0.63 | | | | | | | | | 0.38 | -1.32 | 1.85 | 0.99 |
| Refinery gas | | | | | | | | | | | | b | | | | | | | | | | | | |
| Waste | | | | | | | | | 0.15 | 0.00 | 1.11 | 0.77 | | | | | | | | | | | | |
| Wood | | | | b | | | | | | | | b | | | | | | | | | | | | |

a. Not sufficient years to evaluate the regression analysis. It is assumed that the demand for bioethanol and biodiesel in the agricultural sector remains constant with the value of year 2009.

b. Coefficient of determination lower than 60%. Future demand is assumed to be the average of the last ten years if available. If not available, it is used the average of available data

***Table 72.** Assumed energy demand by sector in fuel in cases where regression was not satisfactory*

| **kTOE** | **Agriculture** | **Commercial** | **Industrial** | **Transport by air** | **Transport by rail** | **Transport by river** |
|---|---|---|---|---|---|---|
| Biodiesel | 29.11 | | | | | |
| Bioethanol | 0.24 | | | | | |
| Charcoal | | | 9.74 | | | |
| Diesel | | | | | 29.12 | 661.01 in 2010, 1464.31 in 2030 |
| Fuel oil | 0.48 | 1.51 | | | 2.14 | |
| Gasoline | | | | | 0.00 | |
| Kerosene | | 0.00 | 96.49 | | | |
| Non energy | | | 325.41 | | | |
| Refinery gas | | | 0.00 | | | |
| Wood | 332.01 | | 10.43 | | | |

**Table 73.** *Assumptions about power generation technologies*

| Power technologies | Available in current portfolio | Available in future portfolio | Installed capacity in 2009 (MW)[6] | Lifetime (years) | Construction time (years) | Capacity factor (%) | Capacity credit (%) | Capital cost[9] (US$2009/kW) | | | O&M cost (US$2009/kW) | | | Electrical efficiency[10] (%) Heat co-product efficiency in brackets | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | Currently installed units[6] | New units | | |
| | | | | | | | | 2009 | 2020 | 2030 | 2009 | 2020 | 2030 | 2009 | 2009 | 2020 | 2030 |
| Natural gas combined cycle | ✓ | ✓ | 0 | 30[1] | 2[1] | 0.85[1] | 100 | 700[2] | 700[2] | 700[2] | 25[2] | 25[2] | 25[2] | - | 57[2] | 59[2] | 61[2] |
| Natural gas simple cycle GT[15]– Large | ✓ | ✓ | 2478 | 30[1] | 2[1] | 0.85[1] | 100 | 400[2] | 400[2] | 400[2] | 20[2] | 20[2] | 20[2] | 38.1 | 36[2] | 38[2] | 40[2] |
| Simple cycle gas turbine GT[15]– Small | ✓ | ✓ | 628.84 | 30[1] | 2[1] | 0.85[1] | 100 | 400[2] | 400[2] | 400[2] | 20[2] | 20[2] | 20[2] | 30.9 | 31[6] | 31[6] | 31[6] |
| Natural gas reciprocating engine | ✓ | ✓ | 15.25 | 30[1] | 2[1] | 0.85[1] | 100 | 443[4] | 443[4] | 443[4] | 20[4] | 20[4] | 20[4] | 30.9 | 31[6] | 31[6] | 31[6] |
| Hydro power plant – Large | ✓ | ✓ | 8525 | 50[2] | 4[2] | Variable[3a] | 85[11] | 1860[2] | 1900[2] | 2050[2] | 45[2] | 46[2] | 49[2] | 84 | 84[6] | 84[6] | 84[6] |
| Hydro power plant – Small | ✓ | ✓ | 518.8 | 50[2] | 4[2] | Variable[3b] | 85[11] | 3130[2] | 3150[2] | 3160[2] | 59[2] | 60[2] | 60[2] | 84 | 84[6] | 84[6] | 84[6] |
| Coal power plant – Large | ✓ | ✓ | 990 | 40[1] | 4[1] | 0.85[1] | 100 | 1400[2] | 1400[2] | 1400[2] | 44[2] | 44[2] | 44[2] | 38.1 | 35[2] | 35[2] | 35[2] |
| Coal power plant – Small | ✓ | ✓ | 53.24 | 40[1] | 4[1] | 0.85[1] | 100 | 2032[5] | 2032[5] | 2032[5] | 44[2] | 44[2] | 44[2] | 30.9 | 31[6] | 31[6] | 31[6] |
| Diesel reciprocating engine | ✓ | ✓ | 7.06 | 30[1] | 2[1] | 0.85[1] | 100 | 443[4] | 443[4] | 443[4] | 20[4] | 20[4] | 20[4] | 30.9 | 31[6] | 31[6] | 31[6] |
| Wind turbine | ✓ | ✓ | 18.4 | 20[2] | 1.5[2] | Variable[3c] | 20[12] | 1470[2] | 1390[2] | 1370[2] | 22[2] | 21[2] | 21[2] | 100 | 100[2] | 100[2] | 100[2] |
| Biomass CHP – Medium | ✓ | ✓ | 315.34 | 25[2] | 2[2] | Variable[3d] | 90[13] | 2830[2] | 2790[2] | 2590[2] | 106[2] | 102[2] | 97[2] | 4.9 (37.8)[7] | 35 (35)[2] | 35 (35)[2] | 35 (35)[2] |
| Biomass CHP – Small | × | ✓ | 0 | 25[2] | 2[2] | Variable[3e] | 90[13] | 4710[2] | 4540[2] | 4310[2] | 177[2] | 170[2] | 162[2] | - | 30 (35)[2] | 30 (35)[2] | 30 (35)[2] |
| Biomass co-firing | × | ✓ | 0 | 40[2] | 2[2] | 0.7[2] | 100[14] | 550[2] | 530[2] | 510[2] | 21[2] | 20[2] | 19[2] | - | 37[2] | 37[2] | 37[2] |
| Syngas co-firing in simple cycle GT[15] | × | ✓ | 0 | 30[2] | 2[2] | 0.7[2] | 100[14] | 550[2] | 530[2] | 510[2] | 21[2] | 20[2] | 19[2] | - | 36[8] | 38[8] | 40[8] |
| Syngas co-firing in combined cycle GT[15] | × | ✓ | 0 | 30[2] | 2[2] | 0.7[2] | 100[14] | 550[2] | 530[2] | 510[2] | 21[2] | 20[2] | 19[2] | - | 57[8] | 59[8] | 61[8] |
| Biogas reciprocating engine | × | ✓ | 0 | 25[2] | 2[2] | 0.7[2] | 90[13] | 2340[2] | 2230[2] | 2110[2] | 89[2] | 85[2] | 80[2] | - | 30 (35)[2] | 30 (35)[2] | 30 (35)[2] |

[1] (IEA-NEA, 2010)

[2] (IEA, 2012a), using values corresponding to Africa

[3a] Assumed capacity factor as described in Section F.4.2.1. For LCOE calculations it is used the average of 1998-2011, i.e. 50.01% (XM, 2013)

[3b] Assumed capacity factor as described in Section F.4.2.1. For LCOE calculations it is used the average of 1998-2011, i.e. 50.01% (XM, 2013)

[3c] Assumed capacity factor as described in Section F.4.2.1. For LCOE calculations it is used the average of 2004-2011, i.e. 34.30% (XM, 2013)

[3d] Assumed capacity factor as described in Section F.4.2.1. For LCOE calculations it is used the average of 2004-2011, i.e. 59.19% (XM, 2013)

[3e] Assumed capacity factor as described in Section F.4.2.1.

[4] (Thermoflow, 2011), cost database

[5] Down-scaled using the equation $Cost_{Small} = Cost_{Large}(600MW_{Large}/50MW_{Large})^{0.15}$

[6] (UPME, 2011b)

[7] Numbers corresponding to bagasse-fuelled CHP steam power plants in sugar industry

[8] Assumed to respectively match the efficiencies of simple and combined cycles without co-firing

[9] It includes owner's costs but exclude interest during construction

[10] Electrical efficiency based on the lower heating value (LHV)

[11] Capacity credit for hydro power is close to 100% according to (Sims, et al., 2011). It is assumed a value of 85%, in line with (Mora Alvarez, 2012)

[12] Capacity credit for wind power ranges between 5-40% depending on market and location and decreases with increasing penetration level (Sims, et al., 2011). It is assumed a value of 20%, in line with (Mora Alvarez, 2012)

[13] Capacity credit for bioenergy is close to 100% according to (Sims, et al., 2011). It is assumed a value of 90%, in line with (DLR, 2005).

[14] Capacity credit for bioenergy is close to 100% according to (Sims, et al., 2011). It is assumed that since co-firing occurs in a thermal power plant, it has the same capacity credit of a thermal power plant, i.e. 100%

[15] GT stands for gas turbine

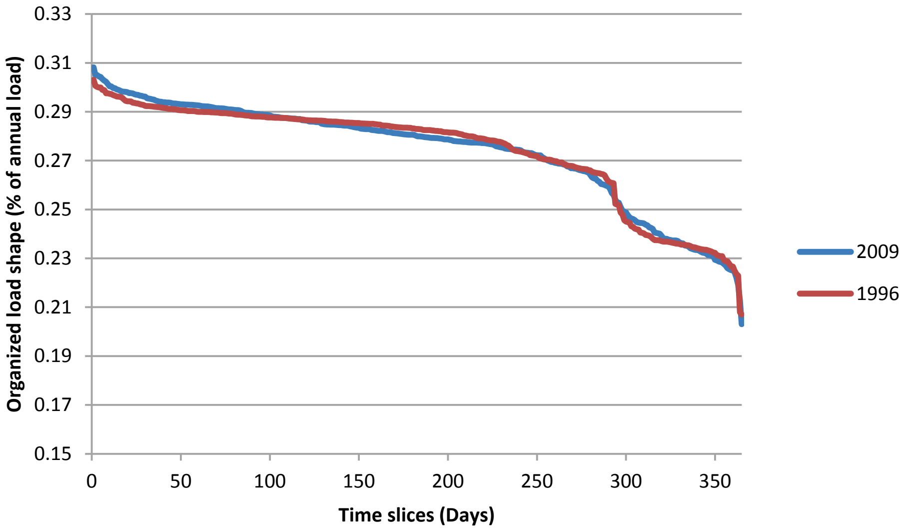


*Figure 132. Organized energy load shape (% of annual load), taken from (XM, 2013)*

*Table 74. Exogenous capacity added by technology until 2019*

| Addition | Capacity added (MWe) | Technology | Year | Reference |
|---|---|---|---|---|
| Porce III | 660 | Hydro power plant - Large | 2012 | (Portafolio, 2011a; UPME, 2009) |
| Amoya | 78 | Hydro power plant - Large | 2012 | (El Colombiano, 2013; UPME, 2009) |
| Termo Flores | 163 | Natural gas simple cycle - Large | 2012 | (IFC, 2008; UPME, 2009) |
| Amaime | 19.9 | Hydro power plant - Small | 2012 | (Portafolio, 2011b; UPME, 2009) |
| Termocol | 202 | Natural gas simple cycle - Large | 2014 | (BNamericas, 2012; UPME, 2009) |
| Gecelca III | 150 | Coal power plant - Large | 2014 | (UPME, 2009) |
| Popal | 20 | Hydro power plant - Small | 2014 | (UPME, 2009) |
| Bajo Tulua | 20 | Hydro power plant - Small | 2014 | (UPME, 2009) |
| Tunjita | 20 | Hydro power plant - Small | 2014 | (UPME, 2009) |
| Cucuana | 60 | Hydro power plant - Large | 2015 | (UPME, 2009) |
| El Quimbo | 420 | Hydro power plant - Large | 2015 | (Portafolio, 2012a; UPME, 2009) |
| Sogamoso | 800 | Hydro power plant - Large | 2015 | (UPME, 2009) |
| Gecelca 3.2 | 250 | Coal power plant - Large | 2016 | (UPME, 2009) |
| San Miguel | 42 | Hydro power plant - Large | 2016 | (Sector Electricidad, 2012; UPME, 2009) |
| Rio Ambeima | 45 | Hydro power plant - Large | 2016 | (Sector Electricidad, 2012; UPME, 2009) |
| Carlos Lleras Restrepo | 78 | Hydro power plant - Large | 2016 | (Sector Electricidad, 2012; UPME, 2009) |
| Termotasajero II | 160 | Coal power plant - Large | 2016 | (BNamericas, 2013; UPME, 2009) |
| Ituango Fase I | 1200 | Hydro power plant - Large | 2017 | (UPME, 2009) |
| Termonorte | 88 | Natural gas simple cycle - Large | 2018 | (Portafolio, 2013; UPME, 2009) |
| Ituango Fase II | 1200 | Hydro power plant - Large | 2019 | (UPME, 2009) |
| Porvenir II | 352 | Hydro power plant - Large | 2019 | (UPME, 2009) |

*Table 75. Capacity exogenously added to comply with the biogas and landfill gas targets in Scenarios I and II*

| Capacity exogenously added to comply with targets (MWe) | Scenario I | | | | Scenario II | | | |
|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2025 | 2030 | 2015 | 2020 | 2025 | 2030 |
| Reciprocating engines fuelled with biogas from animal waste | 8,70 | 58,82 | 109,63 | 152,30 | 8,70 | 58,82 | 109,63 | 152,30 |
| Reciprocating engines fuelled with landfill gas and biogas from animal waste/wastewater | 3,75 | 22,60 | 41,27 | 60,12 | 8,45 | 50,76 | 92,90 | 135,21 |

***Table 76.*** *Maximum annual capacity addition by technology*

| **Technology** | **Biomass resource** | **Max. annual capacity addition (MWe)** |
|---|---|---|
| Natural gas combined cycle | - | 575 |
| Natural gas simple cycle – Large | - | 575 |
| Natural gas simple cycle – Small | - | 100 |
| Natural gas reciprocating engine | - | 100 |
| Hydro power plant – Large | - | 1552 |
| Hydro power plant – Small | - | 60 |
| Coal power plant – Large | - | 410 |
| Coal power plant – Small | - | 100 |
| Diesel reciprocating engine | - | 100 |
| Wind turbine | - | 50 |
| Biomass CHP – Small | Bagasse from jaggery cane | 25.4 |
| Biomass co-firing | Wood and forestry residues | 99 |
| Syngas co-firing in simple cycle GT | Wood and biomass residues | 123.9 |
| Biomass CHP – Medium | Rice husk | 3.0 |
|  | Bagasse and leaves on a large-scale | 43.2 |
|  | Palm residues | 43.1 |
|  | Wood and forestry residues | 96.1 |
| Biogas reciprocating engine | Biogas from biodiesel plants | 6.6[1] |
|  | Biogas from wastewater plants | 0.07 |
|  | Biogas from animal waste | 8.7 |
|  | Landfill gas | 3.6 |

Notes:

[1] Assuming a FEF factor of 100% given that 100% of this resource is targeted to be used by 2030.

***Table 77.*** *Fuel assumptions*

| Fuel Name | Fuel Grouping | Net Energy Content (MJ) | per Physical Unit | LHV/HHV Ratio | Density (kg/liter) | % Carbon Content$^{a}$ | % Sulfur Content$^{a,b}$ | % Nitrogen Content$^{a}$ | % Ash Content$^{a}$ | % Moisture Content$^{a}$ | % Methane Content$^{a}$ | % Oxidized$^{a}$ | References |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bagasse | Bioenergy | 9.316 | kg | 0.90 | 0.6000 | 58.73 | 0.04 | 0.38 | 3.47 | 46.59 | 0.00 | 100 | Averaged values of data in (Gonzalez-Salazar, et al., 2014a) |
| Bagasse small scale | Bioenergy | 9.316 | kg | 0.90 | 0.6000 | 58.73 | 0.04 | 0.38 | 3.47 | 46.59 | 0.00 | 100 | Averaged values of data in (Gonzalez-Salazar, et al., 2014a) |
| Biodiesel | Bioenergy | 36950 | Ton | 0.95 | 0.8800 | 76.41 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 99 | LHV and density taken from (MIT, 2010), carbon content taken from (Agudelo, Gutiérrez, & Benjumea, 2011) |
| Biogas from animal waste | Bioenergy | 21.649 | $m^3$ | 0.90 | 0.0011 | 45.83 | 0.50 | 0.00 | 0.00 | 0.00 | 39.06 | 100 | (Gonzalez-Salazar, et al., 2014a) |
| Cane | Bioenergy | 7200 | Ton | - | - | - | - | - | - | - | - | - | (Patzek & Pimentel, 2005; BNDES - CGEE, 2008; Nogueira, 2008) |
| Cane leaves and top | Bioenergy | 10.082 | kg | 0.90 | 1.0000 | 50.06 | 0.09 | 0.92 | 9.57 | 41.00 | 0.00 | 100 | Averaged values of data in (Gonzalez-Salazar, et al., 2014a) |
| Cane leaves small scale | Bioenergy | 10.082 | kg | 0.90 | 1.0000 | 50.06 | 0.09 | 0.92 | 9.57 | 41.00 | 0.00 | 100 | Averaged values of data in (Gonzalez-Salazar, et al., 2014a) |
| Cane small scale | Bioenergy | 7200 | Ton | - | - | - | - | - | - | - | - | - | (Patzek & Pimentel, 2005; BNDES - CGEE, 2008; Nogueira, 2008) |
| Charcoal | Bioenergy | 28880 | Ton | 0.90 | 0.2500 | 88.00 | 0.00 | 1.40 | 1.00 | 5.00 | 0.00 | 100 | (Heaps, 2012) |
| Coal and Coal Products | Coal | 29310 | Ton | 0.95 | 1.3300 | 74.60 | 2.00 | 1.50 | 8.00 | 5.00 | 0.00 | 98 | (Heaps, 2012) |
| Crude NGL and Feedstocks | Oil | 41870 | Ton | 0.95 | 0.8740 | 83.50 | 1.00 | 1.00 | 0.05 | 0.00 | 0.00 | 99 | (Heaps, 2012) |
| Diesel | Oil | 43856 | Ton | 0.95 | 0.8370 | 85.96 | 0.05 | 0.00 | 0.01 | 0.00 | 0.00 | 99 | LHV taken from (UPME, 2010b), carbon content from (Agudelo, Gutiérrez, & Benjumea, 2011), sulfur and lead content from (Ecopetrol, 2013b), everything else from (Heaps, 2012) |
| Ethanol | Bioenergy | 26700 | Ton | 0.90 | 0.7920 | 52.17 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 100 | LHV taken from (MIT, 2010), carbon content calculated from formula $C_2H_6O$, everything else from (Heaps, 2012) |
| Forestry and wood residues | Bioenergy | 15080 | Ton | 0.90 | 0.8918 | 43.80 | 0.00 | 0.09 | 0.00 | 18.70 | 0.00 | 100 | LHV and density from (Gonzalez-Salazar, et al., 2014a), everything else from (Heaps, 2012) |
| Gas landfill and water treat. | Bioenergy | 16.993 | $m^3$ | 0.90 | 0.0013 | 39.96 | 0.50 | 0.00 | 0.00 | 0.00 | 26.71 | 100 | (Gonzalez-Salazar, et al., 2014a) |
| Gasoline | Oil | 44422 | Ton | 0.95 | 0.7400 | 84.60 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 99 | LHV taken from (UPME, 2010b), sulfur and lead content from (Ecopetrol, 2013b), everything else from (Heaps, 2012) |
| Heat | Other fuels | 1 | MJ | 1.00 | - | - | - | - | - | - | - | - | (Heaps, 2012) |
| Industrial gas | Gas | 39.513 | $m^3$ | 0.90 | 0.0008 | 73.40 | 0.00 | 0.03 | 0.00 | 0.00 | 100 | 100 | Assumed to be the same as natural gas |
| Kerosene | Oil | 44750 | Ton | 0.95 | 0.8100 | 85.00 | 0.04 | 0.98 | 0.00 | 0.00 | 0.00 | 99 | (Heaps, 2012) |
| LPG | Oil | 47310 | Ton | 0.95 | 0.5400 | 82.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 100 | (Heaps, 2012) |
| Metallurgical Coke | Coal | 26380 | Ton | 0.95 | 1.3500 | 85.00 | 0.75 | 1.00 | 2.75 | 5.00 | 0.00 | 98 | (Heaps, 2012) |
| Natural Gas | Gas | 39.513 | $m^3$ | 0.90 | 0.0008 | 73.40 | 0.00 | 0.03 | 0.00 | 0.00 | 100 | 100 | (UPME, 2010b), assumed to be 100% methane |
| Other Energy | Other fuels | 1 | MJ | 1.00 | - | - | - | - | - | - | - | - | (Heaps, 2012) |
| Palm Fresh Fruit Bunches | Bioenergy | 16.608 | kg | 0.90 | 1.0000 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0 | Averaged values of data in (Gonzalez-Salazar, et al., 2014a) |
| Palm oil | Bioenergy | 36.500 | kg | - | - | - | - | - | - | - | - | - | (Fehrenbach, Giegrich, Gärtner, Reinhardt, & Rettenmaier, 2007) |
| Palm residues | Bioenergy | 11.239 | kg | 0.90 | 1.0000 | 49.80 | 0.06 | 0.88 | 8.40 | 37.73 | 0.00 | 100 | Averaged values of data in (Gonzalez-Salazar, et al., 2014a) |
| Petroleum Products | Oil | 44800 | Ton | 0.95 | 0.7400 | 84.60 | 0.04 | 0.60 | 0.00 | 0.00 | 0.00 | 99 | (Heaps, 2012) |
| Refinery Feedstocks | Oil | 44800 | Ton | 0.95 | 0.8740 | 83.50 | 1.00 | 1.00 | 0.00 | 0.00 | 0.00 | 99 | (Heaps, 2012) |
| Refinery gas | Gas | 39.513 | $m^3$ | 0.90 | 0.0008 | 73.40 | 0.00 | 0.03 | 0.00 | 0.00 | 100 | 100 | Assumed to be the same as natural gas |
| Renewable Diesel | Bioenergy | 44100 | Ton | 0.95 | 0.7800 | 85.04 | 0.00 | 0.00 | 0.00 | 0.02 | 0.00 | 0 | (Neste Oil, 2014; Sotelo-Boyás, Trejo-Zárraga, & Hernández-Loyo, 2012) |
| Residual Fuel Oil | Oil | 40190 | Ton | 0.95 | 0.9500 | 84.40 | 2.00 | 1.00 | 0.08 | 0.00 | 0.00 | 99 | (Heaps, 2012) |
| Rice Husk | Bioenergy | 14.007 | kg | 0.90 | 1.0000 | 51.35 | 0.08 | 0.29 | 19.59 | 9.93 | 0.00 | 100 | (Escalante Hernández, Orduz Prada, Zapata Lesmes, Cardona Ruiz, & Duarte Ortega, 2011) |
| Syngas | Bioenergy | 11658 | Ton | 0.95 | 0.0002 | 44.40 | 0.00 | 4.33 | 0.00 | 20.62 | 6.89 | 0 | Composition taken from (SGC, 2011; Risø DTU, 2010) for Milena gasifier, LHV calculated in Aspen Hysys® |
| Wood | Bioenergy | 15500 | Ton | 0.90 | 0.7100 | 43.80 | 0.00 | 0.09 | 0.00 | 15.00 | 0.00 | 100 | (Heaps, 2012) |
| Wood pellets | Bioenergy | 16900 | Ton | 0.90 | 0.7100 | 43.80 | 0.08 | 0.00 | 1.50 | 10.00 | 0.00 | 100 | (IEA Bioenergy, 2011) |

[a] % by weight, [b] sulfur retention is assumed to be 0% for all fuels, except coal, in which is 30% by weight

***Table 78.*** *Characteristics of conversion processes (Part I)*

| Conversion process | Inputs | | Outputs | | Energy efficiency | Emissions | References |
|---|---|---|---|---|---|---|---|
| Sugar cane mill | Cane w/ leaves | 1 ton | Bagasse | 0.2588 ton [a] | 100% | | [a] (Gonzalez-Salazar, et al., 2014a) |
| | | | Cane juice | 0.5182 ton [a] | | | |
| | | | Tops and leaves | 0.2229 ton [a] | | | |
| | Cane w/ leaves | 1 MJ | Bagasse | 0.3348 MJ [a] | | | |
| | | | Cane juice | 0.3528 MJ [a] | | | |
| | | | Tops and leaves | 0.3122 MJ [a] | | | |
| Sugar factory | Cane w/o leaves | 1 Ton | Sugar | 0.12 Ton [a] | 32.76% [b] | | [a] (BID-MME, Consorcio CUE, 2012)<br>[b] Calculated as the energy content in sugar as output divided by the energy content in cane as input |
| Sugar factory with annexed distillery | Cane w/o leaves | 1 Ton | Sugar | 0.093 Ton [a] | 33.37% [b] | | [a] (BID-MME, Consorcio CUE, 2012)<br>[b] Calculated as the energy content in sugar and bioethanol as outputs divided by the energy content in cane as input |
| | | | Bioethanol | 0.019 Ton [a] | | | |
| Bioethanol distillery (autonomous) | Cane juice | 1 ton | Bioethanol | 0.095 ton [a] | 51.62% | • Biogenic $CO_2$ (Ton/TJ-Ethanol): 36.2593 [c]<br>• Methane (kg/ TJ-Ethanol): 5.3436 [c] | [a] Conditions and characteristics corresponding to a process with microbial fermentation, distillation and dehydration producing 80 liters-ethanol/ton-cane w/o leaves (assumed constant), data taken from (Ferreira-Leitao, Fortes Gottschalk, Ferrara, Lima Nepomuceno, Correa Molinari, & Bon, 2010)<br>[b] Electricity in this case is treated as an auxiliary fuel in LEAP, i.e. energy consumed per unit of energy produced in a process. It is energy consumed but not converted and therefore not included in the calculation of the overall energy efficiency of the process. It is assumed 47 MJ/l-ethanol, taken from (Macedo, Leal, & Da Silva, 2004)<br>[c] (BID-MME, Consorcio CUE, 2012), methane is assumed to be released to the atmosphere |
| | Cane juice | 1 MJ [a] | Bioethanol | 0.5162 MJ | | | |
| | Electricity | 0.027 MJ [b] | | | | | |
| Palm oil mill | Fresh fruit bunches | 1 ton | Palm oil | 0.2138 ton [a] | 69.48% [b] | | [a] Conditions of the palm mill described in (BID-MME, Consorcio CUE, 2012)<br>[b] Estimated as the energy fraction of the fresh fruit bunches transformed into palm oil and palm residues |
| | | | Kernel oil | 0.020 [a] | | | |
| | | | Palm residues | 0.4240 ton [a] | | | |
| | | | Non-usable by-products | 0.3422 ton [a] | | | |
| | Fresh fruit bunches | 1 MJ | Palm oil | 0.4314 MJ [a] | | | |
| | | | Kernel oil | 0.0040 MJ [a] | | | |
| | | | Palm residues | 0.2634 MJ [a] | | | |
| | | | Non-usable by-products | 0.2648 MJ [a] | | | |
| Biodiesel production | Palm oil | 1.04 ton | Biodiesel | 1 ton [a] | 97.33% | Methane (kg/TJ-Biodiesel): 1355.96 [c] | [a] Conditions and characteristics corresponding to a process with oil refining, transesterification and biodiesel purification producing 233.61 liters-biodiesel/ton-FFB (assumed constant), data taken from (BID-MME, Consorcio CUE, 2012)<br>[b] Electricity and heat are treated as auxiliary fuels, data is taken from (Panapanaan, Helin, Kujanpää, Soukka, Heinimö, & Linnannen, 2009)<br>[c] 1.03 Ton-methane per Ton-FFB (BID-MME, Consorcio CUE, 2012) |
| | Palm oil | 1.0273 MJ [a] | Biodiesel | 1 MJ | | | |
| | Heat | 0.0563 MJ [b] | | | | | |
| | Electricity | 0.0879 MJ [b] | | | | | |

***Table 79.*** *Characteristics of conversion processes (Part II)*

| Conversion process | Inputs | | Outputs | | Energy efficiency | Emissions | References |
|---|---|---|---|---|---|---|---|
| Gasification of wood | Wood | 1 MJ | Syngas | 0.8200 MJ | 82%[a] | | [a] Assumed to be a Milena gasifier as described in (SGC, 2011; Risø DTU, 2010) |
| Gasification of biomass residues | Biomass residues (including rice husk, cane leaves & tops, bagasse, palm residues) | 1 MJ | Syngas | 0.8300 MJ | 83%[a] | | [a] Assumed to a SilvaGas gasifier as described in (SGC, 2011; Risø DTU, 2010) |
| Wood pelletization | Wood<br>Electricity | 1.2500 MJ[a]<br>0.0400 MJ[b] | Wood pellets | 1 MJ | 80%[a] | | [a] (IEA Bioenergy, 2011)<br>[b] Electricity in this case is treated as an auxiliary fuel in LEAP. Data is taken from (IEA Bioenergy, 2011) |
| Renewable diesel production | Palm oil<br>Electricity<br>Natural gas<br>Heat | 0.9114 MJ[a]<br>0.0070 MJ[a]<br>0.1160 MJ[a]<br>0.0097 MJ[a] | Renewable diesel<br>Renewable gasoline<br>Renewable LPG | 0.9070 MJ[a]<br>0.0228 MJ[a]<br>0.0700 MJ[a] | 95.77%[a] | • Biogenic $CO_2$ (Ton/TJ-Ren. diesel): 1.0884[a]<br>• Natural gas is burned to produce hydrogen. Emissions include: 55.8 ton-$CO_2$ no biogenic per TJ-natural gas, 20 kg-CO per TJ-natural gas, 1 kg-$CH_4$ per TJ-natural gas, 5 kg-NMVOC per TJ-natural gas, 150 kg-NOx per TJ-natural gas and 0.1 kg-$N_2O$ per TJ-natural gas[b]<br>• Avoided non-biogenic $CO_2$ emissions by substituting renewable fuel products for fossil fuels include:<br>i. -73.3 tons non-biogenic $CO_2$ per TJ of renewable diesel[c]<br>ii. -68.6 tons non-biogenic $CO_2$ per TJ of renewable gasoline[d]<br>iii. -72.9 tons non-biogenic $CO_2$ per TJ of renewable LPG[e] | [a] Conditions and characteristics of the NExBTL™ hydrotreated vegetable oil conversion process by the company Neste Oil using palm oil as feedstock are used. Data is taken from (Nikander, 2008; Neste Oil, 2014; Sotelo-Boyás, Trejo-Zárraga, & Hernández-Loyo, 2012)<br>[b] IPCC Tier 1 default emissions for combustion of natural gas in power generation, data taken from (Heaps, 2012)<br>[c] IPCC Tier 1 default emission for combustion of diesel fuel in road vehicles, data taken from (Heaps, 2012)<br>[d] IPCC Tier 1 default emission for combustion of gasoline in road vehicles, data taken from (Heaps, 2012)<br>[e] IPCC Tier 1 default emission for combustion of LPG in households (Heaps, 2012) |
| Biomethane production from wood | Syngas from wood | 1 MJ | Biomethane | 0.8048 MJ[a] | 80.48%[a] | Biogenic $CO_2$ emissions: 55.8 tons $CO_2$ per TJ of biomethane[b] | [a] Characteristics of syngas from a MILENA gasifier, OLGA tar removal and TREMP methanation as described in (Risø DTU, 2010)<br>[b] IPCC Tier 1 default emission for combustion of natural gas in households and services (Heaps, 2012) |
| Biomethane production from biomass residues | Syngas from biomass residues | 1 MJ | Biomethane | 0.6867 MJ[a] | 68.67%[a] | Biogenic $CO_2$ emissions: 55.8 tons $CO_2$ per TJ of biomethane[b] | [a] Characteristics of syngas from the SilvaGas gasifier and the PSI/CTU methanation system as described in (Risø DTU, 2010)<br>[b] IPCC Tier 1 default emission for combustion of natural gas in households and services (Heaps, 2012) |
| Biomethane production from biogas | Biogas from animal waste | 1 MJ | Biomethane | 0.93 MJ[a] | 93.00%[a] | Avoided methane release: -0.3906 kg-$CH_4$/kg-biogas[b]<br>Biogenic $CO_2$ emissions: 55.8 tons $CO_2$ per TJ of biomethane[c] | [a] Characteristics of a Pressure Swing Adsorption (PSA) upgrading system as described in (DBFZ, 2012)<br>[b] Assuming a $CH_4$ content of 63.75% by volume, taken from (Gonzalez-Salazar, et al., 2014a)<br>[c] IPCC Tier 1 default emission for combustion of natural gas in households and services (Heaps, 2012) |

***Table 80.*** *Emission factors by fuel and application taken from TED in LEAP (Part I)*

| Fuel | Side | Sector | $CO_2$ Ton per TJ of energy consumed [1] | CO kg per TJ of energy consumed | $CH_4$ kg per TJ of energy consumed | NMVOC kg per TJ of energy consumed | NOx kg per TJ of energy consumed | $N_2O$ kg per TJ of energy consumed | $SO_2$ kg per kg of energy consumed [2] |
|---|---|---|---|---|---|---|---|---|---|
| Bagasse | Demand | Agriculture, commercial | 29.9 * FO * ($CO_2$/C) [biogenic] | 5000 | 300 | 600 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Bagasse | Demand | Industry, non-specified | 29.9 * FO * ($CO_2$/C) [biogenic] | 4000 | 30 | 50 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Bagasse | Transformation | Power generation, heat production, own use | 29.9 * FO * ($CO_2$/C) [biogenic] | 1000 | 30 | 50 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Biodiesel | Demand | Agriculture, commercial, industry, non-specified | 75.2678 [biogenic] | | | | | | |
| Biodiesel | Demand | Road transport | 75.2678 [biogenic] | 810 | 2.3 | 92 | 1040 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Bioethanol | Demand | Agriculture, commercial, industry, non-specified | 73.2236 [biogenic] | | | | | | |
| Bioethanol | Demand | Road transport (vehicles and motorcycles) | 73.2236 [biogenic] | 8000 | 20 | 1500 | 768 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Charcoal | Demand | Agriculture, commercial, residential | 29.9 * FO * ($CO_2$/C) [biogenic] | 7000 | 200 | 100 | 100 | 1 | SC*(1-SR)*($SO_2$/S) |
| Charcoal | Demand | Industry, non-specified | 29.9 * FO * ($CO_2$/C) [biogenic] | 4000 | 200 | 100 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| CNG | Demand | Road transport | 15.3 * FO * ($CO_2$/C) | 400 | 50 | 5 | 600 | 0.1 | 0 |
| Coal | Demand | Agriculture, commercial, residential | 25.8 * FO * ($CO_2$/C) | 2000 | 300 | 200 | 100 | 1.4 | SC*(1-SR)*($SO_2$/S) |
| Coal | Demand | Industry, non-specified, rail transport | 25.8 * FO * ($CO_2$/C) | 150 | 10 | 20 | 300 | 1.4 | SC*(1-SR)*($SO_2$/S) |
| Coal | Transformation | Power gen., heat prod., blast furnace, coke factories, own use | 25.8 * FO * ($CO_2$/C) | 20 | 1 | 5 | 300 | 1.4 | SC*(1-SR)*($SO_2$/S) |
| Coke | Demand | Agriculture, commercial | 25.8 * FO * ($CO_2$/C) | 2000 | 300 | 200 | 100 | 1.4 | SC*(1-SR)*($SO_2$/S) |
| Coke | Demand | Industry, non-specified | 25.8 * FO * ($CO_2$/C) | 150 | 10 | 20 | 300 | 1.4 | SC*(1-SR)*($SO_2$/S) |
| Coke | Transformation | Blast furnace, own use | 25.8 * FO * ($CO_2$/C) | 20 | 1 | 5 | 300 | 1.4 | SC*(1-SR)*($SO_2$/S) |
| Diesel fuel | Demand | Agriculture, commercial | 20 * FO * ($CO_2$/C) | 20 | 10 | 5 | 100 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Diesel fuel | Demand | Industry, non-specified | 20 * FO * ($CO_2$/C) | 10 | 2 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Diesel fuel | Demand | Rail transport | 20 * FO * ($CO_2$/C) | 1000 | 5 | 200 | 1200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Diesel fuel | Demand | River transport | 20 * FO * ($CO_2$/C) | 1000 | 5 | 200 | 1500 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Diesel fuel | Demand | Road transport | 20 * FO * ($CO_2$/C) | 1000 | 5 | 200 | 800 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Diesel fuel | Transformation | Own use | 20 * FO * ($CO_2$/C) | 15 | 3 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Diesel fuel | Transformation | Power generation in gas turbines | 20 * FO * ($CO_2$/C) | 21 | | | 300 | | SC*(1-SR)*($SO_2$/S) |
| Diesel fuel | Transformation | Power generation in engines | 20 * FO * ($CO_2$/C) | 350 | 4 | | 1300 | | SC*(1-SR)*($SO_2$/S) |
| Fuel oil | Demand | Agriculture, commercial | 20 * FO * ($CO_2$/C) | 20 | 10 | 5 | 100 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Fuel oil | Demand | Industry, non-specified | 20 * FO * ($CO_2$/C) | 10 | 2 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Fuel oil | Demand | Rail transport | 20 * FO * ($CO_2$/C) | 1000 | 5 | 200 | 1200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Fuel oil | Demand | River transport | 20 * FO * ($CO_2$/C) | 1000 | 5 | 200 | 1500 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Fuel oil | Transformation | Own use | 20 * FO * ($CO_2$/C) | 15 | 3 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Fuel oil | Transformation | Power generation in gas turbines | 20 * FO * ($CO_2$/C) | 21 | | | 300 | | SC*(1-SR)*($SO_2$/S) |
| Gasoline | Demand | Agriculture, commercial, residential | 20 * FO * ($CO_2$/C) | 20 | 10 | 5 | 100 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Gasoline | Demand | Industry, non-specified | 20 * FO * ($CO_2$/C) | 10 | 2 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Gasoline | Demand | Air transport | 20 * FO * ($CO_2$/C) | 100 | 0.5 | 50 | 300 | 2 | SC*(1-SR)*($SO_2$/S) |
| Gasoline | Demand | Rail transport | 20 * FO * ($CO_2$/C) | 1000 | 5 | 200 | 1200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Gasoline | Demand | River transport | 20 * FO * ($CO_2$/C) | 1000 | 5 | 200 | 1500 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Gasoline | Demand | Road transport (vehicles and motorcycles) | 20 * FO * ($CO_2$/C) | 8000 | 20 | 1500 | 600 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Gasoline | Transformation | Own use | 20 * FO * ($CO_2$/C) | 15 | 3 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |

**Notes:**

[1] FO represents the fraction oxidized by weight of the fuel (%) taken from Table 77. $CO_2$ and C are the molecular weights of carbon dioxide (44.01) and carbon (12.011), respectively.

[2] SC and SR represents the sulfur content by weight of the fuel (%) and the sulfur retention after combustion by weight of the fuel (%), respectively, taken from Table 77. $SO_2$ and S are the molecular weights of sulfur dioxide (64.063) and sulfur (32.064), respectively.

***Table 81.*** *Emission factors by fuel and application taken from TED in LEAP (Part II)*

| **Fuel** | **Side** | **Sector** | **CO2 biogenic Ton per TJ of energy consumed** [1] | **CO kg per TJ of energy consumed** | **CH4 kg per TJ of energy consumed** | **NMVOC kg per TJ of energy consumed** | **NOx kg per TJ of energy consumed** | **N2O kg per TJ of energy consumed** | **SO2 kg per kg of energy consumed** [2] |
|---|---|---|---|---|---|---|---|---|---|
| Industrial gas | Demand | Agriculture, industry, non-specified | 15.3 * FO * ($CO_2$/C) | 30 | 5 | 5 | 150 | 0.1 | 0 |
| Industrial gas | Demand | Commercial | 15.3 * FO * ($CO_2$/C) | 50 | 5 | 5 | 50 | 0.1 | 0 |
| Industrial gas | Transformation | Power generation, own use | 15.3 * FO * ($CO_2$/C) | 20 | 1 | 5 | 150 | 0.1 | 0 |
| Kerosene | Demand | Agriculture, commercial, residential | 20 * FO * ($CO_2$/C) | 20 | 10 | 5 | 100 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Kerosene | Demand | Industry, non-specified | 20 * FO * ($CO_2$/C) | 10 | 2 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Kerosene | Demand | Air transport | 20 * FO * ($CO_2$/C) | 100 | 0.5 | 50 | 300 | 2 | SC*(1-SR)*($SO_2$/S) |
| Kerosene | Transformation | Own use | 20 * FO * ($CO_2$/C) | 15 | 3 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| LPG | Demand | Agriculture, commercial, residential | 20 * FO * ($CO_2$/C) | 20 | 10 | 5 | 100 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| LPG | Demand | Industry, non-specified | 20 * FO * ($CO_2$/C) | 10 | 2 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| LPG | Transformation | Own use | 20 * FO * ($CO_2$/C) | 15 | 3 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Natural gas | Demand | Agriculture, commercial, residential | 15.3 * FO * ($CO_2$/C) | 50 | 5 | 5 | 50 | 0.1 | 0 |
| Natural gas | Demand | Industry, non-specified | 15.3 * FO * ($CO_2$/C) | 30 | 5 | 5 | 150 | 0.1 | 0 |
| Natural gas | Transformation | Renewable diesel production, own use | 15.3 * FO * ($CO_2$/C) | 20 | 1 | 5 | 150 | 0.1 | 0 |
| Natural gas | Transformation | Power generation in gas turbines | 15.3 * FO * ($CO_2$/C) | 46 | 6 |  | 190 |  | 0 |
| Natural gas | Transformation | Power gen. in gas turbines (small-scale), gas flaring | 15.3 * FO * ($CO_2$/C) | 20 | 1 | 5 | 150 | 0.1 | 0 |
| Natural gas | Transformation | Oil refining | 15.3 * FO * ($CO_2$/C) | 30 | 5 | 5 | 150 | 0.1 | 0 |
| Oil | Demand | Agriculture, commercial | 20 * FO * ($CO_2$/C) | 20 | 10 | 5 | 100 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Oil | Demand | Industry, non-specified | 20 * FO * ($CO_2$/C) | 10 | 2 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Oil | Demand | River transport | 20 * FO * ($CO_2$/C) | 1000 | 5 | 200 | 1500 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Oil | Transformation | Own use | 20 * FO * ($CO_2$/C) | 15 | 3 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Oil | Transformation | Oil refining | 20 * FO * ($CO_2$/C) | 10 | 2 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Refinery gas | Demand | Agriculture, commercial | 15.3 * FO * ($CO_2$/C) | 50 | 5 | 5 | 50 | 0.1 | 0 |
| Refinery gas | Demand | Industry, non-specified | 15.3 * FO * ($CO_2$/C) | 30 | 5 | 5 | 150 | 0.1 | 0 |
| Refinery gas | Transformation | Oil refining | 15.3 * FO * ($CO_2$/C) | 30 | 5 | 5 | 150 | 0.1 | 0 |
| Refinery gas | Transformation | Oil refining | 15.3 * FO * ($CO_2$/C) | 30 | 5 | 5 | 150 | 0.1 | 0 |
| Refinery feedstocks | Transformation | Oil refining | 20 * FO * ($CO_2$/C) | 10 | 2 | 5 | 200 | 0.6 | SC*(1-SR)*($SO_2$/S) |
| Biomass residues | Demand | Agriculture, commercial | 29.9 * FO * ($CO_2$/C) | 5000 | 300 | 600 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Biomass residues | Demand | Industry, non-specified | 29.9 * FO * ($CO_2$/C) | 4000 | 30 | 50 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Biomass residues | Transformation | Own use, power generation | 29.9 * FO * ($CO_2$/C) | 1000 | 30 | 50 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Syngas | Transformation | Power generation, heat production | 0.3007 (ton/ton-syngas) |  |  |  | 12.6 |  | 0.948 (kg/TJ-syngas) |
| Wood/residues | Demand | Agriculture, commercial, residential | 29.9 * FO * ($CO_2$/C) | 5000 | 300 | 600 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Wood/residues | Demand | Industry | 29.9 * FO * ($CO_2$/C) | 2000 | 30 | 50 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Wood/residues | Transformation | Power generation, heat production, own use | 29.9 * FO * ($CO_2$/C) | 1000 | 30 | 50 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |
| Wood/residues | Transformation | Charcoal production | 29.9 * FO * ($CO_2$/C) | 590 | 15 |  | 65 |  | SC*(1-SR)*($SO_2$/S) |
| Wood pellets | Transformation | Power generation | 29.9 * FO * ($CO_2$/C) | 1000 | 300 | 600 | 100 | 4 | SC*(1-SR)*($SO_2$/S) |

**Notes:**

[1] FO represents the fraction oxidized by weight of the fuel (%) taken from Table 77. $CO_2$ and C are the molecular weights of carbon dioxide (44.01) and carbon (12.011), respectively.

[2] SC and SR represents the sulfur content by weight of the fuel (%) and the sulfur retention after combustion by weight of the fuel (%), respectively, taken from Table 77. $SO_2$ and S are the molecular weights of sulfur dioxide (64.063) and sulfur (32.064), respectively.

# Appendix for Chapter G

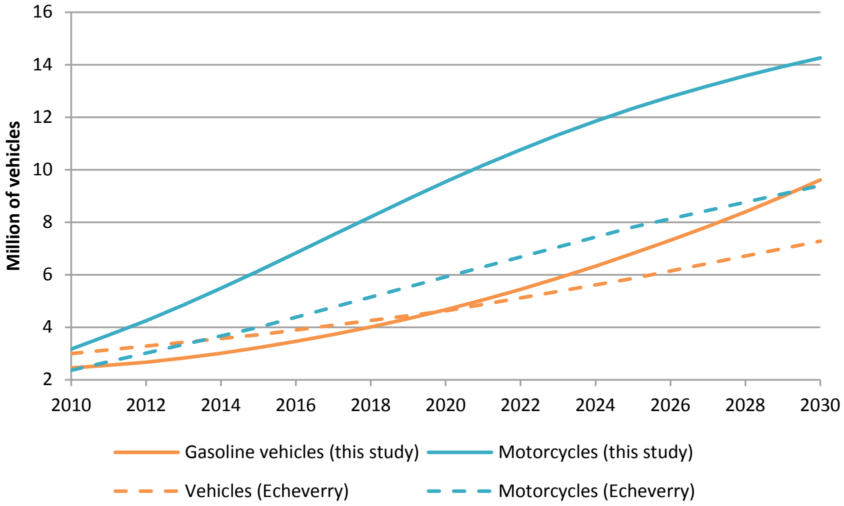


***Figure 133.*** *Results of vehicle ownership and comparison to other studies*

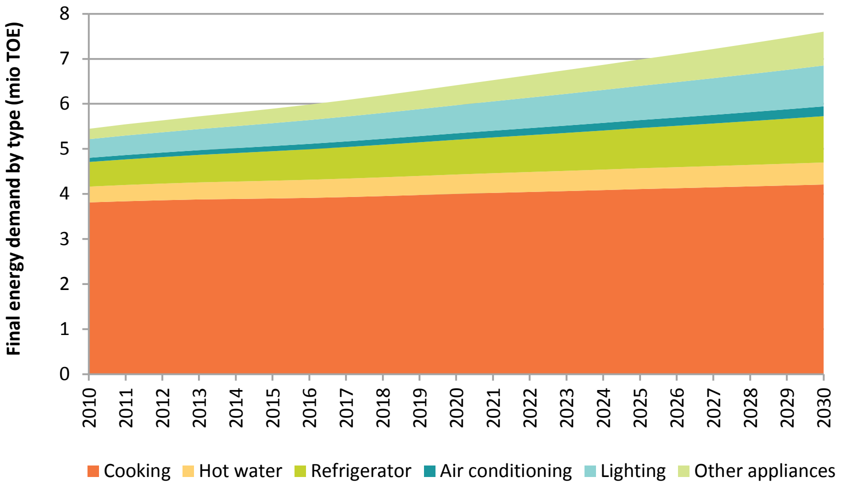


***Figure 134.*** *Final energy demand by type in the residential sector for baseline scenario*

***Table 82.*** *Levelized cost of electricity (LCOE) by technology*[24]

| **US$2009/MWh** | **Levelized cost of electricity (LCOE)** | | |
|---|---|---|---|
| | **2009** | **2020** | **2030** |
| Natural gas combined cycle | 67.5 | 66.9 | 66.9 |
| Natural gas reciprocating engine | 73.0 | 72.6 | 72.6 |
| Wind power turbine | 85.3 | 77.8 | 77.0 |
| Natural gas simple cycle – Large (> 50 MW) | 86.0 | 85.7 | 85.7 |
| Natural gas simple cycle – Small (≤ 50 MW) | 86.0 | 85.7 | 85.7 |
| Coal power plant – Large (> 50 MW) | 92.6 | 92.9 | 92.9 |
| Coal power plant – Small (≤ 50 MW) | 104.7 | 104.5 | 104.5 |
| Hydro power plant – Large (> 10 MW) | 128.8 | 128.7 | 137.9 |
| Biomass CHP – Medium (>5 MW, ≤ 25 MW) | 131.4 | 123.2 | 117.2 |
| Fuel oil fuelled gas turbine – Small (≤ 50 MW) | 151.2 | 150.9 | 150.9 |
| Hydro power plant – Small (≤ 10 MW) | 191.1 | 188.4 | 188.7 |
| Diesel reciprocating engine | 196.9 | 196.6 | 196.6 |
| Diesel fuelled gas turbine – Small (≤ 50 MW) | 244.9 | 244.6 | 244.6 |

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[24] Estimated as $LCOE = \frac{\sum_t (Investment_t + O\&M_t + Fuel_t + Decommissioning_t)\cdot(1+r)^{-t}}{\sum_t (Electricity_t)\cdot(1+r)^{-t}}$, according to the equation proposed by (IEA-NEA, 2010)

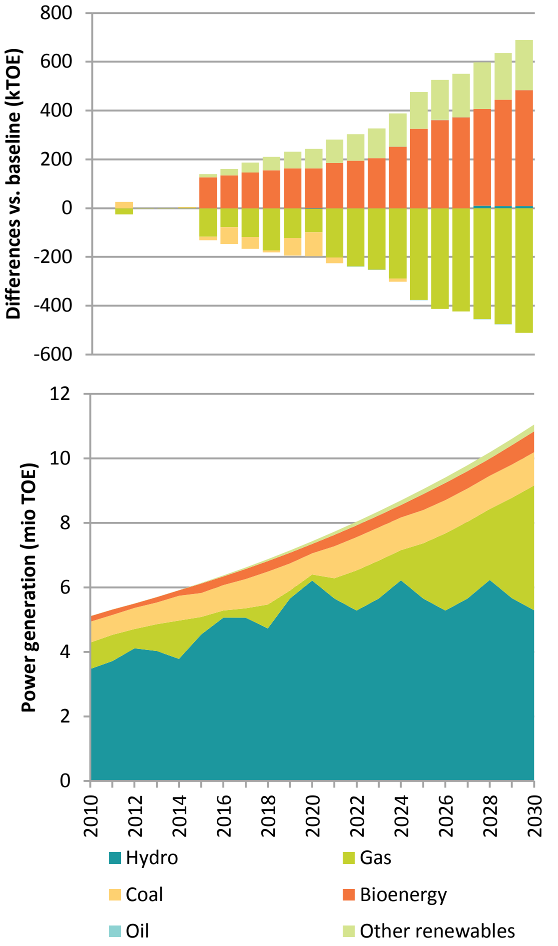

*Figure 135.* *Power generation by source for Scenario II*

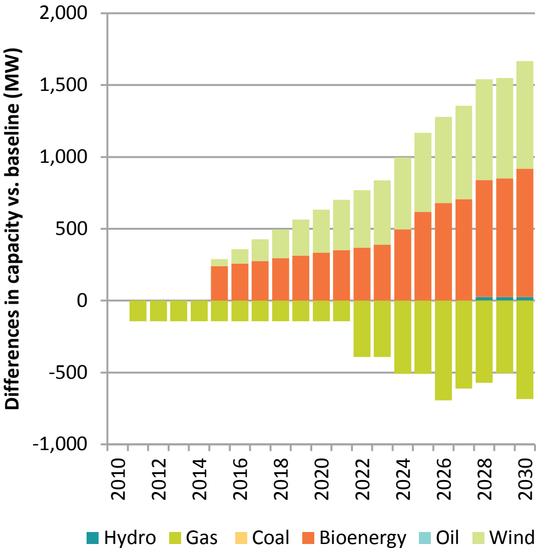

*Figure 136.* *Differences in installed power generation capacity between Scenario II and baseline scenario*

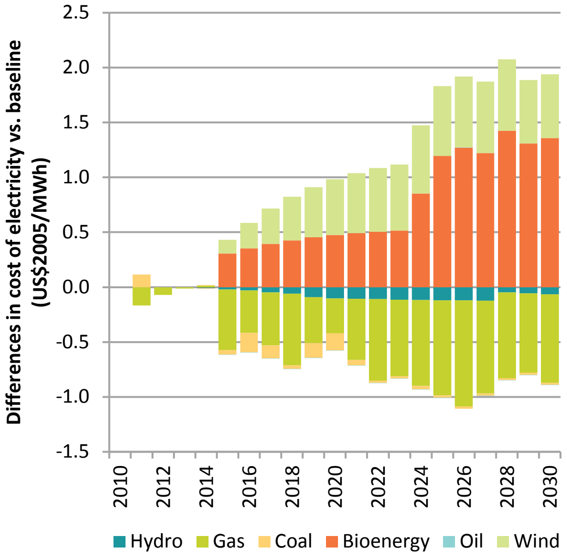

*Figure 137.* *Differences in cost of electricity by technology between Scenario II and baseline*

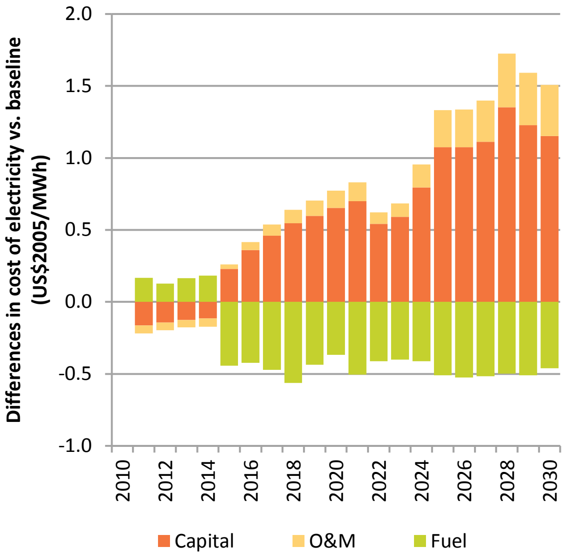

*Figure 138.* *Differences in cost of electricity by cost type between Scenario II and baseline*

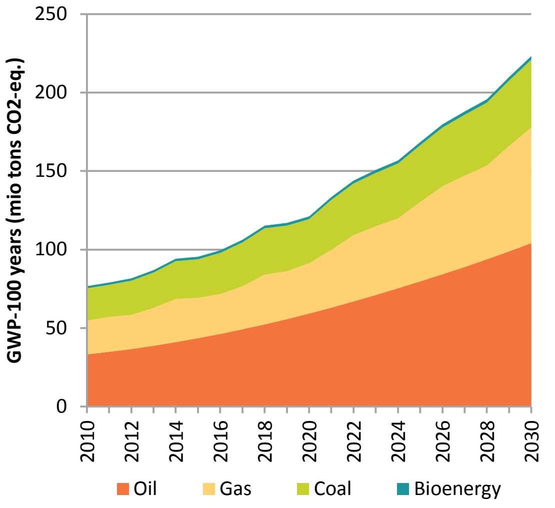

***Figure 139.*** *GWP-100 years disaggregated by fuel for the baseline scenario*

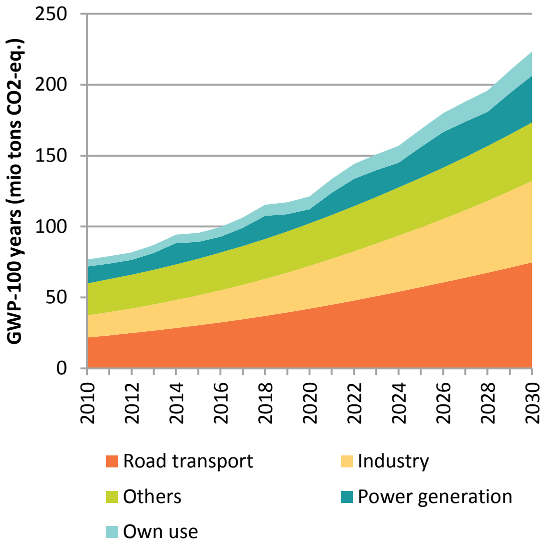

***Figure 140.*** *GWP-100 years disaggregated by category for the baseline scenario*

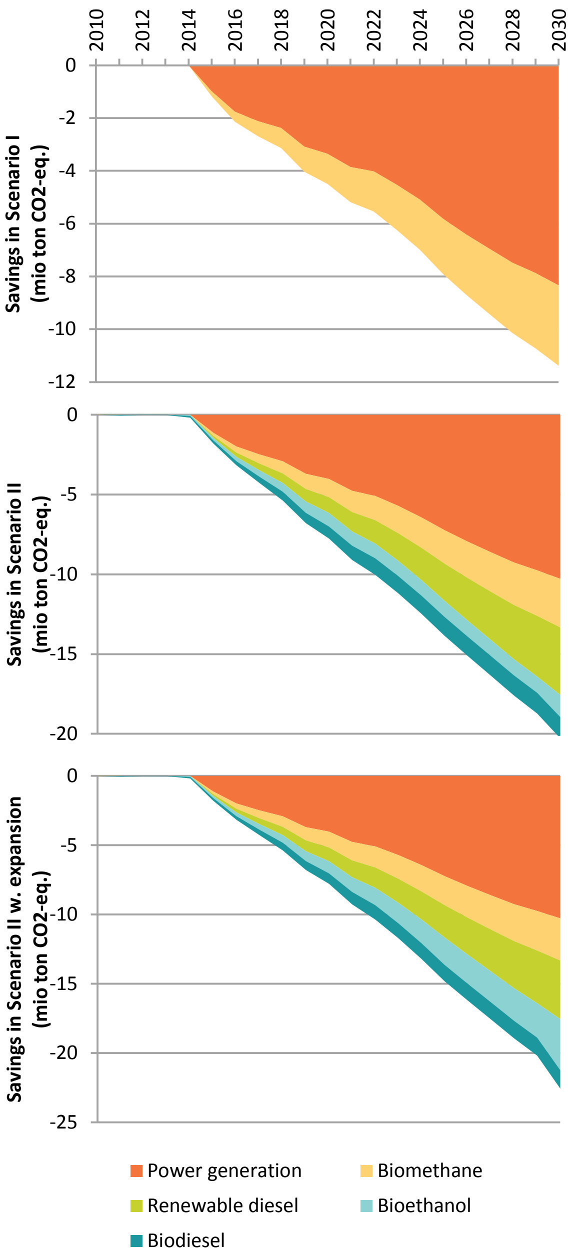

***Figure 141.*** *Domestic bioenergy-induced emissions reductions by category and scenario*

# Supplementary material for Chapter G

## 1. Overview

The results presented in Chapter G show that the most effective policy measures for reducing greenhouse gas emissions should address biomethane, power generation and CHP applications. Their advantages are twofold: they are able to avoid the release of fossil based methane and, at the same time, contribute to the reduction of $CO_2$ emissions by replacing fossil fuels in gas or electricity supply. This supplementary section presents a preliminary analysis of the use of biogas for energy production for the conditions of Colombia. Three main technology routes are analyzed:

- Route 1: Biogas upgrade to produce biomethane to be injected into the natural gas grid
- Route 2: Biogas upgrade to produce biomethane to be compressed and used as compressed natural gas (CNG)
- Route 3: Biogas combustion in reciprocating engines for combined heat and power (CHP)

## 2. Approach

The approach for analyzing these routes consists of two separate analyses and is illustrated in Figure 142. Firstly, a technical analysis of the energy conversion and emissions is performed for the different routes. The technology routes are defined using technical characteristics of state-of-the-art conversion technologies available in public literature. These technology routes are entered into the Energy System Model (ESM) as scenarios and are simulated and compared to the baseline scenario defined in Section F.4. The ESM model then calculates the annual energy production and the lifetime energy-related emissions reduction associated with each technology route following the same method described in Section F.2.3. Secondly, the cost of deploying these technologies is preliminarily estimated using publicly available data. By integrating the results of the technical analysis performed in the ESM model with the economic analysis, the cost of reducing the lifetime emissions for each route is then calculated.

## 3. Technical analysis

In order to make a consistent comparison, it is assumed that the amount of biogas as energy input is the same for the three technology routes, and that it amounts to 1,000 TJ/year. This assumed functional unit is equivalent to about ten medium-size biogas digestors (500 $m^3$/hour) working at a capacity factor of 100%. General assumptions used in the calculation of the emission reduction potential are shown in Table 83.

*Table 83. General assumptions regarding the technical analysis of technology routes*

| Assumption | Value | Details |
|---|---|---|
| LHV biogas (MJ/$sm^3$) | 21.64 | Taken from Table 77 |
| Methane content in biogas (% mass) | 39.06 | Taken from Table 77 |
| LHV biomethane (MJ/$sm^3$) | 39.51 | Same as natural gas |
| Input energy in biogas (TJ) | 1000 | Assumed |
| Input volume of biogas (mio $m^3$) | 46.19 | Calculated |
| Input mass of biogas (mio ton) | 0.051 | Calculated |
| Year of implementation | 2015 | Assumed |
| Life time of the routes (years) | 15 | (Heffels, McKenna, & Fichtner, 2012) |

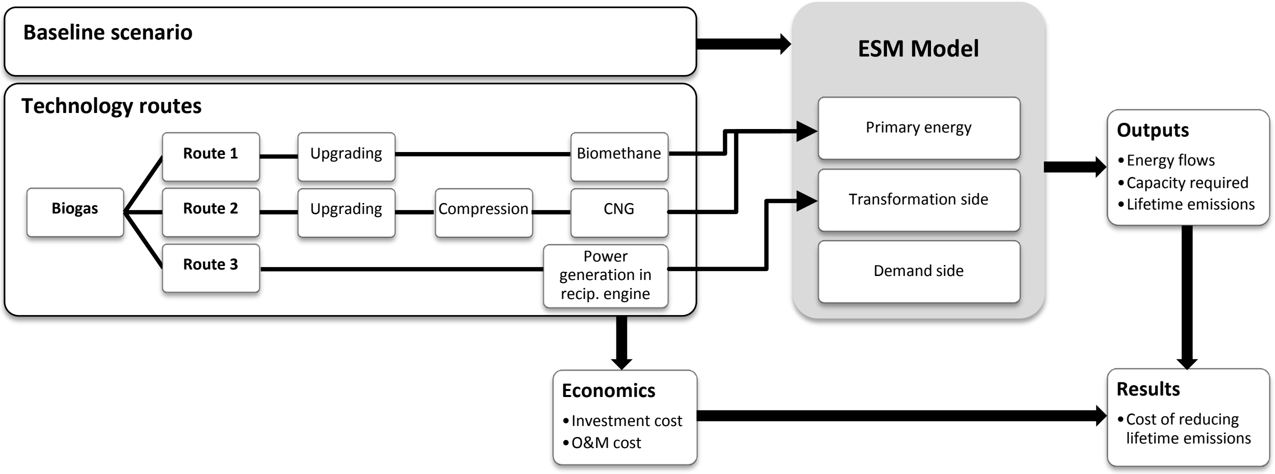

*Figure 142. Approach for analyzing the different technology routes*

## 3.1. Route 1: biogas to produce biomethane

Biogas from the anaerobic digestion of animal waste contains methane and carbon dioxide along with other trace components (water, hydrogen sulphide, carbon monoxide, etc.). In this study, the mass content of methane in biogas amounts to 39.06% (see Table 83).

As described in Section F.3.4.3, biomethane production through biogas upgrading is a process to increase the methane content of biogas in order to achieve quality characteristics of natural gas. Various commercially available upgrading methods exist, including absorption, water scrubbing, pressure swing adsorption (PSA), chemical and organic physical scrubbing, membranes, etc. (Andriani, Wresta, Atmaja, & Saepudin, 2014). Today, the most commonly used methods are water scrubbing and pressure swing adsorption (PSA). In this thesis, the pressure swing absorption method was the selected technology for biogas upgrading analyzed in Chapter F and Chapter G. However, after performing a more thorough literature review of biogas upgrading technologies, it was found that water scrubbing is actually superior to pressure swing absorption with regard to investment costs, methane losses and energy requirements (see Table 84). For this reason, it was decided to select the water scrubbing method for analysis in this chapter. This choice offers a better technical and economic performance and it does not affect the analysis and results presented earlier in Chapter F and Chapter G.

***Table 84.*** *Technical and economic characteristics of PSA and water scrubbing*

| **Characteristics** | **Pressure swing absorption (PSA)** | **Water scrubbing** |
|---|---|---|
| Cost per m$^3$ (€/m$^3$) [a] | 0.26 | 0.15 |
| Maintenance cost (€/year) [a] | 56000 | 15000 |
| Average energy requirement (kWh/m$^3$) [a] | 0.42 | 0.31 |
| Methane losses (%) [a,b,c] | 2-10 | <2 |
| Methane content in product gas (%) [a,b,c] | >96 | >97 |

**References**

[a] (Andriani, Wresta, Atmaja, & Saepudin, 2014)

[b] (DBFZ, 2012)

[c] (Warren, 2012)

Water scrubbing is a relatively simple process in which biogas is mixed with water under pressure (typically between 10 and 20 bar) in a packed scrubber column. Biogas is compressed and enters from the bottom of the scrubber column, while water is pumped from the top and flows downwards in a counter flow. Since the solubility of $CO_2$ in water is much higher than that of $CH_4$[25], the $CO_2$ dissolves in water while the $CH_4$ remains in a gas phase. Water scrubbing is also able to remove hydrogen sulphide and ammonium in addition to $CO_2$. After removal of $CO_2$ and other contaminants in the water scrubbing column, it is necessary to remove water to fulfill pipeline specs (typically around 112 mg per m$^3$ (Uniongas, 2015)) using a dehydration unit. In this study a glycol dehydration unit is used to remove water from biomethane. Finally, dehydrated biomethane is injected into the natural gas grid in order to directly substitute natural gas. Biomethane production capacities range from 100 to 1,000 m$^3$ of biogas per hour (Urban, Girod, & Lohmann, 2009; Warren, 2012), and a typical medium scale size of 500 m$^3$ of biogas per hour is selected for analysis. Note that here, this capacity per unit is rounded to 502 m$^3$ of biogas per hour, in order to have an integer number of biodigestor units, which in this case is 15. Other assumptions used for the water scrubbing technology for biogas upgrading are shown in Table 85. As a consequence, various scrubbing columns must operate in parallel.

## 3.2. Route 2: biogas to produce CNG

In this technology route, biogas from the anaerobic digestion of animal waste is upgraded to produce biomethane, which is further compressed and utilized as compressed natural gas (CNG) in the transport sector. Thus, the water scrubbing technology is followed by a compressor set. There are commercially available technologies to compress natural gas up to 400 bar. In this study, a modularized GE multistage reciprocating compressor set is used, named "CNG-in-a-box", which is able to compress natural gas up to 325 bar (GE Oil and Gas, 2014). Each unit is able to compress up to 560 m$^3$/h of biomethane and as a consequence it is required to have several units working in parallel. Compressed biomethane is then used as a substitute for CNG used as a vehicle fuel in road transport. The main technical characteristics and assumptions of this product are shown in Table 85.

## 3.3. Route 3: biogas for combined heat and power (CHP)

In this technology route, biogas from the anaerobic digestion of animal waste is combusted in a reciprocating engine for combined heat and power (CHP). Biogas is not upgraded, but it requires removal of hydrogen sulphide and condensate water to avoid corrosion in the engine, piping, fitting and other components (Stamatelatou, Antonopoulou, & Lyberatos, 2011).

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[25] The solubility of a gas in a liquid is directly proportional to the partial pressure of the gas in the liquid. The partial pressure can be described by the following equation:

$$p = \mathrm{H} \cdot c$$

Where p is the partial pressure, H is the Henry's law constant and c is the concentration of the dissolved gas in the liquid (i.e. solubility). Since the Henry's law constant of methane is 22 times higher than that of $CO_2$, the solubility of methane is proportionally lower compared to $CO_2$.

***Table 85.** Technical assumptions of technology routes*

| Route | Assumption | Value | Details and characteristics |
|---|---|---|---|
| Route 1 | Capacity factor (%) | 70 | Assumed to be the same as for Route 3 |
| | Efficiency of biogas upgrading (%) | 98 | Upgrading technology assumed to be water scrubbing, data taken from (Andriani, Wresta, Atmaja, & Saepudin, 2014) |
| | Electricity demand for upgrading biogas (kWh/m$^3$-biogas) | 0.31 | Taken from (Andriani, Wresta, Atmaja, & Saepudin, 2014) |
| | Processing capacity per scrubbing column (m$^3$/h, biogas) | 502 | Taken from (Warren, 2012) |
| Route 2 | Capacity factor (%) | 70 | Assumed to be the same as for Route 3 |
| | Efficiency of biogas upgrading (%) | 98 | Upgrading technology assumed to be water scrubbing, data taken from (Andriani, Wresta, Atmaja, & Saepudin, 2014) |
| | Electricity demand for upgrading biogas (kWh/m$^3$) | 0.31 | Taken from (Andriani, Wresta, Atmaja, & Saepudin, 2014) |
| | Processing capacity per scrubbing column (m$^3$/h, biogas) | 502 | Taken from (Warren, 2012) |
| | Capacity per compression unit (m$^3$/h, biomethane) | 560 | CNG-in-a-box, data taken from (GE Oil and Gas, 2014) |
| | Electricity demand for compressing biomethane (kWh/m$^3$-CNG) | 87.54 | Calculated using Aspen HYSYS® |
| Route 3 | Capacity factor (%) | 70 | Taken from Table 73 |
| | Electrical efficiency (%) | 42 | Jenbacher engine Type 6 (GE Power & Water, 2014) |
| | CHP efficiency (%) | 84 | Jenbacher engine Type 6 (GE Power & Water, 2014) |
| | Net power output per engine (MWe) | 2.16 | Jenbacher engine Type 6 (GE Power & Water, 2014) |

Additionally, cleaned biogas must be compressed for delivery to the engine. Reciprocating engines proved to be more efficient, cost effective and reliable than other power generation technologies (e.g. gas turbines, micro gas turbines and Stirling engines) for combusting biogas from anaerobic digestion. Today, biogas combustion in reciprocating engines for combined heat and power (CHP) is a mature and well established technology commonly employed in Europe, U.S., China, India and various developing countries (IEA, 2012c).

Various original equipment manufacturers (OEM) offer standalone biogas power generators, including: Wärtsilä, GE Jenbacher, Caterpillar Energy Solutions, MTU, etc. In this study, a set of multiple GE Jenbacher spark ignited engine type 616 (2.16 MWe) working in parallel was used for analysis. This engine offers 2.16 MW of electrical power with 42% electrical efficiency and 2.16 MW of thermal energy with 42% thermal efficiency, which means a CHP efficiency of 84% (GE Power & Water, 2014). The main assumptions and characteristics of this reciprocating engine are shown in Table 85. The annual processing capacity per modularized unit as well as the overall annual processing capacity of all units working in parallel for all the technology routes is summarized in Table 86.

## 4. Economic analysis

The cost of deploying the different technology routes is estimated following a method consisting of three steps:

1. The capital, maintenance and operational costs are estimated for the different technologies.
2. The net present value of the total costs of the system over the lifetime is estimated.
3. The cost of reducing emissions is estimated by dividing the net present value of total cost by the lifetime emissions reduction.

**First step**

In the first step, the capital, maintenance and operation costs are estimated for the three technology routes. The costs are estimated at two levels: 1) the level of a single operation unit (e.g. a scrubbing column or a natural gas compressor) and 2) at an overall level to account for all operation units working in parallel. It is important to mention that cost data for the different technologies are currently not available for Colombia. For this reason, it was decided to use a generic approach, in which cost data is taken from publicly available sources, harmonized and adapted to be consistently compared. The cost data, assumptions and references used in this approach are shown in Table 87. Note that economic data was not always available for Colombia, and therefore some assumptions were needed. The procedure shown in Section C.4.3 for collecting and processing data was also used here. The approach is to use data corresponding to Colombia to the greatest possible extent and then use data corresponding to other countries. It is acknowledged that this approach provides only an estimation with limited accuracy, as using data from different sources and for different locations adds uncertainty to the assessment.

**Second step**

The net present value of the total cost of the system over the lifetime for route $R$ in year $t$ is estimated using the following equation:

Eq. 154 $$NPV_R = \sum_t \left(I_{R,t} + O_{R,t} + M_{R,t}\right) \cdot (1+r)^{-t}$$

Where $NPV_R$ is the net present value of the lifetime costs of technology route $R$, $I_{R,t}$ is the investment cost of route $R$ in year $t$, $O_{R,t}$ is the annual operational cost, $M_{R,t}$ is the annual maintenance cost and $r$ is the discount rate.

***Table 86.** Production capacities of technology routes*

| Technology | Characteristics | Route 1 | Route 2 | Route 3 |
|---|---|---|---|---|
| Biodigestor | Capacity of a biodigestor unit (m$^3$ of biogas/hour) | 502 | 502 | 502 |
| | Annual operating hours (hours/year) | 6,132 | 6,132 | 6,132 |
| | Capacity of a biodigestor unit (million m$^3$ of biogas/year) | 3.08 | 3.08 | 3.08 |
| | Number of biodigestor units required | 15 | 15 | 15 |
| | Overall biodigestion capacity (million m$^3$ of biogas/year) | 46.19 | 46.19 | 46.19 |
| Processing technologies | Type of processing unit | Scrubbing column | Scrubbing column | Recip. engine |
| | Processing capacity per prod. unit (million m$^3$ of biogas/year) | 3.08 | 3.08 | 5.11 |
| | Number of processing units required | 15 | 15 | 9 |
| | Overall processing capacity (million m$^3$ of biogas/year) | 46.19 | 46.19 | 46.19 |
| Compression | Compressors required | No | Yes | No |
| | Capacity per compression unit (million m$^3$ of biomethane/year) | - | 34.72 | - |
| | Number of compression units | 0 | 7 | 0 |
| | Overall compression capacity (million m$^3$ of biomethane/year) | 0 | 24.30 | 0 |

***Table 87.** Annual costs of technology routes*

| Cost type | Characteristics | Route 1 | Route 2 | Route 3 |
|---|---|---|---|---|
| Annual costs per unit | Investment cost per biodigestor unit and related eq. (mio $/unit) | 4.083 [a] | 4.083 [a] | 4.083 [a] |
| | Investment cost per transformation unit (mio $/unit) | 1.720 [b] | 1.720 [b] | 3.226 [a] |
| | Investment cost per compression unit (mio $/unit) | 0.6 [a] | 0.6 [a] | 0.6 [a] |
| | Annual maintenance cost per biodigestor unit (mio $/unit) | 0.272 [c] | 0.272 [c] | 0.272 [c] |
| | Annual operational cost per biodigestor unit (mio $/unit) | 0.216 [c] | 0.216 [c] | 0.216 [c] |
| | Annual maintenance cost per transformation unit (mio $/unit) | 0.034 [b] | 0.034 [b] | 0 [e] |
| | Annual operational cost per transformation unit (mio $/unit) | 0.212 [b] | 0.212 [b] | 0.307 [d] |
| | Annual maintenance cost per compression unit (mio $/unit) | - | 0.024 [f] | - |
| | Annual operational cost per compression unit (mio $/unit) | - | 0.050 [g] | - |
| Overall annual costs | Investment cost for all biodigestion units (mio $) | 61.26 | 61.26 | 61.26 |
| | Investment cost for all transformation units (mio $) | 25.80 | 25.80 | 29.04 |
| | Investment cost for all compression units (mio $) | 0.00 | 4.2 | 0.00 |
| | Overall investment cost (mio $) | 87.06 | 91.26 | 90.29 |
| | Overall annual maintenance costs (mio $) | 4.62 | 4.78 | 4.10 |
| | Overall annual operational costs (mio $) | 6.44 | 6.80 | 6.02 |

**Notes:**

[a] Data taken from (GE, 2014).

[b] Data taken and adapted from (Warren, 2012).

[c] Data taken and adapted from (Balossou, Kleyböcker, McKenna, Möst, & Fichtner, 2012).

[d] Data taken from (IEA, 2012a). It includes operation and maintenance costs, using values corresponding to Africa.

[e] It is assumed to be zero, given that the annual operational cost of the reciprocating engine already includes maintenance.

[f] It is assumed to be 4% of the capital cost of a compression unit.

[g] Calculated using the electricity demand for compressing biomethane (see Table 85) and an electricity price of 11.29 $/MMBtu (see Table 48).

Other general assumptions include the following:

- A discount rate of 10% is assumed, following the same rationale used for analyzing the economics of power generation technologies in Colombia, explained in Section F.3.4.1.
- Since some costs are available in euros (e.g. (Warren, 2012)), an exchange rate of 1.3 $US per euro is assumed.

**Third step**

The cost of reducing lifetime GHG emissions is then calculated using the following equation:

Eq. 155 $LC_{GHG} = \frac{NPV_{LC}}{(GHG_{Baseline} - GHG_R)}$

Eq. 156 $GHG_R = \sum_t GHG_{R,t}$

where $LC_{GHG}$ is the cost of reducing lifetime GHG emissions, $NPV_{LC}$ is the net present value of the total cost of the system, $GHG_{Baseline}$ are the lifetime GHG emissions in the baseline scenario, $GHG_R$ are the lifetime GHG emissions in route $R$, $GHG_{R,t}$ are the emissions in year $t$ disaggregated by route $R$.

Emissions in year $t$ disaggregated by route $R$ are calculated as follows:

Eq. 157 $GHG_{R,t} = GHG_{R,p} \cdot \dot{m}_{bg,t}$

where $GHG_{R,p}$ are the greenhouse gas emissions by route associated with producing and using 1 kg of biogas and $\dot{m}_{bg,t}$ is the annual mass flow of biogas, which is equal to all routes (i.e. 0.051 mio ton/year). For routes 1 and 2, in which biogas is upgraded into biomethane, $GHG_{R,p}$ is calculated following the same procedure described in Eq. 125 to Eq. 129. For route 3, in which biogas is burned to produce combined heat and power, $GHG_{R,p}$ is calculated following the same procedure described in Eq. 110 to Eq. 114. Generally speaking, the greenhouse gas emissions associated with producing and using 1 kg of biogas in the different routes have four components: a) emission of biogenic $CO_2$, which is contained in biogas and released into the atmosphere, b) emission of biogenic $CO_2$ by burning biogas (or upgraded biogas) for energy purposes, c) reduction in methane emissions that would otherwise be released into the atmosphere by not using biogas and d) emissions from other pollutants, e.g. CO and NOx, by burning biogas or upgraded biogas. More details of these effects are described in sections F.3.4.1 and F.3.4.3.

## 5. Results

The annual energy inputs and outputs of technology routes are shown in Table 88. While the energy input is the same for all technology routes (1000 TJ or 46.19 mio $m^3$ of biogas), the energy outputs vary. Route 1 produces about 23.54 mio $m^3$ of biomethane annually, which is injected into the natural gas grid and is therefore a direct substitute for natural gas. Route 2 produces 0.1 mio $m^3$ of compressed biomethane, which is a substitute for compressed natural gas (CNG) in road transport. Finally, Route 3 produces 116.42 TWh of heat and 116.42 TWh of electricity, which substitute the heat and electricity partly produced with fossil fuels. GHG emissions reduction caused by the different technology routes is presented in Figure 143. In general, the three routes present annual emissions reductions that vary between 460 to 500 ton $CO_2$-eq. per GJ of biogas used. The emissions reduction of Route 1 appears to be constant at 478 ton $CO_2$-eq. per GJ of biogas over the entire lifetime. There are two reasons for this behavior. Firstly, biogas upgraded into biomethane avoids a fixed amount of methane release into the atmosphere. This amount is proportional to the methane content in biogas ($x_{bg,CH4}$ = 0.3906 kg-$CH_4$/kg-biogas) and the overall mass flow of biogas (0.051 mio ton/year) and is equal for all routes (about 420 ton $CO_2$-eq. per GJ of biogas, as shown in Figure 144). Secondly, biomethane replaces natural gas, whose emission factors for the different final uses are assumed to be constant over the lifetime (see sections F.3.4.1 and F.3.4.3). Substitution of biomethane for natural gas causes a reduction of non-biogenic $CO_2$ emissions that on average amounts to 57.85 ton $CO_2$-eq. per GJ of biogas (see Figure 144).

***Table 88.*** *Annual energy input and output of technology routes*

| Route | Annual energy input | Annual energy output | |
|---|---|---|---|
| Route 1 | 46.19 mio $m^3$ of biogas | 23.54 | mio $m^3$ of biomethane |
| Route 2 | 46.19 mio $m^3$ of biogas | 0.10 | mio $m^3$ of CNG |
| Route 3 | 46.19 mio $m^3$ of biogas | 116.42 | TWh power |
| | | 116.42 | TWh heat |

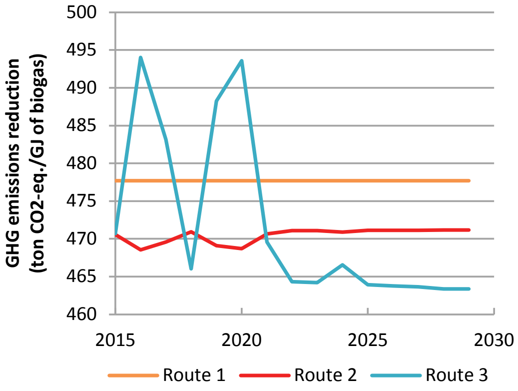

***Figure 143.*** *GHG emissions reduction by technology route*

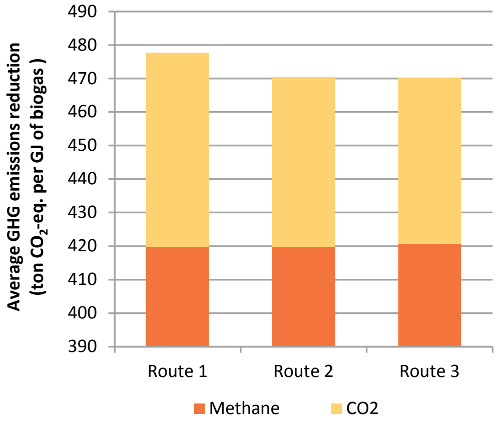

***Figure 144.*** *Average GHG emissions reduction by technology route and effect*

Emissions reduction of Route 2 is lower than Route 1 and varies slightly between 468 and 471 ton $CO_2$-eq. per GJ of biogas used over the lifetime as shown in Figure 143. Similarly to Route 1, emissions reduction of Route 2 comprises two components: 1) avoiding the release of fossil-based methane into the atmosphere and 2) substitution of biomethane for fossil fuels. While the amount of methane prevented from being released into the atmosphere is the same as in Route 1 (420 ton $CO_2$-eq. per GJ of biogas), Route 2 requires a significant amount of electricity for compressing the biomethane. This demand for electricity lowers the emissions reduction of Route 2 compared to Route 1, since electricity is partly produced by means of fossil fuels. On average, the emissions reduction related to the substitution of methane for fossil fuels reduces from 57.85 ton $CO_2$-eq. per GJ of biogas in Route 1 to 50.64 ton $CO_2$-eq. per GJ of biogas in Route 2. In addition, since the contribution of fossil fuels to electricity production in the baseline scenario (see details in Section G.2.3.2) and in all technology routes varies from year to year as a consequence of the El Niño phenomenon, the emissions reduction of Route 2 varies accordingly.

Emissions reduction of Route 3 varies between 463 and 494 ton $CO_2$-eq. per GJ of biogas over the lifetime and is on average lower than those of Routes 1 and 2. Similarly to Routes 1 and 2, methane prevented from being released to the atmosphere contributes to 420 ton $CO_2$-eq. per GJ of biogas. However, the power and heat produced in Route 3 replace the power and heat partly produced by means of fossil fuels in a proportion that changes from year to year. Emissions reduction in Route 3 peaks in dry years, when hydro power reduces (e.g. 2016, 2020 and 2024) as biogas-based power replaces fossil fuels and the opposite occurs in wet years. Lifetime emission reduction for the different technology routes is shown in Figure 145. The technology route with the largest lifetime emissions reduction is Route 1, which is able to reduce in total 7,165 ton $CO_2$-eq. per GJ of biogas. Route 1 is followed by Route 3, which is able to reduce a total of 7,078 ton $CO_2$-eq. per GJ of biogas over the entire lifetime. In third place, Route 2 is able to reduce 7,057 ton $CO_2$-eq. per GJ of biogas over the entire lifetime.

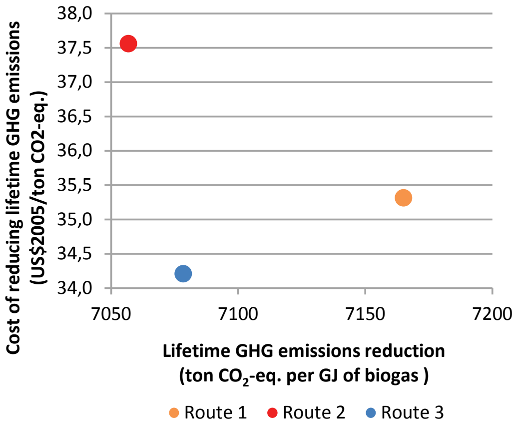

**Figure 145.** *Lifetime GHG emissions reduction by technology route vs. cost*

Finally, the cost of reducing lifetime GHG emissions for the different technology routes is also presented in Figure 145. The route presenting the lowest cost of reducing lifetime GHG emissions is Route 3 with 34.21 US$2005/ton $CO_2$-eq. Route 3 is closely followed by Route 1, which is able to reduce lifetime GHG emissions to 35.31 US$2005/ ton $CO_2$-eq. Finally, Route 2 at 37.56 US$2005/ ton $CO_2$-eq presents the highest cost of reducing lifetime GHG emissions of all the different routes.

## 6. Summary and discussion

The use of biogas from the anaerobic digestion of animal waste for biomethane production (Route 1), CNG production (Route 2) and power generation & CHP (Route 3) is analyzed from a technical and economic perspective. These three technology routes present various advantages: 1) they are among the most effective technologies for reducing GHG emissions by avoiding methane release and by replacing fossil fuels, 2) they are mature and well established and 3) they are commercially available as modularized and stand-alone technologies able to be deployed in different locations and applications. Fossil fuels that can be replaced by implementing these three technology routes include natural gas in Route 1, compressed natural gas (CNG) in Route 2 and fossil-fuel based electricity and heat in Route 3. By using 1000 TJ of raw biogas annually, 23.54 mio $m^3$ of natural gas can be replaced in Route 1, 0.1 mio $m^3$ of CNG can be replaced in Route 2 or 116.5 TWh of heat and 116.5 TWh of electricity can be replaced in Route 3.

In general, it is found that the three technology routes are able to reduce annual GHG emissions by values ranging between 460 and 500 ton of $CO_2$-eq. per GJ of biogas. Annual emissions reductions of Routes 1 and 2 are relatively unchanging at 478 and 470 ton of $CO_2$-eq. per GJ of biogas. In contrast, the annual emissions reduction of Route 3 varies between 463 and 494 ton of $CO_2$-eq. per GJ of biogas, as a result of a variable annual contribution of fossil fuels to heat and electricity production over the lifetime. A calculation of the lifetime emissions reduction reveals that Route 1 presents the largest reductions with 7,165 ton $CO_2$-eq. per GJ of biogas and is followed by Routes 2 and 3 with 7,078 and 7,057 ton $CO_2$-eq. per GJ of biogas, respectively. This shows that the lifetime emissions reductions of the three routes are very similar and only small differences are expected. When examining the causes of the emissions reductions for the three routes, it is found that more than 87% of the emissions result from avoiding methane release into the atmosphere, while the rest of the reduction is the result of replacing fossil fuels. Regarding costs, it is found that Route 3 offers the lowest cost of reducing lifetime GHG emissions with 34.21 US$2005/ton $CO_2$-eq. and is followed by Route 1 and 2 with 35.31 and 37.56 US$2005/ton $CO_2$-eq., respectively. This shows that while biogas combustion in a reciprocating engine might offer comparable lifetime emissions reduction relative to biomethane production, it can operate at a slightly lower cost under the aforementioned assumptions.

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strategic planning, policy analysis, bioenergy, energy systems, land use, biomass potential

Consapevole, dichiara

CONSAPEVOLE: (1) del fatto che in caso di dichiarazioni mendaci, oltre alle sanzioni previste dal codice penale e dalle Leggi speciali per l'ipotesi di falsità in atti ed uso di atti falsi, decade fin dall'inizio e senza necessità di alcuna formalità dai benefici conseguenti al provvedimento emanato sulla base di tali dichiarazioni; (2) dell'obbligo per l'Università di provvedere al deposito di legge delle tesi di dottorato al fine di assicurarne la conservazione e la consultabilità da parte di terzi; (3) della procedura adottata dall'Università di Ferrara ove si richiede che la tesi sia consegnata dal dottorando in 2 copie di cui una in formato cartaceo e una in formato pdf non modificabile su idonei supporti (CD-ROM, DVD) secondo le istruzioni pubblicate sul sito: http://www.unife.it/studenti/dottorato alla voce ESAME FINALE – disposizioni e modulistica; (4) del fatto che l'Università, sulla base dei dati forniti, archivierà e renderà consultabile in rete il testo completo della tesi di dottorato di cui alla presente dichiarazione attraverso l'Archivio istituzionale ad accesso aperto "EPRINTS.unife.it" oltre che attraverso i Cataloghi delle Biblioteche Nazionali Centrali di Roma e Firenze; DICHIARO SOTTO LA MIA RESPONSABILITA': (1) che la copia della tesi depositata presso l'Università di Ferrara in formato cartaceo è del tutto identica a quella presentata in formato elettronico (CD-ROM, DVD), a quelle da inviare ai Commissari di esame finale e alla copia che produrrò in seduta d'esame finale. Di conseguenza va esclusa qualsiasi responsabilità dell'Ateneo stesso per quanto riguarda eventuali errori, imprecisioni o omissioni nei contenuti della tesi; (2) di prendere atto che la tesi in formato cartaceo è l'unica alla quale farà riferimento l'Università per rilasciare, a mia richiesta, la dichiarazione di conformità di eventuali copie; (3) che il contenuto e l'organizzazione della tesi è opera originale da me realizzata e non compromette in alcun modo i diritti di terzi, ivi compresi quelli relativi alla sicurezza dei dati personali; che pertanto l'Università è in ogni caso esente da responsabilità di qualsivoglia natura civile, amministrativa o penale e sarà da me tenuta indenne da qualsiasi richiesta o rivendicazione da parte di terzi; (4) che la tesi di dottorato non è il risultato di attività rientranti nella normativa sulla proprietà industriale, non è stata prodotta nell'ambito di progetti finanziati da soggetti pubblici o privati con vincoli alla divulgazione dei risultati, non è oggetto di eventuali registrazioni di tipo brevettale o di tutela. PER ACCETTAZIONE DI QUANTO SOPRA RIPORTATO

Firma del dottorando

Monaco, li 9 March 2016 Firma del Dottorando ____________________

Firma del Tutore

Visto: Il Tutore Si approva Firma del Tutore ____________________