Combining an accelerated deployment of bioenergy and land use strategies: review and insights for a post-conflict scenario in Colombia

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Abstract

After a 50-year armed conflict, negotiations with guerrilla groups are likely to lead to peace agreements in Colombia. A post-conflict context would open up the possibility of modernizing agriculture, improving living standards in rural areas and making good use of the vast natural resources. Sustainable bioenergy combined with improved land use strategies is of particular interest in this context. However, while bioenergy is today the second largest renewable resource after hydropower, no official plans exist for exploiting it in a post-conflict context.

Our study investigates the impacts that an accelerated deployment of bioenergy could have in Colombia until 2030, under different land use pathways. Firstly, we review the country's socioeconomic, land use, energy and emissions context. Then, we identify lessons that Colombia could learn from Brazil to accomplish the proposed targets. Secondly, we explore various scenarios deploying different technologies (bioethanol, biodiesel, renewable diesel, biomethane and biomass-based power generation & CHP) and land use pathways that are likely to be implemented in a post-conflict scenario (zero deforestation, agricultural intensification and extensification). Thirdly, we analyze variations in energy demand and supply, greenhouse gas emissions, land use change and biofuel trade.

We find that biomethane and biomass-based power generation & CHP could reduce emissions more effectively than first-generation biofuels. However, their abatement is only 5% relative to a baseline scenario. Combining all bioenergy technologies with zero deforestation, agricultural intensification and extensification could boost abatements up to 280%, a value four times higher than the national commitments by 2030. Our study shows that relatively simple land use and energy models using free software can produce results of quality comparable to more complex and widely accepted models (e.g. IAMs). These results might be helpful to policymakers evaluating the role of bioenergy in a post-conflict context and to other developing countries with significant bioenergy potential and similar conditions.

Keywords: bioenergy; biofuels; land use change; energy policy; agricultural intensification; deforestation; greenhouse gas emissions; post-conflict; energy modeling.

Nomenclature

Acronyms

AFOLU	agriculture, forestry and other land use
BAU	business as usual
CAGR	compound annual growth rate
CHP	combined heat and power
ENSO	El Niño and La Niña Southern Oscillation
ESM	energy system model
GDP	gross domestic product
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
LEAP	Long-range Energy Alternatives Planning System
LULUCF	Land use, land-use change and forestry
LUTM	land use and trade model
R&D	research and development
toe	ton of oil equivalent

1. Introduction

Colombia has abundant natural resources. It is one of the seven countries in the world where more than half of the potentially available global arable land is concentrated [1]. It holds the sixth largest renewable water resources [2] and the sixth largest area of primary forest in the world [3]. It is also the most biodiverse country in the world per square kilometer [4]. However, these natural resources have been linked to the armed conflict in both positive and negative ways [5]. On the negative side, armed groups have caused land grabbing, deforestation, water and air pollution and illegal mining [5, 6]. In addition, the armed conflict and the development of illicit crop production negatively affected agricultural output growth. On the other hand, violence from armed groups has caused the abandonment and underutilization of extensive land areas, which has indirectly led to environmental preservation [5].

Today, Colombia is contemplating peace agreements after a 50-year armed conflict, which could enhance human capital (i.e. reducing poverty and inequality), physical capital (i.e. enhancing investment conditions and improving the land tenure system through access to land) and social capital (i.e. increasing the labor force by minimizing displacement by violence) [7]. It would also open up the possibility of modernizing and boosting agriculture, improving living standards in rural areas and making good use of the vast natural resources. Sustainable bioenergy is of particular interest in this scenario. Firstly, there is vast biomass energy potential that remains untapped [8, 9, 10, 11, 12, 13]. Secondly, sustainable production of bioenergy can help towards the modernization of agriculture, enhance rural development [14], reduce oil dependence, diversify energy portfolios and reduce emissions [15, 16, 17]. However, bioenergy is not a definitive solution, and multiple barriers exist which prevent its exploitation in a sustainable manner. Deforestation [18, 19, 20, 21] and crops for food vs. biofuels [22] leading to direct and indirect land-use change [23], pressure on water resources and a large variation in life cycle emissions [16, 24] are some of the hurdles to overcome in order to further exploit bioenergy potential [16, 25, 26]. These challenges are further complicated in Colombia, where resources and experience in policymaking, long-term planning and sustainability are limited [27]. While today bioenergy is the second largest renewable primary energy resource (3.8 million tons of oil equivalent –Mtoe–) after hydropower (4.2 Mtoe) [8], only a limited number of studies have previously explored its further deployment [28, 29] and the magnitude of its impact has not been investigated in detail. More importantly, no official plans exist today for exploiting bioenergy in the long-term at a national level.

We aim at filling this void. Our study aims at investigating the impacts that an accelerated deployment of bioenergy could have in Colombia until 2030, under different land use pathways. Specifically, we explore changes in energy demand and supply, energy-related GHG emissions, land use and biofuel trade from alternative bioenergy technologies and land use pathways. We focus on five key bioenergy technologies based on expert judgment from over 30 experts [30, 31]: 1) bioethanol, 2) biodiesel, 3) renewable diesel, 4) biomethane and 5) biomass-based power generation & CHP. In addition, we consider alternative land use pathways that are likely to be implemented in a post-conflict scenario, viz. zero deforestation, agricultural extensification and intensification. To facilitate the soundness of the findings presented, they are reflected to the experience of Brazilian bioenergy policy since the 1970s.

The present paper is part of a comprehensive research activity aimed at providing guidelines for bioenergy exploitation in Colombia [13, 30, 31, 32, 33]. This paper is structured as follows. Firstly, we present in Section 2 a thorough review of the country's socioeconomic context, land use, energy use, greenhouse gas emissions and status of bioenergy. In Section 3, we describe some of the lessons that Colombia could learn from Brazil in order to accomplish an accelerated deployment of bioenergy under different land use pathways. In Section 4, we discuss the different scenarios, technologies and land use pathways proposed in the study. In Section 5, we present an overview of the modeling framework as well as details of the methods. In Section 6, we present and discuss the impacts of implementing the different scenarios on the country's energy supply, GHG emissions, land use and trade. Finally, in Section 7 we discuss the most significant results of the investigation and draw some conclusions.

2. Context

2.1. Socioeconomic context

Today, Colombia is the country in Latin America with the third largest population (47.8 million, after Brazil and Mexico), the fourth largest gross domestic product –GDP– (609 billion US$2011, after Brazil, Mexico and Argentina) [34] and the fifth largest primary energy demand (37 Mtoe) [8]. In the last 50 years, Colombia has been characterized by an almost uninterrupted positive economic growth. Since the early 1980s, the country has shifted from an agricultural economy to one based on minerals and energy resources. This shift has allowed the country to grow at 3 to 4% annually since 1980, which has been higher than the average in the region [34]. In the last ten years, public expenditure has doubled, per capita income has increased by 60% and foreign investment has increased five-fold [35, 36]. However, a combination of widespread corruption, ineffective policies, weak institutions and armed conflict has hindered better wealth distribution. Unlike neighboring countries, Colombia has experienced a 50-year armed conflict, the longest-running armed conflict in the Western hemisphere [37], characterized by widespread violence, political instability, disregard for the rules of law and aggression against the civilian population [38, 6]. Rooted in an extensive history of struggles for political, economic and social rights, the internal conflict has resulted in one million casualties, six million civilians internally displaced and thousands of hectares of usurped land [39]. Violence and unrest in rural regions combined with a decline in agriculture caused massive migration to cities. Between 1975 and 2009, the urban population rose by 145% (from 14 to 34 million), while the rural population increased only 16% (from 10 to 11.5 million). The rural-urban migration led not only to a concentration of the population in urban areas, but also to a concentration of the poor in the countryside. Today, rural areas account for only 25% of the country's population, but more than 40% of the poor [34, 40].

2.2. Land use

Various factors impacted the biophysical landscape in the late Twentieth Century in Colombia. Firstly, massive migration to cities led to a very low utilization of land and labor and a low agricultural productivity compared to its vast potential [41]. Secondly, policies favored the production of grain crops and cattle farming, which are not labor intensive and discriminated against small farmers [41]. Thirdly, small landholders in the Andean region saturated and migrated to lowland forest frontiers of the Amazon and lower Andes [42]. Fourthly, the armed conflict and the illegal drug economy trespassed the agricultural frontiers and drove deforestation in order to cultivate illicit crops [43]. The combination of these factors resulted in various impacts. Firstly, an accelerated deforestation process occurred with clearing annual rates of above 230 kha, particularly in the Andean, Amazon and Pacific regions [42]. Secondly, land for cattle farming over-expanded. Between 1975 and 2009, it doubled its share in the cover of land area from 16% (18 Mha) to 35% (39 Mha) [44], even though only 13% of the land area is suitable for pasture [41]. Cattle farming surged, at the expense of forest and cropping areas, and contributed to 90% of the cleared areas in 2000 [42]. Thirdly, land for crop farming reduced and is underutilized. Between 1975 and 2009, it reduced its share in the cover of land area from 5% (5 Mha) to 3% (3 Mha) [44], even though 16% of the land area is suitable for crops [41]. Fourthly, smallholder agriculture declined as industrial agriculture (e.g. palm oil, cane and soybeans) increased. The latter was characterized by using highly mechanized cropping on the most suitable land, being market-oriented and concentrated within the control of fewer land holders [42, 45]. Today, however, agricultural productivity in Colombia lags behind world averages with few exceptions (e.g. sugar cane, coffee, banana, etc.) [46].

Land use change, from pastures to crops and deforestation, is a major contributor to GHG emissions in the country, as shown in later sections. De Pinto et al. found in a recent study that one additional hectare allocated to agriculture increases emissions by in average 2.5 tCO_2-eq per year, while one hectare deforested in the Amazon result in a loss of carbon stock of about 367 tCO_2-eq [47]. Thus, it would take 146 years for an additional hectare of agricultural land to cause the same emissions than one deforested hectare of Amazon forest [47]. De Pinto et al. estimate a business-as-usual (BAU) scenario using the IMPACT model, which is characterized by an increase of 2.6 Mha in pasture lands and a decrease of 3.4 Mha of natural forest between 2008 and 2030. This would result in an increase in GHG emissions by 85.4 $MtCO_2$-eq in the same period. De Pinto et al. recommend various solutions to reduce emissions associated with land use change. Their first priority is a reduction in pasture land via cattle intensification, as it represents a "win-win" policy that reduces emissions and increase revenues. Their second priority is a reduction in deforestation, which increases carbon stock but reduces revenues. Finally, their third priority is palm oil expansion, which increase emissions and reduce revenues.

Alternatives to stop deforestation and the overexpansion of cattle farming, while ensuring sustainable wood and food have been recently proposed or tested in the country. These include:

- Reducing Emissions from Deforestation and Forest Degradation (REDD+), i.e. compensation to tropical forest nations that demonstrate emission reductions from deforestation and forest degradation [48].
- REDD+ combined with biofuels [49].
- Sustainable Supply Chain initiatives (SSC), i.e. management of the environmental, social and economic impacts throughout the lifecycle of goods and services [48].
- Silvopastoral Systems (SPS), i.e. replacement of traditional treeless cattle pastures by a combination of fodder plants, shrubs and trees and cattle farming [50, 51].
- Intensive Silvopastoral Systems (ISS), i.e. combination of animal production with fodder shrubs at high densities (>10,000 plants/ha), intercropped with highly-productive pastures and timber trees.
- Combinations thereof [50, 52, 53, 51].

2.3. Energy

The socioeconomic and political transformations experienced in the last few decades in Colombia have brought serious consequences to the energy sector and the environment. Between 1975 and 2009, primary energy demand[1] doubled (from 17 to 37 Mtoe), increasing at a compound annual growth rate –CAGR– of 2.3% [8]. While this rate of increase was similar to other countries in the region [54], Colombia only accounted for 4% of the primary energy demand in Latin America in 2009 [55]. Compared to primary energy demand, GDP grew at a CAGR of 3.7%. This promoted an annual reduction of 1.4% in energy intensity (from 0.16 to 0.09 toe/US$2005), which was significantly higher than other countries in the region [54]. The share of fossil fuels in the primary energy demand increased from 69% to 77%, while the share of renewables reduced from 31% to 23%. While this was actually contrary to the trend experienced by other countries in the region [54], it is expected to continue in the future [30, 56]. Oil was and continues to be the source with the highest shares (45%) in the energy mix, followed by natural gas, which grew from 10 to 22%. In contrast, bioenergy (i.e. woodfuel, cane bagasse[2] and biomass residues[3]) reduced from 26 to 10%.

Final energy use also doubled between 1975 and 2009. Demand for modern energy services, such as electricity and natural gas increased at CAGR of 4.5% and 5.4% respectively. Furthermore, demand for crude oil increased at a CAGR of 1.6% and traditional biomass reduced at a CAGR of 0.5%. The substantial increase in demand for electricity and natural gas is partly explained by a higher level of access to these services. Between 1975 and 2009, access to electricity increased from 63 to 97%, while access to natural gas increased from 0 to 48% [57, 58]. Despite these improvements, Colombia is still below the average of Latin America [57, 58]. Today, 1 million people living in remote areas still lack access to electricity [59]. Hydro dominates power generation with an average contribution of 72%, followed by gas (16%), coal (9%) and to a lesser extent, oil, bioenergy and wind [8]. Over-dependence on a hydro-dominated system has proven vulnerable to droughts caused by El Niño-Southern Oscillation (ENSO). For instance, in 1992 and 1997, severe droughts caused reductions in the water inflow of reservoirs by more than 30% and were also responsible for blackouts [60]. To reduce the over-dependence on uncertain weather conditions, new gas- and coal-fired power plants were built [61]. This increased the reliability of the system, but raised emissions and concerns regarding energy security [60]. In the transport sector, vehicle ownership grew exponentially from 0.5 to 6 million vehicles between 1975 and 2009 [62, 63, 64] and their demand for energy increased three-fold at a CAGR of 2.8%. The bulk of this demand was mostly covered by fossil fuels (e.g. gasoline, diesel and compressed natural gas –CNG–) [8], while biofuels (e.g. bioethanol and biodiesel) contributed to about 4% [8].

2.4. GHG emissions

More people demanding more energy and resources resulted in increased emissions. Between 1990 and 2010, GHG emissions almost doubled, growing from 130 to 224 $MtCO_2$-eq [65, 66]. The bulk of these emissions corresponded to agriculture, forestry and other land use –AFOLU–, which contributed to 52% of the emissions in 1990, and 58% in 2010 (half of it associated with CH_4 emissions from enteric fermentation and cattle farming). AFOLU emissions grew two-fold in this period, at a CAGR of 3.35% and are expected to continue growing in the future [67]. They were followed by energy emissions, which actually reduced their share from 41% in 1990 to 32% in 2010 and grew at a CAGR of 1.5%. 55-60% of the energy emissions correspond to power generation and road transport. Emissions from waste grew three-fold at a CAGR of 6% and contributed to 6% of the overall emissions in 2010. The remaining ~4% corresponded to emissions from industrial processes. Colombia's share of GHG emissions is rather similar to the Latin America average, which is characterized by 65% AFOLU emissions, 21% energy emissions, 10% emissions from industry and 3% emissions from waste [68]. However, Colombia's share of GHG emissions in Latin America is small compared to other countries of a similar size. In fact, Colombia contributed to 3.4% to the GHG emissions in Latin America, despite accounting for 6% of the region's GDP [56]. This is the result of low energy consumption and high hydroelectricity production compared to other Latin American countries [54, 56].

Regarding energy-related emissions, they increased by 35% between 1990 and 2010 [65, 66]. A decomposition analysis showed that changes in the overall and sectorial GDP were the main factors explaining this increase [54]. Sheinbaum et al. found that while there was a significant reduction in energy intensity, it was counterbalanced by a higher dependence on fossil fuels, thus leading to an increase in emissions [54]. Various studies suggest that GHG emissions in Colombia would further increase in the future. Calderón et al. compared four climate mitigation models (GCAM, TIAM-ECN, Phoenix and MEG4C) and found that energy-related emissions may increase from 66 $MtCO_2$-eq in 2004 to 100-160 $MtCO_2$-eq in 2030. They argue that Colombia's current low carbon economy may not be sustainable in the future, due to the country's economic growth and higher dependence on fossil fuels [56]. They highlight that coal-based power

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[1] Defined as the sum of final energy use by sector and losses in energy transformation.

[2] Includes bagasse from sugarcane but excludes bagasse from jaggery cane.

[3] Mostly palm oil residues.

generation may increase as vast coal reserves are available at a low price. ECLAC also estimates significantly higher overall GHG emissions by 2030, i.e. 400 MtCO$_2$-eq [69]. According to ECLAC, energy-related GHG emissions alone would grow from 66 MtCO$_2$-eq in 2004 to a value ranging between 110 and 200 MtCO$_2$-eq, depending on the underlying scenario [69]. On the other hand, in its report to the UNFCCC, the national government estimates an increase in overall GHG emissions from 224 to 335 MtCO$_2$-eq between 2010 and 2030 in a business-as-usual (BAU) scenario [66]. Furthermore, the government commits to a 20% reduction in GHG emissions (-67 MtCO$_2$-eq) by 2030, relative to the baseline.

2.5. Biomass and bioenergy

Colombia is today's 10th largest global producer of ethanol, 5th largest global producer of palm oil and first in Latin America, although the country remains far from the values expected of Brazil and Argentina [70]. Bioenergy plays an important role in the energy mix of the country as it is today the second largest renewable energy resource after hydroelectricity. In 2009, bioenergy 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 Mtoe) [8]. Colombia is also characterized by a vast biomass energy potential that remains untapped. Various studies have recently estimated a theoretical potential ranging between 5 and 18 Mtoe [13]. From this potential, a fraction ranging between 1 and 10 Mtoe might be technically available at current conditions for energy exploitation. Recent studies also found that biomass energy consumption stimulates economic growth in the country, which in turn motivates further biomass energy consumption in the long-run [71]. This is a trend also observed in other developing countries in Latin America [72] and the world [73, 74].

The current use of biomass for energy purposes in Colombia can be divided into four main categories, which are discussed below. Firstly, and most predominantly, it is used in the form of wood and charcoal as a traditional fuel for cooking and water heating [8]. 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.

2.5.1. 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), and the Institute of Planning and Promoting of Energy Solutions in Non-Interconnected Zones (IPSE). While the UPME and IPSE are in charge of capacity planning and support of policy making, the 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 of 2002 and 939 of 2004 and Decree 4892 of 2011), policy guidelines for the promotion of biofuel production (Conpes 3510 of 2008) and programs on the promotion of the efficient and rational use of energy and alternative energies (Law 697 of 2001, Resolution 180919 of 2010, Law 1715 of 2014). This support for 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 [75]. Regarding environmental protection, the Ministry of Environment and Sustainable Development (MADS) coordinates policy making and regulations regarding environmental management and permitting, forestry conservation, climate change mitigation and land use planning. The MAVDT leads the Colombian National Environmental System (SINA), one of the most advanced in Latin America [5]. It has also formulated the Green Growth Policy, which seeks to improve welfare of population in general and of the poor in particular through better environmental management practices, such as reducing impacts of mining, strengthening the system of environmental management, etc. [5].

2.5.2. Wood

In 2009, the demand for wood in Colombia amounted to 2.48 Mtoe, mostly used for cooking in rural areas –albeit very inefficiently– and for producing charcoal [8]. For this purpose, 13.6 Mm^3 of roundwood were produced, mostly extracted from primary forests and, to a lesser extent, from plantations [44]. About two fifths of this production was illegal, as wood was not only extracted from permitted areas, but also from protected forests and national parks [76]. Deforestation is a complex and very critical problem in the country, and it has eaten up 14 Mha between 1970 and 2010 [42, 77]. Apart from logging for timber, many other complex factors explain patterns of deforestation including, cattle ranching [78], the illegal economy of illicit crops [79, 43], regional accessibility, forest neighborhood, land tenure and access to credit [80, 42, 45, 81]. A switch to using wood and perennial feedstocks for second generation biofuels like lignocellulosic ethanol via thermochemistry and biochemistry could improve the added value in Colombia. According to NREL [82], the price of producing lignocellulosic ethanol via thermochemistry could be 33% lower than in the U.S., i.e. about 0.8 US$2005/l. However, it could also increase the pressure on further deforestation.

2.5.3. 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 defined the blending of 10% bioethanol by volume (E10) to be used in road transport gasoline fuel. The mandate is regulated by the Ministry of Mines and Energy and is accompanied by tax incentives for selling bioethanol and importing process machinery. In 2009, an installed capacity of 2 million l/day enabled a bioethanol production of 334 million liters (167 ktoe), which contributed 2.3% of the energy demand in road transport [8]. Bioethanol is currently produced using sugar cane as a feedstock, which is cultivated exclusively in the Valley of the Cauca River. Climatic and soil conditions in this region allow the cultivation of sugar cane at yields as high as 120 tons/ha throughout the entire year and not only in sessional harvests (e.g. zafra). Cane cultivation amounted to 217 kha in 2009, of which 80% was allocated to sugar production and 20% to bioethanol [83]. The production of bioethanol currently yields about 9,120 liters per ha [83]. 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 is concentrated by removing water, yeast and organic matter, which are then recirculated into the bioethanol fermentation reactor. 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) [83].

If all production of sugar cane were destined for ethanol production, it would cover about 50% of the current gasoline demand in the country [46]. Demand for transport energy and bioethanol are likely to increase in the future [64, 46], which would require expansion beyond the Valley of the Cauca River. Bioethanol expansion is not likely to have a land constraint in Colombia [46, 84], similarly to the case of Brazil [85, 86]. While expanding bioethanol may have positive impacts such as economic development, job creation, reduced emissions and enhanced energy security [24, 46, 86], it may also have economic and social consequences. Firstly, it would put pressure on agricultural markets and increase the price of sugar, which would mostly impact poor households [46, 87, 88]. Secondly, it would put pressure on water, land use and fragile ecosystems [89, 90]. Thirdly, it may increase land concentration and a loss of access to land and natural resources for peasant farmers, poor communities and indigenous people [46, 89, 91]. Fourthly, bioethanol is expensive and it remains unclear how much governmental support will be needed before it becomes independent from subsidies [87, 92]. Fifthly, there are concerns that the Bonsucro certification, needed to access international markets (e.g. the EU), is deeply influenced by configurations of power and interest (aka corruption) at local, national and transnational levels [93].

Alternatives to cane-based bioethanol in Colombia have been recently proposed or tested in the country. Examples include lignocellulosic bioethanol [94, 95, 96], cassava-based bioethanol [94, 97], red beet-based bioethanol [98], bio-oil from bagasse [99] and sugar cane biorefineries [100]. These are mid- and long-term alternatives that address some of the concerns associated with cane-based bioethanol and which deserve greater attention from industry, governmental agencies and decision makers.

2.5.4. 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 of bioethanol. Production of biodiesel reached 276 million liters in 2009 (167 ktoe), which contributed 2.3% of the overall energy demand in road transport [8]. An installed production capacity of 1.8 million liters per day is currently required to supply the growing biodiesel demand. Biodiesel is currently produced using palm oil as feedstock, which was identified as the crop with the highest yield in liters per ha in early feasibility studies [101, 102]. Palm oil is widely cultivated across the country, but most representative plantations are located in the eastern, northern and central regions. 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 [83]. The palm oil-cultivated area has been boosted since the introduction of the biodiesel blend mandate, and today Colombia is the 5th largest grower worldwide and the first in Latin America. 20% of the oil production in the country is allocated for biodiesel production [83]. Typical yields are about 20 tons of fresh fruit bunches (FFB) and 3.5 tons of oil per ha, which are higher than alternative oil crops [83]. Biodiesel is produced via continuous transesterification with reported yields as high as 4,530 liters per ha [83]. Wastewater is produced at palm oil extraction mills and biodiesel production plants and is treated via surface-aerated basins (lagoons). Lagoons significantly reduce the biochemical oxygen demand (BOD) but do not capture methane, which becomes the largest contributor to the lifecycle GHG emissions of the process [83]. 30% of the current diesel fuel demand in the country could be covered if all the production of palm oil were destined for biodiesel production [46]. Falck-Zepeda et al. concluded that regarding energy security, palm-based biodiesel would be the alternative that most covered the diesel fuel demand in Latin America [46]. Similarly to bioethanol, demand for biodiesel is expected to increase [64, 46], which would require an expansion that is not likely to be land-constrained [46, 84]. However, studies on biofuel expansion are non-conclusive. Some studies report feasibility of B20 by 2020 [103], while some others consider it unattainable [104].

Biodiesel expansion offers various advantages, for instance municipalities cultivating palm oil today present lower levels of unmet basic needs and bigger fiscal incomes than municipalities where palm oil is not cultivated [105]. In addition, 50% of the new palm oil plantations have occurred in pastures, which have increased productivity, jobs and climate change mitigation in those areas [104]. However, there are various complex challenges to be solved. Firstly, violence and land tenure concentration tended to be historically higher in municipalities cultivating palm oil [105, 106]. Sustainable development in these regions might be hindered by institutional conditions (e.g. corruption, bureaucracy and land concentration) and social conditions (e.g. inequality and violence) [105, 106]. Secondly, land grabbing occurred either through the use of violence or by framing lands as marginal, abandoned or underutilized [106]. Thirdly, biodiesel expansion might put pressure on land for cropping (and prices), forests and natural savannas [104, 46], which would increase the GHG intensity of palm oil and biodiesel [107, 83, 108]. Fourthly, multi-stakeholder initiatives such as the Roundtable on Sustainable Palm Oil (RSPO) face challenges to effective implementation in the country, partly because environmental and territorial authorities lack the resources for planning the expansion in the territory [106, 103], but also because understanding of sustainability in the country is very different to that of industrialized countries [109]. Fifthly, current subsidies in the country tend to benefit biodiesel producers but not oil producers, and become ineffective in the long-term [110, 91].

Proposed alternatives to palm-based biodiesel in the country include jatropha-based biodiesel with double lifetime GHG emissions compared to palm-based biodiesel [97], palm-based biorefineries [111, 112], palm-based renewable diesel [94], palm-derived Methyl Ester (PME) [113] and bio-oil production from palm empty fruit bunches [99]. These are mid- and long-term alternatives that address some of the concerns associated with palm-based biodiesel and that deserve greater attention from industry, governmental agencies and decision makers.

2.5.5. Biomass-based power generation and combined heat and power (CHP)

Today, biomass-based power generation and CHP exist in the sugar cane and palm oil industries. In the first case, bagasse is used as a fuel to generate process steam and power. Steam is used to feed steam turbines driving knives, shredders and mills and to feed bioethanol distillation towers. Two configurations are typically used: back pressure steam turbines and condensing-extraction steam turbines. Back-pressure steam turbines are characterized by expanding steam to a pressure above atmospheric, which is subsequently used as process heat. It offers high efficiencies in CHP conversion, but low capacity to generate electricity, still enough to cover in situ power needs and generate some surplus power [114]. Condensing-extraction steam turbines have the capability of extracting a portion of the 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 power generated compared to the back-pressure configuration [115]. Electrical efficiencies range from 5 to 10% for the back-pressure configuration and from 10 to 30% for the condensing-extraction configuration, however the conversion of live steam energy into useful forms of energy (electricity and process heat). Today, the average electrical efficiency of bagasse-based power plants in Colombia is about 24%, while the CHP efficiency ranges between 45% and 65% [83]. 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 9 MWe of installed capacity [116]. By 2009, there were six cogeneration power plants in operation and two planned, totaling 58 MW of installed capacity generating 0.6 TWh [83, 116]. Cogeneration is also used in the palm oil industry to produce steam and power. Steam is used in the sterilization of fresh fruit bunches (FFB) as well as in the digestion of fruits in steam vessels to separate off the oil from the solid material. 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 and 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 [83]. Improved configurations have been proposed in literature, e.g. polygeneration of biodiesel, electricity and pellets [117].

Cogeneration in other sectors producing significant amount of organic residues has been tested in the country with limited success. A small-scale cogeneration 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 [9]. An incinerator of municipal residues installed on the island of San Andrés ceased operation because of an insufficient volume of residues. The installation of a wood gasifier in Necoclí (Antioquia), a non-interconnected zone (NIZ), ceased operation because the town eventually gained connection to the national grid [118]. Other barriers associated with renewable power systems in the country are available in [119, 120], while barriers specifically for biomass-based power generation are described in [30].

3. Lessons from Brazil

For deploying the different bioenergy technologies and land use pathways proposed here, Colombia could learn some lessons from Brazil. Brazil is a reference point regarding bioenergy not only in South America but also in the world [70, 87, 89]. The two countries have many similarities, but also some important differences. They have similar GNI/capita, participation of forests in the total country areas (~50%), important livestock productions and biofuels programs. Most of the differences arise from the scales of both countries since Brazil has a population, surface area and GDP 4.3, 7.5 and 5.3 times larger, respectively, compared to Colombia. Brazil has by far the largest population (190 million in 2010) and GDP (US$ 3.2 billion in 2014) in Latin America, but a similar GNI/capita close to the regional average. Commercial agriculture has seen great progress since the 1970s, making Brazil one of the largest food producers and exporters in the world with soybeans, corn, coffee and meat being the major products.

Lessons that Colombia could learn from the past experience of Brazil can be divided in four categories: improved land use, GHG mitigation plans, bioethanol program and biomass-based power generation.

Firstly, Brazil has been active in guiding the land use for a more sustainable profile. Brazil has a total area of 851 Mha, with forests occupying 450 Mha, pastures 180 Mha and crops 60 Mha. The participation of native forests (mostly Amazon forest) is about 50%. Pastures are much larger than cropland, which represents both good potential for optimization and a threat for crops. Various measures to improve the country's land use have been implemented. First, since 1965 the Forest Code protects 20 to 80% of the native vegetation in all rural properties, monitors and acts to reduce deforestation. Second, the Agroecological Zoning Program identified 64 Mha and 30 Mha of degraded or underutilized land available for the sustainable cultivation of sugar cane and palm oil (7.5 % and 3.5 % of the country land, respectively) [121]. This shows that there is sufficient area for sustainable expansion of biofuel feedstock production. Third, several technologies are being employed to intensify agriculture and reduce the threat of deforestation: double cropping of corn and beans, rotation of soybeans and corn, reducing fertilizer use and increasing yields, recovery of degraded pasture and intensification of cattle husbandry. As a result, corn production increased 75% between 2003 in 2013, while cropped areas increased 21% (13 to 16 Mha); meat and milk production increased 40%, while pasture areas decreased by 4 Mha. Fourth, the increasing rate of deforestation in the Amazon forest was reversed in 2004, when it reached 27,379 km^2 and decreased to 4,656 km^2 in 2012 [122].

Secondly, Brazil has been successful in designing and implementing plans to reduce national GHG emissions. The GHG emissions inventory in Brazil has a peculiar profile, which is similar to the one in Colombia. In 2005, LULUCF represented 57.5% of the total country emissions and agriculture contributed to 20.5%. Energy and industry added 15.0% and 3.6%, respectively, while wastes only contributed 1.9%. Besides controlling deforestation –the main component of LULUCF emissions– the government acted with a wider vision to reduce the country's GHG emission (2,032.3 MtCO$_2$-eq) and launched the National Plan of Climate Change (Law no. 12.187/2009) and the Low Carbon Agriculture (ABC) program. These programs made a significant amount of financial resources to promote five sub-programs: Recovery of Degraded Pasture (15 Mha), Integration of Agriculture/Livestock/Forest (4 Mha), No Tillage Agriculture (8 Mha), Biologic Nitrogen Fixation (5.5 Mha), Planted Forests (3 Mha) and Animal Waste Treatment (4.4 Mm^3). The expected impact of these programs, if fully implemented, is the reduction of GHG emission in the range of 134 to 163 MtCO$_2$-eq.

Thirdly, Brazil has almost a century of experience on fuel ethanol use and four decades operating E20 blends. In 1931, the government issued the first mandate to blend 5% of ethanol in all imported gasoline. In 1975, pressed by the escalating oil prices, the government launched the National Alcohol Program (PROÁLCOOL), with a goal of 20% gasoline substitution. Between 1975 and 1979, ethanol production increased rapidly from 600 to 3,400 Ml. In 1979, the second oil shock forced the government to put pressure on the automakers, who introduced neat ethanol cars into the market [123]. In 1985, the oil prices returned to pre-crisis levels and the ethanol program stagnated around 11 billion liters/year until around 2002 when oil prices started to increase again. In 2003, Flex Fuel Vehicles (FFVs) started to be produced and sold in the country, becoming the basis for a new expansion phase that lasted until the economic crisis in 2008. Today, 34 Mt of sugar cane are produced in the country, 45% allocated to sugar and 55% to ethanol. The ethanol market is ~30 billion liters and is expected to grow to 44 billion liters in 2024 [124]. Today, the ethanol market operates without subsidies and is totally deregulated, with the government acting only to adjust the blend rate. Success of the bioethanol program in Brazil was possible due to the implementation of a comprehensive public policy, which can provide guidelines to Colombia. This policy has been characterized by enabling: 1) the development of feedstock production chains, agricultural zoning and crops improvements, 2) mechanisms of stabilization of production chains threatened by changes in prices of oil and sugar, 3) the establishment of industry (e.g. FFV, ethanol plants, CHP, etc.), infrastructure, R&D and standardization, 4) consolidation of biofuel consumer segment through regulatory and tax incentives, among others [125].

Lastly, Brazil has been successful in deploying biomass-based power generation and CHP, which today accounts for 5% of the consumption. Similarly to Colombia, the electric power matrix is dominated by hydro with 74% of the domestic electricity supply, which totaled 509 TWh in 2010. The massive participation of hydro power in the electricity generation has the advantage of being a renewable source with low GHG emissions, but leaves the country dependent on the weather for its electric power supply. This impact has been reduced by increasing thermal power generation and renewable sources. Renewable sources in the form of small hydro, wind and biomass have been stimulated by the government since the launch of the Program of Incentive to Alternative Energy Source of Electric Energy (PROINFA) in 2004, which offered long term contracts with attractive prices for up to 1,100 MW of each source. While PROINFA support has certainly benefited biomass-based power generation, its success is mostly due to its linkage to the sugar cane industry. An effective collection of the by-products of the sugar cane crop (i.e. bagasse, tops and leaves) combined with increasingly modern combined heat and power plants with condensing extraction turbines, has enabled sugar mills to export surplus electricity to the grid. In fact, sugar mills are becoming important surplus electricity producers with 19.4 TWh in 2014 (4% of national consumption), but still far from the estimated potential of 129 TWh/year (27% of national consumption), due to several barriers [126].

4. Scenarios

To analyze the impacts of an accelerated deployment of various bioenergy technologies under different land use pathways, we contrast four alternative scenarios with a baseline scenario. The baseline scenario assumes no future changes in energy policies and a continuation of past trends in energy demand and supply. Details are presented in the supplementary information section and in separate references [30, 31]. The baseline also assumes a deforestation rate of 100 kha/year until 2030, which is below the deforestation rate of the last 20 years (238 kha/year) [47], but is in line with the average rates since the 1950s and estimations from FAO [44]. The baseline also assumes a continuation of past trends in growth of cropland and pasture land for livestock and yields; details are presented in the supplementary information section and in separate references [32, 30]. Regarding bioethanol production, the baseline scenario assumes that in the future it may only be produced in the Valley of the Cauca River, which is currently the only large-scale cultivated area [83]. Four alternative future scenarios are investigated based on expert judgment from over 30 experts [30, 31] and are described in further detail below.

Scenario I targets the deployment of biomethane production, biomass-based power generation & CHP and does not change the current blend mandate of first-generation biofuels, i.e. E10 (10 v% bioethanol, 90 v% gasoline) and B10 (10 v% biodiesel, 90 v% diesel fuel). Scenario I uses the same assumptions regarding agriculture, livestock, deforestation and land use as the baseline. It considers large-scale production of sugar cane only in the Valley of the Cauca River. Its long-term bioenergy goals by technology include:

- Biomethane: use 5% of biomass residues and 1% of biogas from animal waste resources nationwide to produce biomethane for injection into the natural gas network by 2030.
- Power generation & CHP: achieve a renewable power generation target of 10% by 2025 by deploying biomass combustion in steam turbine CHP power plants, co-firing wood pellets in coal power plants and biogas/landfill gas combustion in reciprocating engines. Small-hydro and wind are also considered in the target, but large-hydro is excluded. Additionally, it targets the nationwide use of 5% of the biogas from animal waste and municipal water treatment plants, 100% of the methane produced in the palm oil industry and 10% of the municipal landfill gas for power generation & CHP by 2030.

Scenario II targets a combined deployment of biomethane production, biomass-based power generation & CHP with further growth of first-generation biofuels (e.g. bioethanol, biodiesel and renewable diesel). Scenario II also uses the same assumptions on agriculture, livestock, deforestation and land use as the baseline. It considers large-scale production of sugar cane only in the Valley of the Cauca River. Its long-term goals for biomethane and power generation are the same as for Scenario I, while its long-term goals for biofuels include:

- Biodiesel (palm oil based): increase the quota mandate to B20 in 2020 and B30 in 2030.

- Bioethanol (cane based): 1) increase the quota mandate to E20 in 2025 and 2) implement an E85 fuel program in 2030.
- Renewable diesel (palm oil based): achieve a 10% energy contribution of renewable diesel to the total diesel fuel production in 2030.

Scenario III shares bioenergy targets and assumptions on agriculture, livestock, deforestation and land use with Scenario II, but considers extending the cultivation of sugar cane on a large-scale beyond the Valley of the Cauca River, which is not examined in Scenarios I and II.

Scenario IV shares the same targets and assumptions as Scenario III, but considers an alternative land use pathway that is likely to be implemented in a post-conflict scenario. Besides extending the cultivation of sugar cane, it also considers a combination of agricultural and cattle yield intensification with a zero net deforestation rate, which is in line with recent studies on land use in Colombia [47]. In particular, Scenario IV aims at accomplishing the following three land use measures:

- Stop net deforestation in the Amazon by 2020. During COP21 in Paris, Colombia committed to its most ambitious governmental strategy for environmental preservation: reducing the net deforestation in the Amazon to zero [127]. These commitments can push institutions on a high level to preserve forests and also motivate farmers to adopt alternatives to deforestation on a small-scale [128].
- 30% increase in cattle yields compared to the baseline [129]. This measure can, for example, expand the deployment of techniques that are proven on a small-scale in the country, such as Silvopastoral Systems [50, 51, 69] and Intensive Silvopastoral Systems [50, 52, 53, 51].
- 60% increase in yields of agricultural crops compared to the baseline [129]. This measure is in agreement with other studies suggesting agricultural intensification in order to meet the growth in demand for food and biofuels resulting from increasing population and income [129, 130, 131, 132]

This land use pathway offers various advantages relative to the other scenarios. Firstly, it is in line with the Green Growth Policy formulated by the Colombian Government [133, 5] and with OECD recommendations [134] for enhancing environmental, social and economic development in the post-conflict [5]. Secondly, it offers higher agricultural and livestock production and trade [129], more effective land use [129], and enhanced GHG gas mitigation through avoided deforestation [52] and land use change [129, 131], compared to business as usual scenario.

5. Modeling framework

5.1. Overview

A brief overview of the methodology applied in this study is described below. A more detailed description as well as relevant model equations can be found in the Supplementary Information section and in [30, 31, 32]. We propose a modeling framework characterized by: 1) providing preliminary assessment of land use change, 2) using energy as the entry point, 3) combining quantitative and qualitative methodologies, 4) addressing the topic of biomass and bioenergy and its interrelations with other sectors and 5) being applicable to developing countries. For this purpose, an approach combining a quantitative and a qualitative element is proposed (see Figure 1).

The qualitative element combines two components: a) technology roadmapping to identify long-term technology targets through expert judgment and b) scenario analysis to investigate different future storylines. Recognizing the importance of biomass in Colombia and the lack of long-term strategic planning to exploit it, a technology roadmap envisioning an accelerated deployment of bioenergy until 2030 was proposed by authors [30]. In this roadmap, expert judgment from over 30 contributors from the government, academia, industry and non-governmental organizations (NGOs) is consolidated regarding long-term vision, goals, and milestones for deploying bioenergy. Key scenarios identified by experts have been already presented in Section 4. On the other hand, the quantitative element comprises four separate tools, namely the energy system model (ESM), the land use and trade model (LUTM), an economic model, and an external climate model. Given that energy is the entry point, the development of an energy model which is as comprehensive as possible is proposed. In contrast, relatively simple models for analyzing land use, trade, economy and considering climate are proposed. For the land use and trade, it is proposed to use a resource-focused statistical model, which is a non-spatially explicit and thus inexpensive and easy to implement.

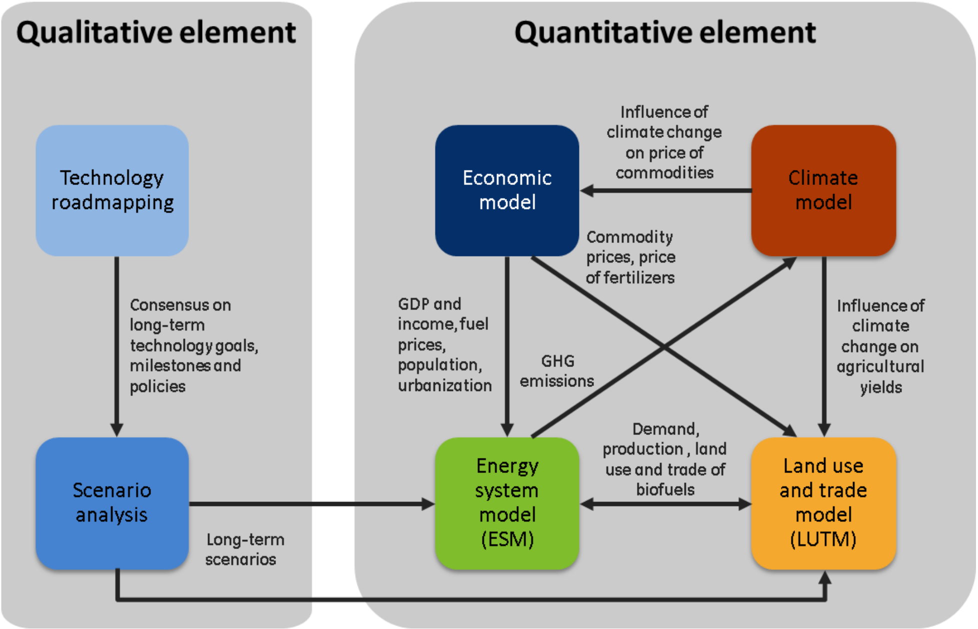

Figure 1. *Modeling framework [31]*

The economic model aims at describing in a simple way economic growth, population growth, prices of energy resources and commodities, as well as the capital costs of technologies. For climate, projections from external models are taken and uses as drivers for the ESM and the LUTM models. This combination of models ensures a high level of accuracy for the entry point (i.e. energy) and a relatively simple approach that can provide a preliminary assessment of the nexus between energy, land use, emissions and economy. Details of the climate and economic models are available in [31]. A brief description of the ESM and LUTM models as the core of the modeling framework is presented in the following sections.

5.2. Energy System Model (ESM)

In the ESM model, we combine bottom-up (end-use) and top-down modeling techniques to replicate the behavior of the country's energy system with regard to demand and transformation (see Figure 2, details in [30]). Bottom-up approaches are employed as much as possible, according to guidelines from earlier references [135, 136]. However, due to the large heterogeneity in the quality and availability of data found in Colombia, the selection of modeling techniques and its level of sophistication is determined by available data. The heterogeneity in quality and availability of data is contrary to the situation in many industrialized countries.

On the demand side, we divide the country's economy into sectors (e.g. residential, industrial, transport, etc.) and estimate the demand for energy resources for each sector through a hybrid approach combining econometric methods with bottom-up (end-use) techniques. End-use techniques include a stock-turnover-economic analysis of the road transport sector, an engineering module of the cane and palm sectors and a dynamic engineering-economy module of the residential sector. We pay particular attention to these three cases, as they constitute most of the demand for bioenergy resources. We use econometric methods to estimate the aggregate demand by fuel in sectors with no detailed data available, e.g. commercial, non-road transport, industrial and agriculture. On the transformation side, we model conversion technologies, distribution losses and own energy use (energy consumed by conversion technologies) by a techno-economic approach. This method allows the estimation of energy production, capacity requirements by technology, losses and demand for resources. We then build a database regarding efficiencies, costs and emissions of conversion technologies using public data and incorporate it into the ESM model.

The ESM model is built on the Long-range Energy Alternatives Planning System (LEAP) [137], a platform used to report energy policy analysis and greenhouse gas (GHG) mitigation assessments that is free for users in developing countries [135]. Due to its characteristics, the model makes use of scenarios. We simulate the lowest cost capacity expansion and dispatch in power generation & CHP through the Open Source Energy Modeling System (OSeMOSYS) [138] incorporated in LEAP. Assumptions on input data to the ESM model include future population, growth in gross domestic product (GDP), energy prices, climate conditions and availability of land. A particularly important assumption is that renewable energy technologies are heavily influenced by El Niño and La Niña Southern Oscillation (ENSO) [61] and their performance is simulated using data from the last 15 years [116]. We validate the ESM model against available statistics. Full details are available in reference [30].

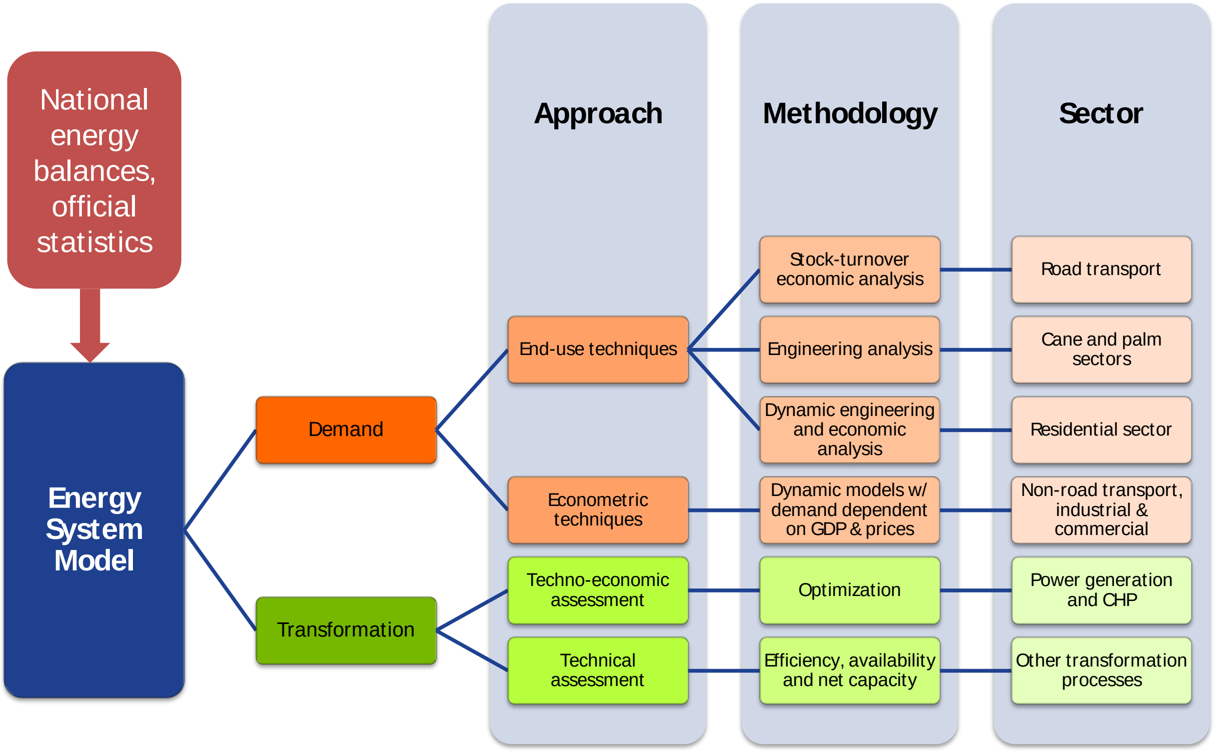

Figure 2. *Summary of the employed modeling techniques in the ESM by branch [31]*

To determine the impact on emissions, we build a database regarding GHG emission factors associated with the use of bioenergy technologies based on Intergovernmental Panel on Climate Change (IPCC) guidelines [139] and multiple references. We then incorporate this database into the ESM model [30, 31]. We only consider the GHG emissions associated with the direct combustion of fuels nationwide following the 2006 IPCC guidelines for national GHG inventories in the energy sector. We exclude fugitive emissions of the energy sector (emissions occurring during the extraction, processing and delivery of fossil fuels to the final use), emissions of industrial processes and product use –IPPU–, emissions of agriculture, forestry and other land use –AFOLU– (e.g. land emissions, emissions from livestock and manure management, cultivation, irrigation, etc.) and emissions from waste (e.g. waste and wastewater generation, disposal and treatment). While it is possible to account for land use change for biofuel production in the LUTM, the direct and indirect emissions associated with this change have been considered beyond the scope of the study.

5.3. Land Use and Trade Model (LUTM)

We develop the LUTM model [30, 31] to estimate the land requirements necessary to accomplish the targets of the different scenarios. In this model, we combine a resource-focused statistical analysis with a demand-driven cost-supply analysis that includes demographic and market data, land use and macro-economic effects. This model estimates land allocation as well as the production, imports and exports of 18 agricultural and forestry commodities during the period 2015-2030 (see Figure 3). We build the LUTM model under the assumption that the fundamental driver of land use and trade is the maximization of profit perceived by local actors (i.e. local producers and importers). For this purpose, we employ an optimization algorithm in Microsoft Excel®. We build the model under the assumption that the fundamental driver of land use and trade is the maximization of profit perceived by local actors (i.e. local producers and importers). Inputs include demand, local biofuel policies, yields, local and international prices and macroeconomic variables. We consider competition at three levels: food vs. biofuels, residues for energy vs. other uses and local production vs. imports. We validate the LUTM model against available statistics (full details in [30]).

5.4. Discussion on the proposed modeling methodology

The proposed method offers various advantages: a) it uses various state-of-the-art modeling techniques that are transparent and replicable, b) it uses generic and well-known platforms (i.e. LEAP and Microsoft Excel®), which makes them relatively inexpensive and easy to replicate, c) it employs scenario analyses to consider possible alternative future storylines and to allow policy analysis and d) it is calibrated and fully supported by official data. The generic character and flexibility of the 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 and resources to adapt and calibrate the models.

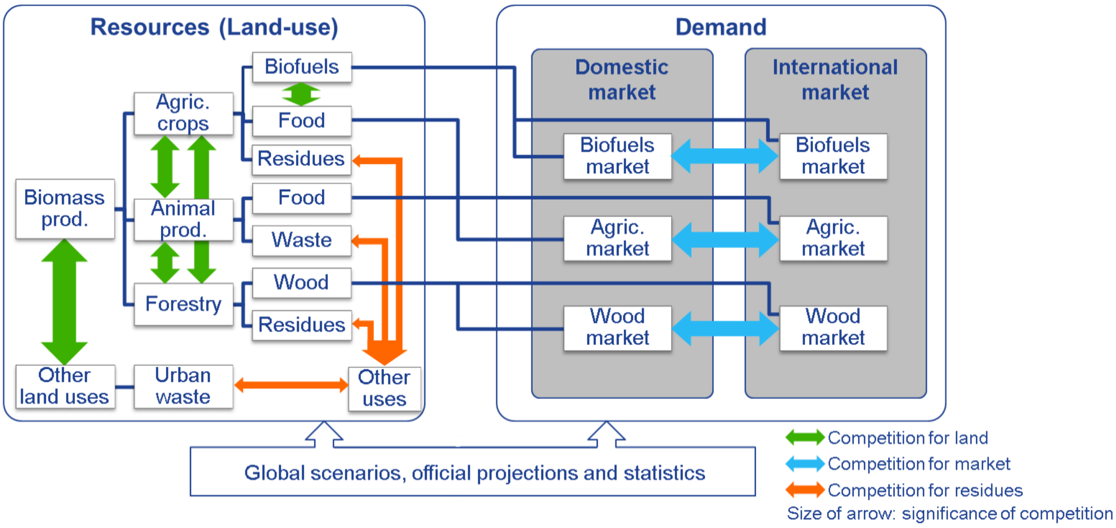

Figure 3. *Modeling method of the LUTM model [32]*

This is actually one of the limitations of the proposed method, i.e. it is data intensive. It requires a substantial amount of data on energy demand and supply, infrastructure, technologies, emissions, microeconomics, macroeconomics, etc. Moreover, the proposed modeling framework involves various uncertainties associated with the development of analytical and modeling tools. One important source of uncertainty relates to the fact that models are calibrated using the latest available statistics, which correspond to 2009 and predate the present study by five years. Other limitations include the following factors: a) the ESM does not estimate lifecycle emissions and does not employ bottom-up techniques and economic analysis for all branches and b) the impacts on rural development, living standards of rural communities, generation of employment, and water demand and supply have been considered out of scope. Because of the aforementioned uncertainties and limitations, results should be interpreted with caution. Results should not be regarded as forecasts but rather as outcomes of scenario analyses. Hence, they are potential representations of future storylines subject to particular conditions, assumptions and limitations.

6. Results

6.1. Impacts on the energy supply

In the baseline scenario, we estimate a significant growth in primary energy demand (from 41 to 94 Mtoe), road transport demand (from 8 to 27 Mtoe), electricity generation (from 5 to 11 Mtoe) and natural gas supply (from 4 to 14 Mtoe) between 2010 and 2030 (Figure 4a). These numbers agree with results of the GCAM, TIAM-ECN and PHOENIX models published by Calderón et al., in which primary energy demand in 2030 ranges between 83 and 119 Mtoe [56]. 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% (Figure 4a). 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 (Figure 4b). This result 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. The decline of biomass and hydro as well as the increase in demand for fossil fuels in the baseline also agrees with estimates published by Calderón et al. for the three models mentioned earlier [56]. New policies on biomethane and power generation in Scenarios I and II could increase the share of bioenergy to ~6% in these sectors by 2030, while further deployment of first-generation biofuels in Scenario II could boost the share in road transport to 24%. Increased shares of bioenergy allow savings in fossil fuels in 2030 ranging from 2% (1.9 Mtoe) in Scenario I, to 6% (4.6 Mtoe) in Scenario II, 7% (5.4 Mtoe) in Scenario III, and 8% (6.4 Mtoe) in Scenario IV (Figure 5). Despite this, the share of bioenergy in primary energy demand still declines to ~10% in all scenarios. Thus, the demand for energy grows more quickly than bioenergy supply in the scenarios considered here, resulting in an increased demand for fossil fuels.

The agreement of our results compared to more mature, complex and widely accepted integrated assessment models such as GCAM, TIAM-ECN and PHOENIX is promising. It demonstrates that robust and reliable energy models can be successfully built in emerging platforms, such as LEAP, which are free for users in developing countries.

6.2. Impacts on land use

Our findings show that in order to accomplish the proposed targets, the land required for producing woodfuel and feedstocks for biofuels (i.e. sugar cane and palm oil) needs to grow (Figure 6). Between 2010 and 2030, the forestland for producing woodfuel in plantations grows in all scenarios from 0.32 to 0.50 Mha (from 0.3 to 0.4% of land coverage).

In the same period, the cropland for cultivating feedstocks for biofuels grows from 0.11 to 0.66 Mha (from 0.1 to 0.6% coverage) in the baseline and Scenario I, to 0.81 Mha in Scenario II (0.7% coverage), to 1.33 Mha in Scenario III (1.2% coverage) and to 1.63 Mha in Scenario IV (1.5% coverage). The bulk of this cropland is used to produce feedstocks for biofuels that are locally consumed. For the baseline and Scenarios I-III, we report that cropland for food production and natural forestland (via deforestation) transform into pastures for cattle farming, forest plantations and cropland for producing feedstocks for biofuels. In these scenarios, the coverage of pastures is expected to increase from 34.4 to ~ 36% (from 38.18 to 40.18 Mha) between 2010 and 2030, while the coverage of natural forestland is predicted to reduce from 54.5 to 52.7% (from 60.5 to 58.5 Mha). Moreover, we expect the coverage of cropland for food production to reduce from 3.8% (4.16 Mha) in 2010 to 3.0% (3.28 Mha) in 2030 in the baseline and Scenario I and to 2.7% (2.94 Mha) in Scenario III. In these scenarios, the coverage of cropland for food production is expected to reduce because of three factors. Firstly and most important, cropland for food production is transformed into pastures for cattle farming as a result 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 the harvested area. Thirdly, more cost-competitive duty-free imports from the U.S., available as of 2012, cause a further reduction in the harvested area for some crops (e.g. rice and corn).

In contrast to the baseline and Scenarios I to III, Scenario IV offers the possibility to increase cropland for food and biofuel production while at the same time reducing pastures and deforestation. Scenario IV is a storyline that could be better planned and attained in a post-conflict context. In Scenario IV, cropland for biofuel production increases by 1.47 Mha between 2010 and 2030, while pastures reduce by 0.23 Mha. In the same period, cropland for food production reduces by 0.52 Mha, even though it increases by 0.83 Mha between 2010 and 2020. Compared to the baseline, Scenario IV offers a reduction in pastures of 3 Mha, a reduced deforested area of 1.3 Mha, an increased cropland for food production of 0.66 Mha and an increased cropland for biofuel production of 0.94 Mha. Scenario IV shows that by combining intensification of cattle farming, intensification of agricultural crops and reduced deforestation, it is feasible to produce not only more food but also more biofuels, while avoiding forest clearance.

Our results for land use in the baseline (i.e. the estimated reduction in natural forests and cropland for food production combined with an increase in pastures) and in Scenario IV (i.e. reduction in pastures and deforestation and increase in cultivation of feedstocks to produce biofuels), agree with the IMPACT model results published by De Pinto et al. [47]. In fact, while in the baseline we estimate an increase in pastures of 2.33 Mha between 2010 and 2030, De Pinto et al. predict it to be 2.6 Mha. Similarly, we estimate a reduction in natural forest of 2.2 Mha, while De Pinto et al. predict it to be 3.4 Mha. Results of Scenario IV also agree with outcomes of IMPACT for their 'pasture reduction', 'zero deforestation' and 'palm expansion' scenarios. Between 2010 and 2030, we estimate a reduction in pastures of 3 Mha, which corresponds to a 30% increase in cattle yield taken from [129]. De Pinto et al. estimate a reduction ranging between 5 and 10 Mha, corresponding to cattle yield increases of 90% and 130%, respectively. In the same period, we estimate a reduction of 1.3 Mha in deforested areas, which is exactly the same as predicted by De Pinto et al. (1.33 Mha). Finally, we estimate a palm expansion of 0.8 Mha that is compliant with land constraints for palm defined in [83], while De Pinto et al. estimate it to be 1.1 Mha.

The agreement of our results compared to those produced by a highly sophisticated and widely accepted model, such as IMPACT, is encouraging. This demonstrates the key advantages of the LUTM model, particularly for developing countries: a relatively simple and inexpensive tool, built in Microsoft Excel® that can estimate preliminary results of a comparable quality to those of more sophisticated models. This is not to say that the LUTM model could replace dedicated models like IMPACT, but perhaps precede them.

6.3. Impacts on trade

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 (Figure 7). In Scenario II, imports of bioethanol might account for 76% of the demand by 2030, while imports of biodiesel might reach 60% of the demand. Imports can even account for 36% of the demand in Scenario III, 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. In Scenario IV, imports of bioethanol might account for 29% of the demand, while imports of biodiesel might account for 15% of the demand. This shows that a combination of cane extensification with cattle and crop intensification and reduced deforestation is still insufficient to accomplish biofuel targets. These results also suggest that while E20 and B20 would be feasible, introducing B30 and E85 programs in 2030 might not be attainable without imports. Our results regarding the attainability of B20 differ from those by Castiblanco et al. [104], but agree with those by Rincón et al. [103].

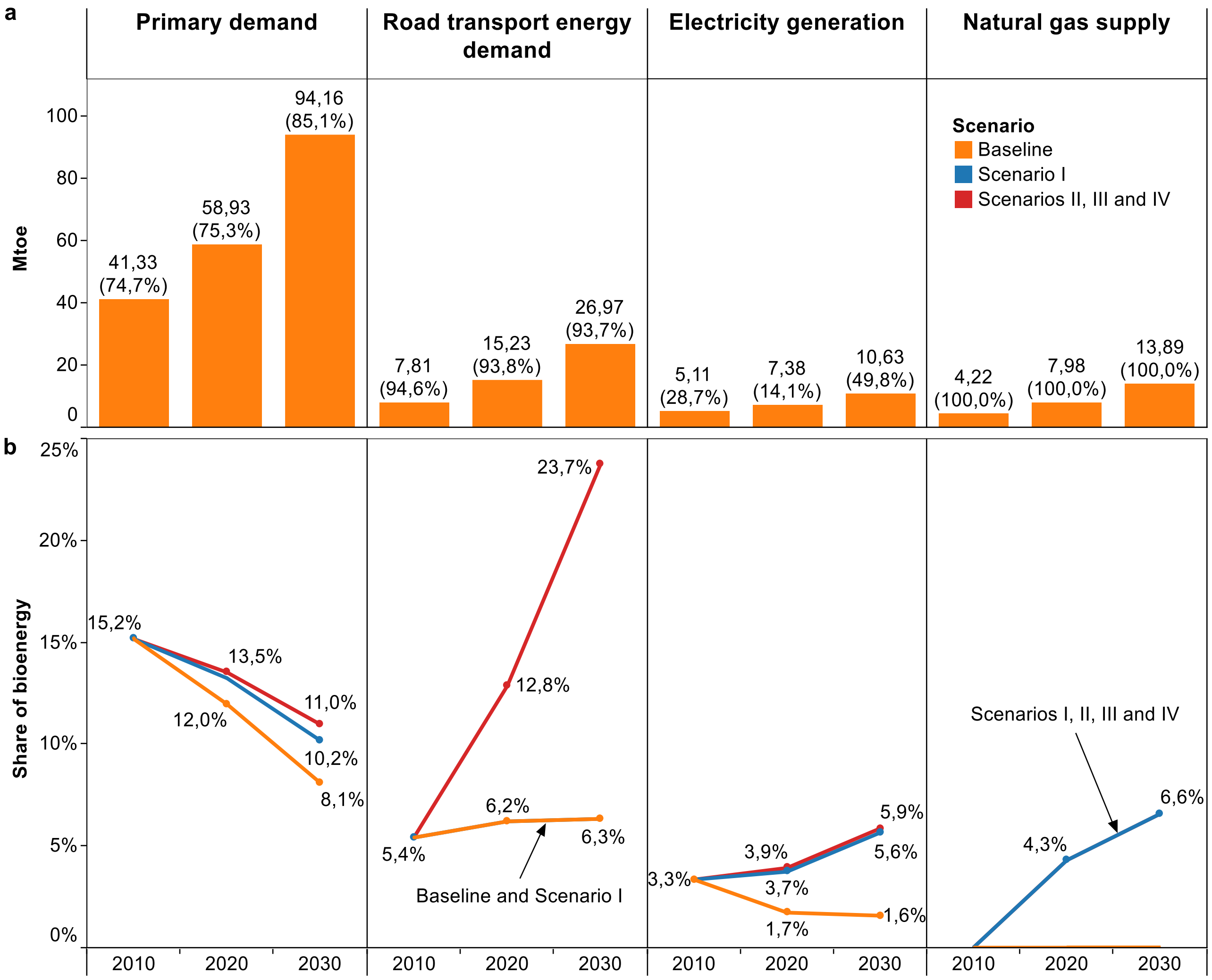

Figure 4. *Energy demand and shares for selected sectors. a, energy demand in million tons of oil equivalent (Mtoe) for selected sectors, share of fossil fuels is shown in brackets. b, shares of bioenergy in selected sectors are shown for the different scenarios.*

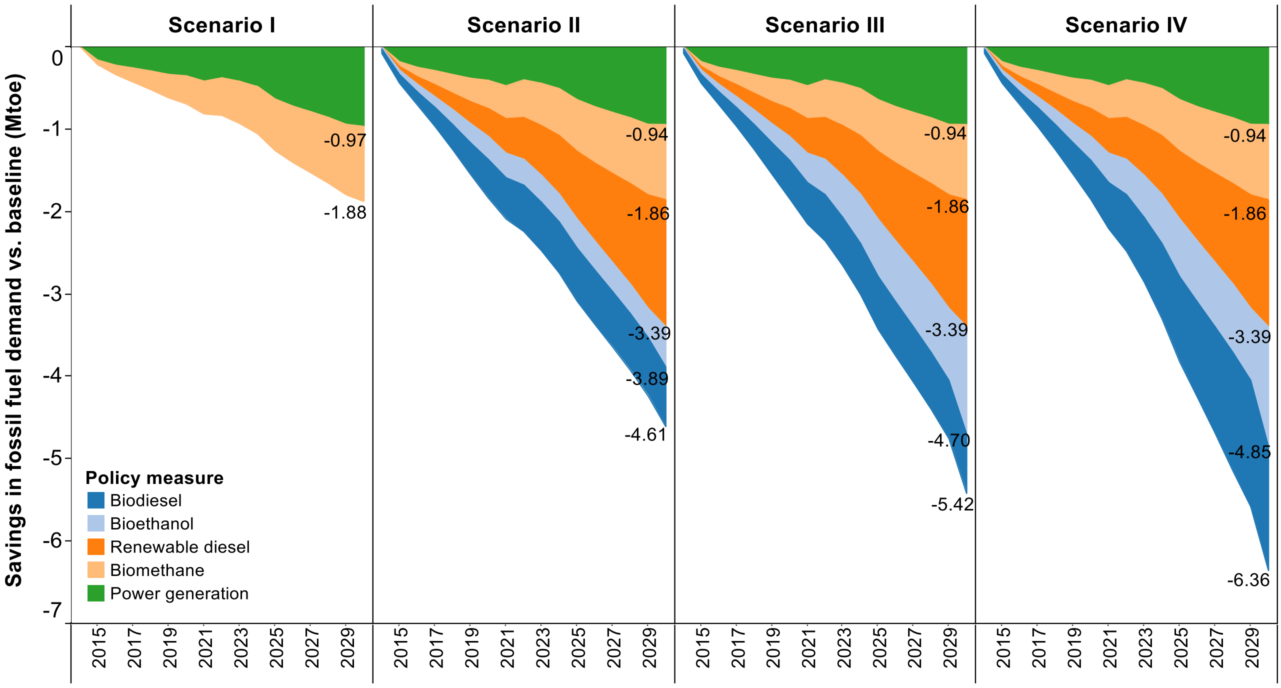

Figure 5. *Savings in fossil fuel demand in million tons of oil equivalent (Mtoe) by scenario compared to baseline scenario. Labels indicate aggregated savings for the different policy measures*

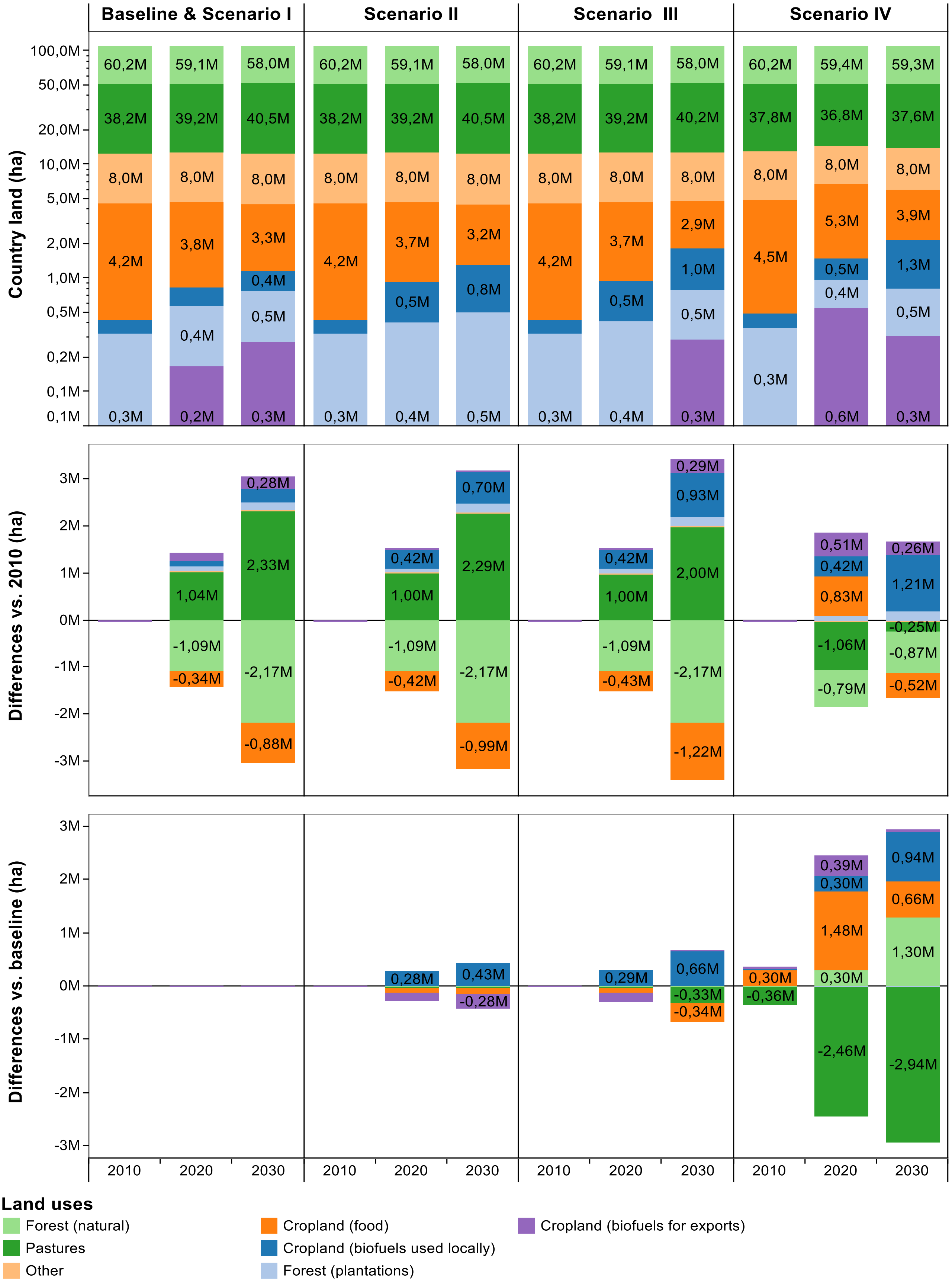

Figure 6. *Selected land uses by scenario. a, land uses in millions of hectares for 2010, 2020 and 2030 shown in logarithmic scale (the overall country land totals 110.95 Mha). b, land-use change in millions of hectares for 2020 and 2030 relative to 2010 disaggregated by scenario and category. c, land-use change in millions of hectares relative to the baseline scenario disaggregated by scenario and category*

However, the increasing relevance of imported biofuels raises additional concerns since positive impacts of the discussed bioenergy policies would not be realized in a desired extent, while it also could shift some of the burden of the policies to other countries. The desired increase in income and employment in rural areas are diminishing with increasing import volumes and shares. Furthermore, a limited domestic output compared to overwhelming import shares could reduce the readiness to invest in R&D and new technologies. On the other hand, imports could loosen the pressure on land use and deforestation but could transfer also possible social and environmental impacts to other countries.

6.4. Impacts on GHG emissions

We find that GHG emissions in the energy sector increase until 2030 for all scenarios (Figure 8a). In the baseline, GHG emissions increase significantly from 76 to 223 million tons of CO_2 equivalent ($MtCO_2$-eq) between 2010 and 2030. The combustion of oil and gas in road transport, power generation and the industry sector causes 76% of this increase (Figure 9). GHG emissions estimated in our baseline lie in the upper bound of the range of results found in prior studies. For instance, ECLAC estimates GHG emissions to range between 110 and 195 $MtCO_2$-eq in 2030 [69].Similarly, GHG emissions based on MEG4C, PHOENIX, GCAM and TIAM-ECN models range between 120 and 180 $MtCO_2$-eq in 2030 [56]. This variance in emissions is due to differences in model assumptions and characteristics [56]. Emission reductions by deploying bioenergy range from 11.4 $MtCO_2$-eq by 2030 in Scenario I, to 20.3 in Scenario II, 22.6 in Scenario III and 24.4 in Scenario IV. These reductions would represent abatements of 5%, 9%, 10% and 11% relative to the baseline, respectively.

Figure 10 shows emission reductions disaggregated by policy measures. The bulk of the reduction in emissions for Scenario I comes from implementing new policy measures on power generation & CHP (74%), followed by new policy measures on biomethane (26%). 76% of the reduction in power generation & CHP comes from avoiding methane release in landfill gas and biogas from animal waste and wastewater, through combustion in reciprocating engines. The remaining 24% reduction comes from the replacement of gas- by biomass-based power generation. Similarly, in Scenarios II-IV, the bulk of the reduction in emissions comes from implementing new policy measures on power generation & CHP (42-52%), followed by new policies on renewable diesel (16-17%), biomethane (12-15%), bioethanol (8-17%), and biodiesel (8-11%). This indicates that emission reductions caused by further deploying first generation biofuels (e.g. bioethanol, biodiesel and renewable diesel) in Scenarios II-IV can equal the emission reductions caused by deploying biomethane and power generation & CHP in Scenario I. Thus, emission reductions in Scenarios II-IV double reductions in Scenario I. It is important to note that emission reductions by avoiding methane release in Scenarios II-IV are slightly higher than in Scenario I. The reason is that an augmented production of biodiesel in those scenarios relative to Scenario I causes an increased generation of methane in wastewater facilities and in the corresponding avoidance by using it for power generation & CHP. Emission reductions caused by further deploying bioethanol and biodiesel in Scenarios II-IV agree with results published by ECLAC [69]. While we estimate an average reduction of 2.9 $MtCO_2$-eq per year by combining bioethanol (E20, E85) and biodiesel (B20, B30), ECLAC estimate it to be about 1.9 $MtCO_2$-eq per year (E10 and B10) [69].

An additional advantage of Scenario IV compared to the other scenarios relates to its ability to reduce GHG emissions associated with land use and land use change for reduced pastures land and decreased deforestation [47, 129]. While the emissions reduction associated with land use and land use change is not captured in the LUTM model, figures from prior art can provide some perspective on the dimension of it. According to Killeen et al. [49], who estimated the potential of implementing REDD+ and biofuels in the country, and De Pinto et al. [47] who used the IMPACT model, a reduced ha of forest being cleared translates in average into a net carbon offset of 100 ton C, which is equivalent to a GHG emissions reduction of 367 tCO_2-eq. A reduced ha of pasture by intensifying cattle yield translates in average into a net GHG emission reduction of 15.5 tCO_2-eq per year [47]. An increased ha used for palm or sugar cane cultivation translates in average into a net GHG emission reduction of 126.5 tCO_2-eq per year [49].

Using Killeen et al. and De Pinto et al. estimates, an additional reduction of 605 $MtCO_2$-eq by 2030[4] could be expected in Scenario IV from improved land use on top of the 24.4 $MtCO_2$-eq associated to energy (see Figure 11). This would total 630 $MtCO_2$-eq, which would represent 280% abatement compared to the baseline. However, more dedicated models are needed to evaluate in detail the GHG emissions associated with land use, which are not covered in this paper. It is also important to note that even though official reports of GHG emissions to the UNFCCC might differ from the ones presented here, emission reductions in Scenario IV might be four times higher than the national reduction commitments by 2030 (67 $MtCO_2$-eq) [66].

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[4] 477 $MtCO_2$-eq/year from avoided deforestation, 45.5 $MtCO_2$-eq/year from reduced pastures, 42.5 $MtCO_2$-eq/year from palm oil plantation and 39.5 $MtCO_2$-eq/year from sugar cane plantations.

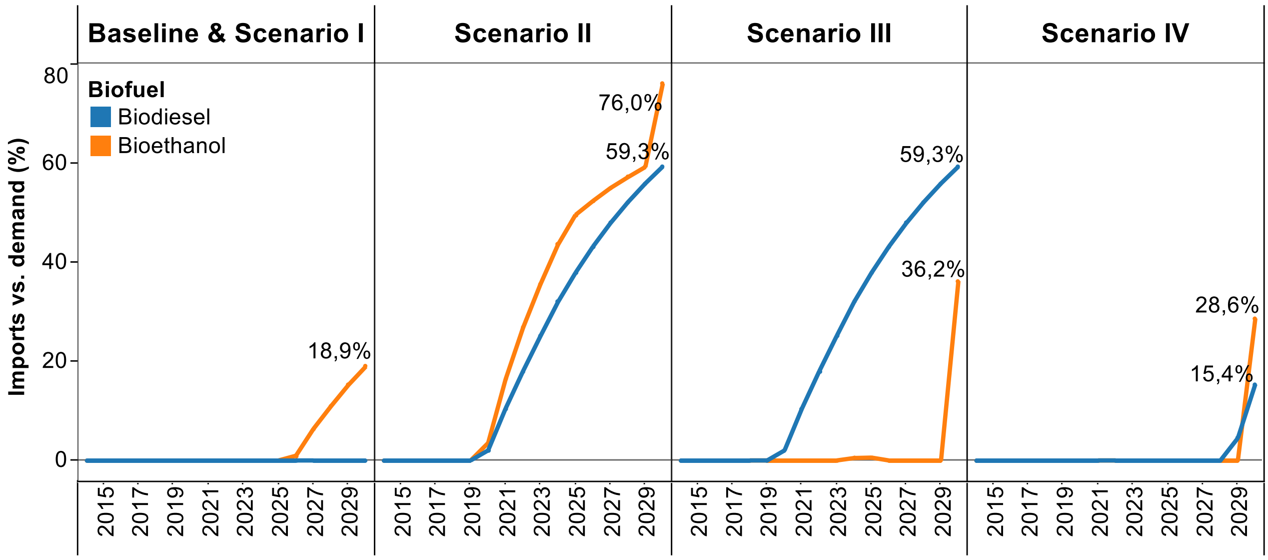

Figure 7. *Imports vs. demand for biofuels by scenario*

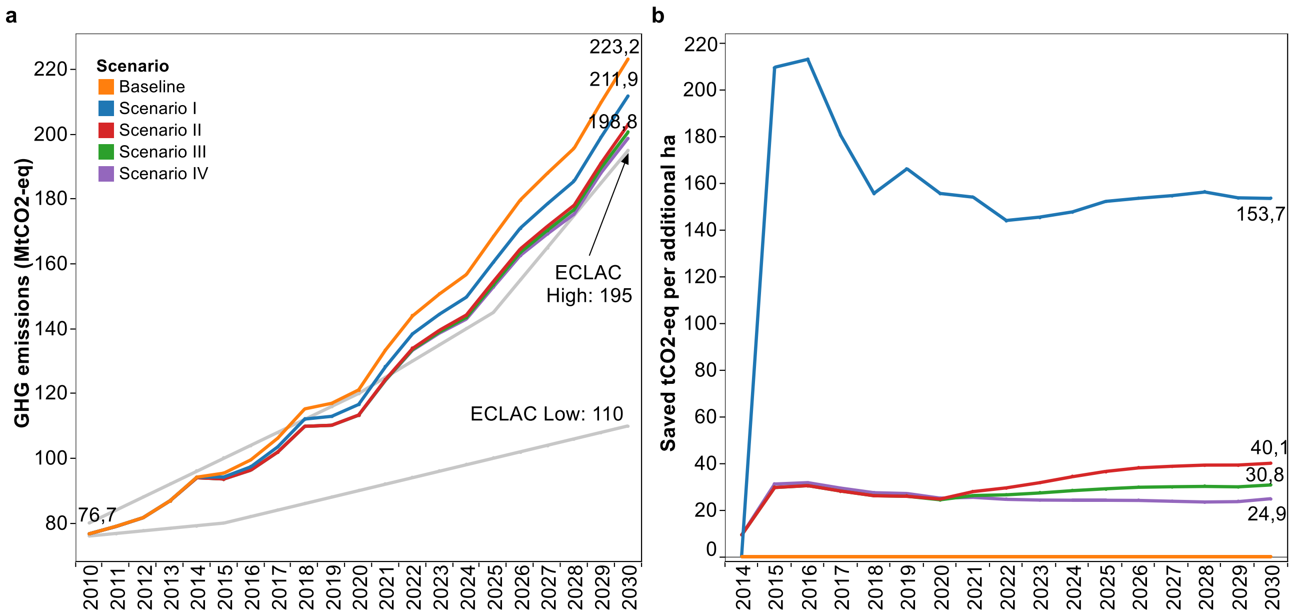

Figure 8. *Energy-related GHG emissions by scenario. a, Energy-related greenhouse gas emissions by scenario in million tons of CO_2 equivalent ($MtCO_2$-eq). b, Energy-related emission reductions per incremental land in saved tons of CO_2 equivalent per additional hectare of land to cultivate biomass resources*

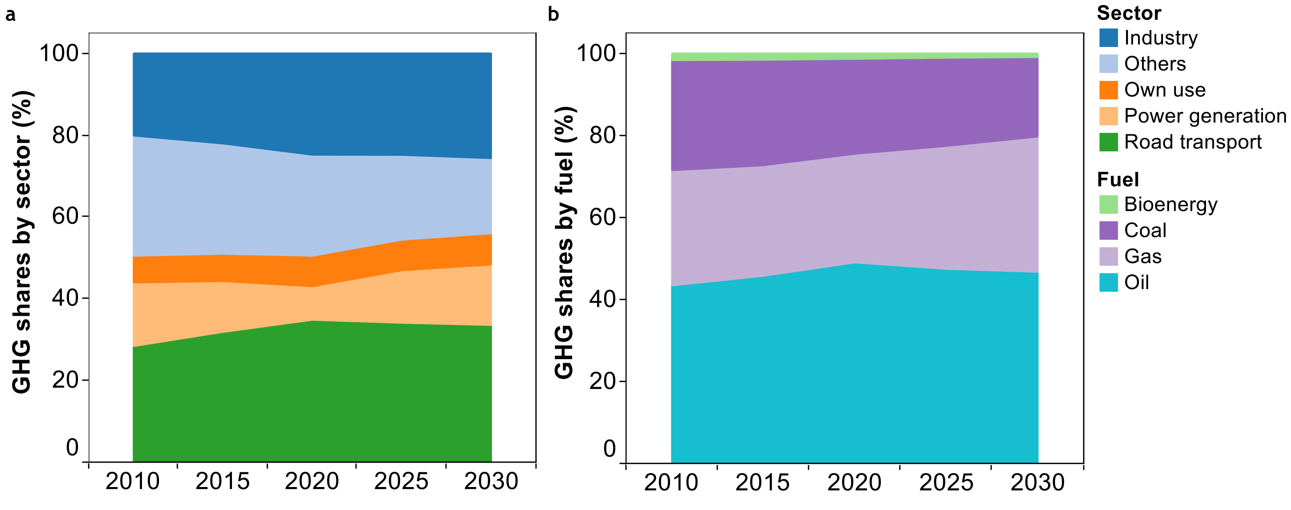

Figure 9. *Shares in energy-related GHG emissions for the baseline scenario disaggregated by sector (a) and fuel (b)*

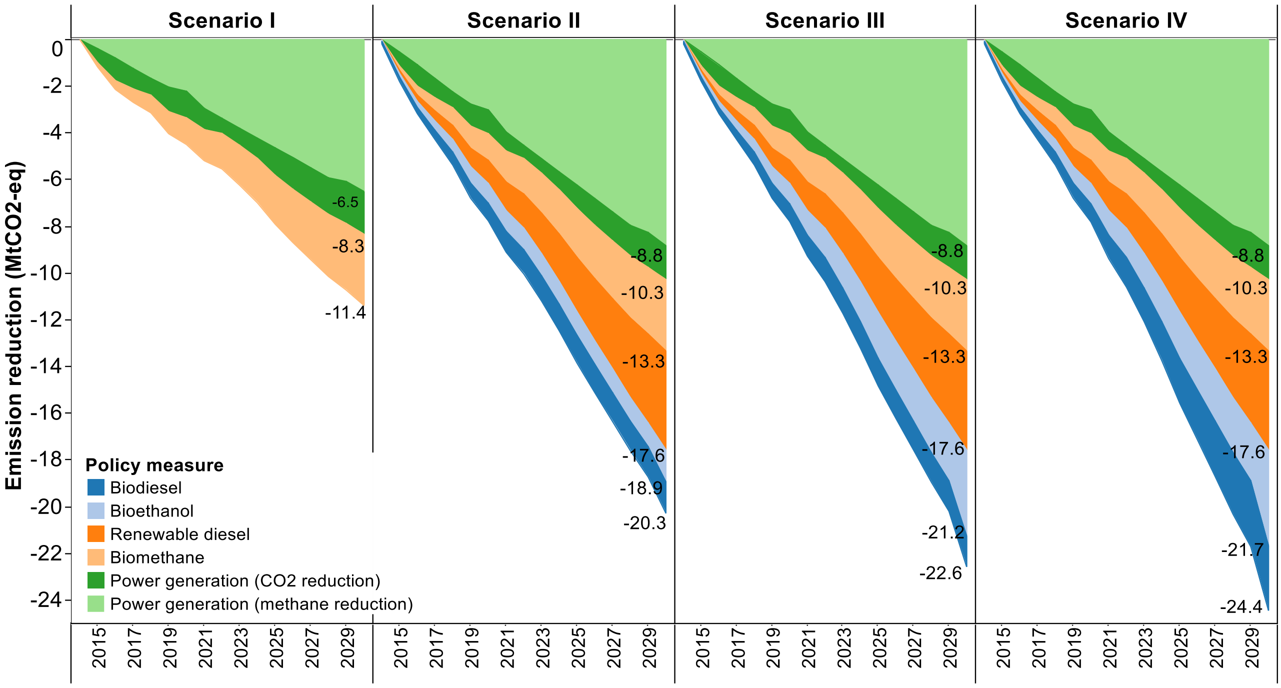

Figure 10. *Reduction in energy-related GHG emissions in million tons of CO_2 equivalent ($MtCO_2$-eq) by scenario and policy measure compared to the baseline scenario. Labels indicate aggregated reductions for the different policy measures. For power generation, the effects of reducing methane and CO_2 emissions are further disaggregated*

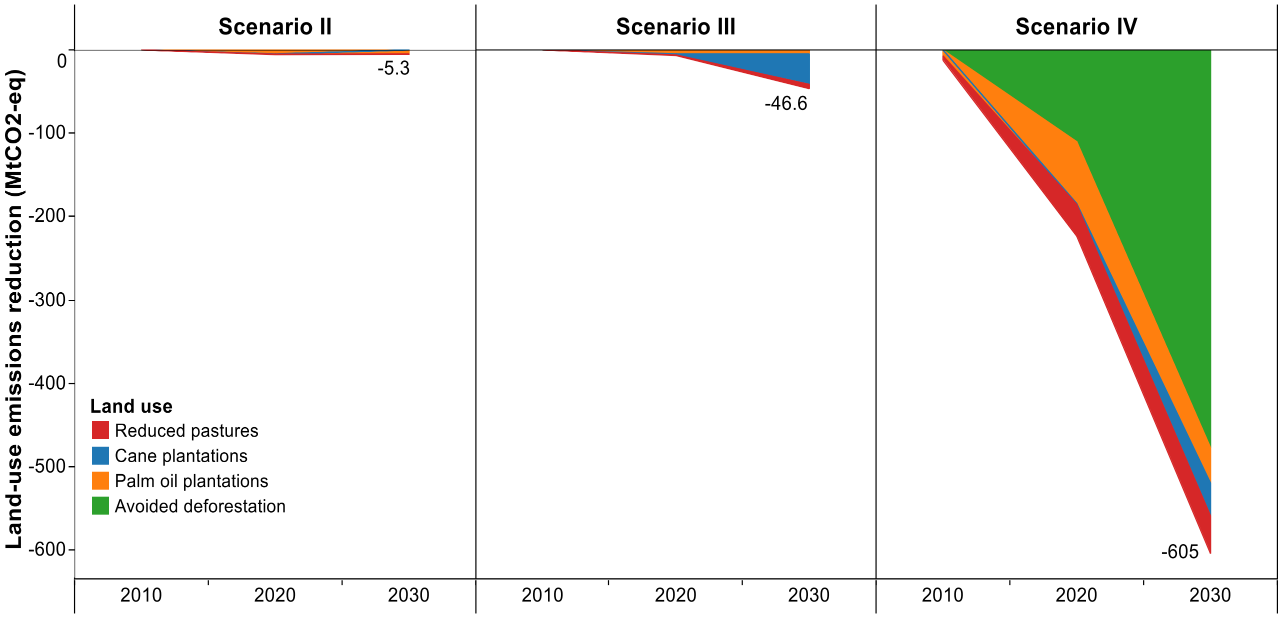

Figure 11. *Reduction in land-use related GHG emissions in million tons of CO_2 equivalent ($MtCO_2$-eq) by scenario and land use type*

Finally, in order to evaluate the effectiveness of the different technologies not only to reduce emissions but also to minimize the land use, we estimate a measure called emission reduction per incremental land. We define it as the difference in energy-related emissions between scenarios and baseline per year divided by the difference in required cultivation land between scenarios and baseline. Figure 8b shows the results by scenario over the period of study. Scenario I offers the highest emission reduction per additional hectare of land used to cultivate biomass resources, i.e. ~150 tCO_2-eq per additional ha, while Scenarios II and III achieve 40 and 30, respectively. Scenario IV achieves 25 tCO_2-eq per additional ha, excluding the emissions reduction due to land use change. This suggests that despite Scenarios II-IV achieving higher emission reductions than Scenario I, they are less effective in reducing emissions per additional hectare of dedicated land use.

7. Conclusions

Our study investigates different pathways to accomplish an accelerated deployment of bioenergy technologies in Colombia. Results suggest that the deployment of technologies for biomethane production, power generation & CHP (in particular, landfill gas- and biogas-fueled power plants) could reduce individually more GHG emissions and more emissions per incremental hectare of land than first-generation biofuels. The advantages over biofuels are threefold: 1) avoiding methane release (a gas with 25 times more impact on Global Warming Potential than CO_2) in landfills, production of biogas from animal waste and wastewater, 2) contributing to the reduction of CO_2 emissions by replacing fossil fuels in gas or electricity supplies and 3) not requiring additional dedicated land. This result is not obvious, given that currently power generation in Colombia 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 (responsible for most methane emissions) within AFOLU contribute to 25% [65], similarly to other Latin American countries [68]. Moreover, these results agree with conclusions from earlier studies conducted for other countries [26, 140, 141]. Deployment of biomethane and power generation & CHP should be prioritized, even though they would represent a combined abatement (i.e. Scenario I) of 5% relative to the baseline.

In order to push emissions reduction, additional measures are required and are also analyzed in this study. Combining biomethane and power generation & CHP with biofuels (i.e. bioethanol, biodiesel and renewable diesel) could double the reduction of emissions and achieve abatements of 9-11% relative to the baseline. However, this reduction would occur at the expense of an increase in dedicated land and associated changes in land use, depending on the scenario.
In the baseline and Scenarios I-III, past trends in deforestation are assumed to continue in the future, with cleared areas being transformed into pastures. In these scenarios, biofuel expansion would be accompanied by a reduction in cropland for food production.

In contrast, Scenario IV considers three land use measures that are likely to be implemented in a post-conflict scenario: agricultural intensification, cattle yield intensification and a zero net deforestation rate. These measures would not only result in reduced pastures (3 Mha) and deforested land (1.3 Mha), but also in increased cropland for food and biofuel production (1.6 Mha). They would also cause additional emissions reduction associated with land use and land use change of 605 $MtCO_2$-eq by 2030, although these need further investigation. The proposed long-term goals for bioethanol and biodiesel could not be attained and imports are needed in all scenarios. Results suggest that cane extensification with cattle and crop intensification and reduced deforestation are still insufficient to accomplish biofuel targets. While E20 and B20 would be feasible, introducing B30 and E85 programs in 2030 might not be attainable without imports. Our results regarding the attainability of B20 differ from those of Castiblanco et al. [104], but agree with those of Rincón et al. [103]. While Scenarios I-III offer abatements of up to 10% relative to the baseline by 2030, they can go up to 280% in Scenario IV if the emissions reduction associated with land use change is considered. More importantly, even though official reports of GHG emissions to the UNFCCC might differ from the ones presented here, emission reductions in Scenario IV might be four times higher than the national reduction commitments by 2030 (67 $MtCO_2$-eq) [66]. Further emission reductions would require a portfolio of additional measures.

For deploying the different bioenergy technologies and land use pathways proposed here, Colombia could learn some lessons from Brazil. Firstly, Brazil has been active in guiding the land use for a more sustainable profile: a) identifying Agroecological Zoning for sugarcane and oil palm, b) defining the Forest Code that protects part of the native vegetation in all rural properties, monitors and acts to reduce deforestation, and c) implementing Low Carbon Agriculture, double cropping and agricultural/cattle intensification. Secondly, Brazil has been successful in designing and implementing plans to reduce national GHG emissions, including recovery of degraded pasture, integration of agriculture/livestock/forest, planted forest, animal waste treatment, etc. Thirdly, Brazil has almost a century of experience on fuel ethanol use and four decades operating E20 blends. Colombia could profit from flex fuel vehicles available today to stimulate an E20 program, which were not available when Brazil started its own program. Fourthly, Brazil has been successful in exploiting by-products of the sugar cane crop (i.e. bagasse, tops and leaves) to generate power that accounts today for 4% of the consumption.

Our results might be helpful to policymakers evaluating the role of bioenergy in a post-conflict context and to other countries with significant bioenergy potential and similar compositions of national GHG emissions. Recommendations for further studies include: a) investigating the life cycle GHG emissions (including emissions associated with land use and land use change) of different bioenergy technologies under the specific conditions of Colombia, b) performing detailed economic analyses of different bioenergy routes and c) identifying modeling frameworks, tools and methodologies to evaluate the impacts of implementing different bioenergy technologies in rural development, water supply, biodiversity, etc.

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References

[1] FAO, „The state of the world's land and water resources for food and agriculture. Managing systems at risk," Food and Agriculture Organization of the United Nations (FAO), Rome and Earthscan, London. http://www.fao.org/docrep/017/i1688e/i1688e.pdf, 2011.

[2] CIA, „The World Factbook," 01 May 2016. [Online]. Available: https://www.cia.gov/library/publications/the-world-factbook/fields/2201.html.

[3] FAO, „Global Forest Resources Assessment. Progress towards sustainable forest management," Food and Agriculture Organization of the United Nations (FAO). FAO Forestry Paper, Rome, 2005.

[4] USAID, „Colombia, country profile," USAID. http://www.usaidlandtenure.net/sites/default/files/country-profiles/full-reports/USAID_Land_Tenure_Colombia_Profile.pdf, 2016.

[5] J. García und D. Slunge, „Environment and Climate Change Management: Perspectives for Post-Conflict Colombia," Sida's Helpdesk for Environment and Climate Change. http://sidaenvironmenthelpdesk.se/wordpress3/wp-content/uploads/2015/12/Colombia-Environment-and-Climate-Change-Policy-Brief-Final-December-8-2015.pdf, Gothenburg, 2015.

[6] G. Lopez, „The Colombian Civil War. Potential for Justice in a Culture of Violence," Center for Global Studies. University of Washington. Policy Briefing Vol 2, No. 1. http://globalstudies.washington.edu/wp-content/uploads/2015/01/v2n1-Lopez.pdf, 2015.

[7] OECD, „OECD Economic Surveys: Colombia 2013: Economic Assessment," OECD Publishing. http://dx.doi.org/10.1787/eco_surveys-col-2013-en, Paris, 2013.

[8] UPME, "Actualización y Revisión de los Balances Energéticos Nacionales de Colombia 1975-2009. Tomo I - Balances Energéticos Nacionales.," Bogotá, 2011.

[9] AENE, "Potencialidades de los cultivos energéticos y residuos agrícolas en Colombia," Report for Unidad de Planeación Minero Energética (UPME), 2003.

[10] T. Arias Chalico, S. Coelho, N. Flores Marco, P. Manzanares Secades, P. Guardabassi, R. Grisoli, C. St.James, M. Ballesteros Perdices, G. Aroca Arcaya, L. Soler Hyde, G. Villalón Pascenti, M. García Burgos and G. Guerrero Pacheco, "Biofuels Assessment on Technical Opportunities and Research Needs for Latin America. BioTop Project No: FP7-213320. Feedstock production in Latin America," BioTop, 2009.

[11] K. Kline, G. Oladosu, A. Wolfe, R. Perlack, V. Dale and M. McMahon, "Biofuel Feedstock Assessment for Selected Countries. To support the DOE study of worldwide potential to produce biofuels with a focus on U.S. imports," Special Report for the U.S. Department of Energy (DOE). ORNL/TM-2007/224, 2008.

[12] H. Escalante Hernández, J. Orduz Prada, H. Zapata Lesmes, M. Cardona Ruiz and M. Duarte Ortega, "Atlas del Potencial Energético de la Biomasa Residual en Colombia," Unidad de Planeación Minero Energética (UPME) y el Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (IDEAM). ISBN: 978-9 58-8504-59-9, Bogotá, 2011.

[13] M. Gonzalez-Salazar, M. Morini, M. Pinelli, P. Spina, M. Venturini, M. Finkenrath and W. Poganietz, "Methodology for estimating biomass energy potential and its application to Colombia," *Applied Energy,* vol. 136, pp. 781-796, 2014.

[14] IEA-UNDP-UNIDO, "Energy poverty. How to make modern energy access universal? Special early excerpt of the World Energy Outlook 2010 for the UN General Assembly on the Millennium Development Goals," International Energy Agency (IEA), Paris, 2010.

[15] A. Eisentraut, "Sustainable production of second-generation biofuels, potential and perspective in major economies and developing countries," IEA Energy Papers, No. 2010/01, OECD Publishing. DOI: http://dx.doi.org/10.1787/5kmh3njpt6r0-en, Paris, 2010.

[16] IEA, "Technology roadmap, Bioenergy for Heat and Power," IEA Technology Roadmaps, International Energy Agency (IEA). DOI: http://dx.doi.org/10.1787/9789264123236-en, Paris, 2012.

[17] D. Sanchez, J. Nelson, J. Johnston, A. Mileva and D. Kammen, "Biomass enables the transition to a carbon-negative power system across western North America," *Nature Climate Change,* vol. 5, pp. 230-234, 2015.

[18] Y. Gao, M. Skutsch, O. Masera and P. Pacheco, "A Global Analysis of Deforestation due to Biofuel Development," CIFOR Working Paper No. 68. Center for International Forestry Research (CIFOR). DOI: 10.17528/cifor/003506, Bogor, 2011.

[19] L. Sonter, D. Barrett, C. Moran and B. Soares-Filho, "Carbon emissions due to deforestation for the production of charcoal used in Brazil's steel industry," *Nature Climate Change,* vol. 5, pp. 359-363, 2015.

[20] R. Bailis, R. Drigo, A. Ghilardi and O. Masera, "The carbon footprint of traditional woodfuels," *Nature Climate Change,* vol. 5, pp. 266-272, 2015.

[21] Y. Gao, M. Skutsch, R. Drigo, P. Pacheco und O. Masera, „Assessing deforestation from biofuels: Methodological challenges," *Applied Geography,* Bd. 31, pp. 508-518, 2011.

[22] J. Baffes and T. Haniotis, "Placing the 2006/08 Commodity Price Boom into Perspective," Policy Research Working Paper 5371. The World Bank. Development Prospect Group. DOI: http://dx.doi.org/10.1596/1813-9450-5371, Washington, 2010.

[23] R. Edwards, D. Mulligan and L. Marelli, "Indirect Land-use change from increased biofuels demand. Comparison of models and results for marginal biofuels production from different feedstocks," JRC Scientific and Technical Reports. JRC, European Commission, Institute for Energy, Ispra, 2010.

[24] IEA, „Technology Roadmap, Biofuels for Transport," International Energy Agency (IEA), Paris, 2011.

[25] GBEP, "The Global Bioenergy Partnership Sustainability Indicators for Bioenergy," Global Bioenergy Partnership Sustainability (GBEP) and Food and Agriculture Organization of the United Nations (FAO). ISBN 978-92-5-107249-3, Rome, 2011.

[26] F. Cherubini and A. Stromman, "Life cycle assessment of bioenergy systems: State of the art and future challenges," *Bioresource Technology,* no. 102, pp. 437-451, 2011.

[27] FAO-GBEP, "Pilot Testing of GBEP Sustainability Indicators for Bioenergy in Colombia," Environment and Natural Resources Management Working Paper No. 59. Global Bioenergy Partnership (GBEP) and Food and Agriculture Organization of the United Nations (FAO). ISBN 978-92-5-108567-7, Rome, 2014.

[28] MRI-UNC-NUMARK, "Sustainable Energy and Biofuel Strategies for Colombia. Preliminary Report I," Inter-American Development Bank (IDB) and Ministry of Mines and Energy (MME) Government of Colombia, Bogotá, 2010.

[29] D. Mora Alvarez, "Large scale integration of renewable energy sources for power generation in Colombia: a sensible alternative to conventional energy sources," Universität Flensburg. PhD thesis, Flensburg, 2012.

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

[31] M. A. Gonzalez-Salazar, M. Venturini, W. R. Poganietz, M. Finkenrath, T. Kirsten, H. Acevedo and P. R. Spina, "A general modeling framework to evaluate energy, economy, land-use and GHG emissions nexus for bioenergy exploitation," *Applied Energy,* pp. 178: 223-249. doi:10.1016/j.apenergy.2016.06.039, 2016.

[32] M. Gonzalez-Salazar, M. Morini, M. Pinelli, P. Spina, M. Venturini, M. Finkenrath and W. Poganietz, "Methodology for biomass energy potential estimation: projections of future potential in Colombia," *Renewable Energy,* pp. 488-505, 2014.

[33] M. Gonzalez-Salazar, „Strategic planning of biomass and bioenergy technologies," PhD thesis. University of Ferrara, Ferrara, 2016.

[34] World Bank, "World Development Indicators (WDI)," 2016. [Online]. Available: http://data.worldbank.org/data-catalog/world-development-indicators. [Accessed 1st March 2013].

[35] A. Gaviria, „Cambio social en Colombia durante la segunda mitad del siglo XX," Documentos CEDE, 2010.

[36] A. Gaviria, "Semana.com," 25 August 2012. [Online]. Available: http://www.semana.com/edicion-30-anos/articulo/sumas-restas/263419-3.

[37] N. Richani, Systems of violence. The political economy of war and peace in Colombia, New York: State University of New York Press, 2013.

[38] ICTJ, „An Overview of Conflict in Colombia," International Center for Transitional Justice (ICTJ). https://www.ictj.org/sites/default/files/ICTJ-Colombia-Conflict-Facts-2009-English.pdf, 2009.

[39] RNI, "Unidad de Víctimas," 1 November 2014. [Online]. Available: http://rni.unidadvictimas.gov.co/?q=node/107. [Accessed 1 December 2014].

[40] J. Rueda Gallardo, „Diagnóstico de la pobreza rural. Colombia 2010-2014,“ Departamento Nacional de Planeación (DNP). Dirección de Desarrollo Rural Sostenible. Subdirección de Producción y Desarrollo Rural. https://colaboracion.dnp.gov.co/CDT/Agriculturapecuarioforestal%20y%20pesca/Pobreza%20Rural.pdf, 2015.

[41] J. Heath und H. Binswanger, „Natural resource degradation effects of poverty and population growth are largely policy-induced: the case of Colombia,“ *Environment and Development Economics. DOI: 10.1017/S1355770X00000383,* pp. 1: 65-84 , 1996.

[42] A. Etter, C. McAlpine und H. Possingham, „Historical Patterns and Drivers of Landscape Change in Colombia Since 1500: A Regionalized Spatial Approach,“ *Annals of the Association of American Geographers,* pp. 98(1): 2-23, 2008.

[43] L. Dávalos, A. Bejarano, M. Hall, H. Correa, A. Corthals und O. Espejo, „Forests and Drugs: Coca-Driven Deforestation in Tropical Biodiversity Hotspots,“ *Environmental Science & Technology ,* pp. 1219-1227, 2011.

[44] FAO, „FAOSTAT,“ Food and Agriculture Organization of the United Nations (FAO). http://faostat.fao.org/, 2016.

[45] D. Armenteras, N. Rodríguez, J. Retana und M. Morales, „Understanding deforestation in montane and lowland forests of the Colombian Andes,“ *Reg Environ Change,* pp. 11: 693–705. DOI 10.1007/s10113-010-0200-y, 2011.

[46] J. Falck-Zepeda, S. Mangi, T. Sulser, P. Zambrano und C. Falconi, „Biofuels and rural economic development in Latin America and the Caribbean,“ Cooperative Programme FAO/Inter-American Development Bank. Working Paper LAC/02/10, Rome, 2010.

[47] A. De Pinto, A. Haruna, B. Creamer, G. Hyman, M. Li, H. Kwon, J. Valencia Garcia, A. Castro Coca, J. Tapasco, J. Martinez und J. Hoyos, „Low Emission Development Strategies for Agriculture and Other Land Uses: The Case of Colombia,“ International Food Policy Research Institute (IFPRI), 2014.

[48] D. Nepstad, S. Irawan, T. Bezerra, W. Boyd, C. Stickler, J. Shimada, O. Carvalho, K. MacIntyre, A. Dohong, A. Alencar, A. Azevedo, D. Tepper und S. Lowery, „More food, more forests, fewer emissions, better livelihoods: linking REDD+, sustainable supply chains and domestic policy in Brazil, Indonesia and Colombia,“ *Carbon Management,* pp. 4(6): 639-658, 2013.

[49] T. Killeen, G. Schroth, W. Turner, C. Harvey, M. Steiniger, C. Dragisic und R. Mittermeier, „Stabilizing the agricultural frontier: Leveraging REDD with biofuels for sustainable development,“ *Biomass and Bioenergy,* pp. 35: 4815-4823, 2011.

[50] E. Murgueitio, Z. Calle, F. Uribe, A. Calle und S. Baldomero, „Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands,“ *Forest Ecology and Management,* pp. 261: 1654-1663, 2011.

[51] L. Rivera, I. Armbrecht und Z. Calle, „Silvopastoral systems and ant diversity conservation in a cattle-dominated landscape of the Colombian Andes,“ *Agriculture, Ecosystems and Environment,* pp. 181: 188-194, 2013.

[52] J. Naranjo, J. Chará und R. Barahona Rosales, „Greenhouse gases in intensive silvopastoral systems with Leucaena leucocephala in Colombia,“ *Livestock Research for Rural Development,* p. 24(8), 2012.

[53] Z. Calle, E. Murgueitio und J. Chará, „Integrating forestry, sustainable cattle-ranching and landscape restoration,“ in *The power of forests*, Food and Agriculture Organization of the United Nations (FAO). Forestry Deparment., 2012.

[54] C. Sheinbaum, B. Ruíz und L. Ozawa, „Energy consumption and related CO2 emissions in five Latin American countries: Changes from 1990 to 2006 and perspectives,“ *Energy,* pp. 36: 3629-3638, 2011.

[55] EIA, „International Energy Statistics,“ 01 05 2016. [Online]. Available: https://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=44&pid=44&aid=2.

[56] S. Calderón, A. Alvarez, A. Loboguerrero, S. Arango, K. Calvin, T. Kober, K. Daenzer und K. Fisher-Vanden, „Achieving CO2 reductions in Colombia: Effects of carbon taxes and abatement targets,“ *Energy Economics,* p. http://dx.doi.org/10.1016/j.eneco.2015.05.010, 2015.

[57] O. G. J. C. M. S. L. Fresneda, „Reducción de la pobreza en Colombia: el impacto de las políticas públicas,“ PNUD, 2009.

[58] M. Parra Torrado, „Infrastructura y pobreza: el caso de los servicios públicos en Colombia,“ Fedesarrollo, 2011.

[59] D. Silva und T. Nakata, „Multi-objective assessment of rural electrification in remote areas with poverty considerations,“ *Energy Policy,* pp. 37: 3096-3108. doi:10.1016/j.enpol.2009.03.060, 2009.

[60] S. Arango und E. Larsen, „The environmental paradox in generation: How South America is gradually becoming more dependent on thermal generation,“ *Renewable and Sustainable Energy Reviews,* pp. 14: 2956-2965, 2010.

[61] R. Quijano, S. Botero und J. Domínguez, „MODERGIS application: Integrated simulation platform to promote and develop renewable sustainable energy plans, Colombian case study,“ *Renewable and Sustainable Energy Reviews,* Bd. 16, pp. 5176-5187, 2012.

[62] J. A. J. B. J. O. G. L. G. R. A. Echeverry, „El transporte como soporte al desarrollo, una visión 2040,“ 2008.

[63] MinTransporte-CEPAL, „Anuario Estadístico de la Comisión Económica para América Latina y el Caribe,“ 2010.

[64] UPME, „Proyección de Demanda de Combustibles Líquidos y GNV en Colombia,“ 2010.

[65] IDEAM, "Inventario Nacional de Fuentes y Sumideros de Gases de Efecto Invernadero 2000-2004," Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM). ISBN: 978-958-96863-7-9, Bogotá, 2009.

[66] Gobierno de Colombia, „Contribución Prevista Determinada a Nivel Nacional,“ Ministerio de Medio Ambiente, 2015.

[67] EPA, „Global anthropogenic non-CO2 greenhouse gas emissions: 1990-2020,“ U.S. Environmental Protection Agency (EPA). Office of Atmospheric Programs, Climate Change Division, Washington, 2006.

[68] A. De la Torre, P. Fajnzylber and J. Nash, "Low-carbon development: Latin American responses to climate change," World Bank Latin American and Caribbean Studies. The World Bank. DOI: 10.1596/978-0-8213-8054-3, Washington, 2010.

[69] ECLAC, „Panorama del cambio climático en Colombia,“ Environment and Human Settlements Division of the Economic Commission for Latin America and the Caribbean (ECLAC) of the UN, Santiago, 2013.

[70] P. Cremonez, M. Feroldi, A. Feiden, J. Teleken, D. Gris, J. Dieter, E. de Rossi und J. Antonelli, „Current scenario and prospects of use of liquid biofuels in South America,“ *Renewable and Sustainable Energy Reviews,* pp. 43: 352-362, 2015.

[71] M. Bildirici, „The relationship between economic growth and biomass energy consumption,“ *Journal of Renewable and Sustainable Energy,* p. http://dx.doi.org/10.1063/1.3699617, 2012.

[72] M. Bildirici, „Economic growth and biomass energy,“ *Biomass and Bioenergy,* pp. 50: 19-24, 2013.

[73] M. Bildirici, „Relationship between biomass energy and economic growth in transition countries: panel ARDL approach,“ *GCB Bioenergy,* pp. 6: 717-726, 2014.

[74] M. Shahbaz, G. Rasool, K. Ahmed und M. Mahalik, „Considering the effect of biomass energy consumption on economic growth: Fresh evidence from BRICS region,“ *Renewable and Sustainable Energy Reviews,* pp. 60: 1442-1450, 2016.

[75] DNP, „Documento Conpes 3510, Lineamientos de Política para Promover la Producción Sostenible de Biocombustibles en Colombia,“ Bogotá, 2008.

[76] IDEAM, „Informe Anual sobre el Estado del Medio Ambiente y los Recursos Naturales Renovables en Colombia, Bosques 2009,“ 2010.

[77] El Tiempo, "Cada año se deforestan 310.349 hectáreas en el país," 25 March 2013. [Online]. Available: http://www.eltiempo.com/archivo/documento/CMS-12711212. [Accessed 15 July 2014].

[78] A. Etter, C. McAlpine, K. Wilson, S. Phinn und H. Possingham, „Regional patterns of agricultural land use and deforestation in Colombia,“ *Agriculture, Ecosystems and Environment,* pp. 114: 369-386, 2006a.

[79] A. Etter, C. McAlpine, S. Phinn, D. Pullar und H. Possingham, „Unplanned land clearing of Colombian rainforests: Spreading like disease?,“ *Landscape and Urban Planning,* pp. 77: 240-254, 2006b.

[80] A. Etter, C. McAlpine, D. Pullar und H. Possingham, „Modelling the conversion of Colombian lowland ecosystems since 1940: Drivers, patterns and rates,“ *Journal of Environmental Management,* pp. 79: 74-87, 2006c.

[81] D. Armentera, G. Rudas, N. Rodriguez, S. Sua und M. Romero, „Patterns and causes of deforestation in the Colombian Amazon,“ *Ecological Indicators,* pp. 6: 353-368, 2006.

[82] R. Bain, „World Biofuels Assessment. Worldwide Biomass Potential: Technology Characterizations,“ National Renewable Energy Laboratory (NREL). http://www.nrel.gov/docs/fy08osti/42467.pdf, 2007.

[83] BID-MME, Consorcio CUE, „Evaluación del ciclo de vida de la cadena de producción de biocombustibles en Colombia,“ Medellín, 2012.

[84] C. Franco, S. Zapata und I. Dyner, „Simulation for assessing the liberalization of biofuels,“ *Renewable and Sustainable Energy Reviews,* pp. 41: 298-307, 2015.

[85] M. Leal, L. Nogueira und L. Cortez, „Land demand for ethanol production,“ *Applied Energy,* pp. 102: 266-271, 2013.

[86] A. Walter, P. Dolzan, O. Quilodrán, J. de Oliveira, C. da Silva, F. Piacente und A. Segerstedt, „Sustainability assessment of bio-ethanol production in Brazil considering land use change, GHG emissions and socio-economic aspects,“ *Energy Policy,* Bd. 39, pp. 5703-5716, 2011.

[87] G. Sorda, M. Banse und C. Kemfert, „An overview of biofuel policies across the world,“ *Energy Policy,* pp. 38: 6977-6988, 2010.

[88] T. Koizumi, „Biofuels and food security,“ *Renewable and Sustainable Energy Reviews,* pp. 52: 829-841, 2015.

[89] R. Janssen und D. Rutz, „Sustainability of biofuels in Latin America: Risks and opportunities,“ *Energy Policy,* pp. 39: 5717-5725, 2011.

[90] H. Duer und P. Christensen, „Socio-economic aspects of different biofuel development pathways,“ *Biomass and Bioenergy,* pp. 34: 237-243, 2010.

[91] D. van der Horst und S. Vermeylen, „Spatial scale and social impacts of biofuel production,“ *Biomass and Bioenergy,* pp. 35: 2435-2443, 2011.

[92] X. Ji und X. Long, „A review of the ecological and socioeconomic effects of biofuel and energy policy recommendations,“ *Renewable and Sustainable Energy Reviews,* pp. 61: 41-52, 2016.

[93] T. Selfa, C. Bain und R. Moreno, „Depoliticizing land and water "grabs" in Colombia: the limits of Bonsucro certification for enhancing sustainable biofuel practices,“ *Agric Hum Values,* pp. 31: 455-468, 2014.

[94] Ecopetrol, „Integrated sustainable management report,“ Bogota, 2013.

[95] A. Duarte, W. Sarache und Y. Costa, „A facility-location model for biofuel plants: Applications in the Colombian context,“ *Energy,* pp. 72: 476-483, 2014.

[96] J. Quintero, J. Moncada und C. Cardona, „Techno-economic analysis of bioethanol production from lignocellulosic residues in Colombia: A process simulation approach,“ *Bioresource Technology,* pp. 139:300-307, 2013.

[97] M. Valencia und C. Cardona, „The Colombian biofuel supply chains: The assessment of current and promising scenarios based on environmental goals,“ *Energy Policy,* pp. 67: 232-242, 2014.

[98] El Tiempo, "Chilenos, encartados con proyecto fallido de etanol," 2014. [Online]. Available: http://m.eltiempo.com/economia/negocios/chilenos-encartados-con-proyecto-fallido-de-etanol/9252045. [Accessed 7 March 2014].

[99] S. Vecino Mantilla, P. Gauthier-Maradei, P. Álvarez Gil und S. Tarazona Cárdenas, „Comparative study of bio-oil production from sugarcane bagasse and palm empty fruit bunch: Yield optimization and bio-oil characterization,“ *Journal of Analytical and Applied Pyrolysis,* pp. 108: 284-294, 2014.

[100] J. Moncada, M. El-Halwagi und C. Cardona, „Techno-economic analysis for a sugarcane biorefinery: Colombian case,“ *Bioresource Technology,* pp. 135: 533-543, 2012.

[101] MME, „Programa de biocombustibles en Colombia,“ Ministerio de Minas y Energía (MME). Gobierno de Colombia. https://www.minminas.gov.co/documents/10180/488888/Programa.pdf/38a0085e-b892-42b2-bc56-86085488cb5c, Bogotá, 2007.

[102] IICA, „Atlas de la Bioenergía y los Biocombustibles en las Américas: II Biodiesel,“ Instituto Interamericano de Cooperación para la Agricultura (IICA). http://www.olade.org/sites/default/files/CIDA/IICA/Atlas%20de%20Bioenergia%20y%20Combustibles%202.pdf, San José, 2010.

[103] L. Rincón, M. Valencia, V. Hernández, L. Matallana und C. Cardona, „Optimization of the Colombian biodiesel supply chain from oil palm crop based on techno-economical and environmental criteria,“ *Energy Economics,* pp. 47: 154-167, 2015.

[104] C. Castiblanco, A. Etter und T. Aide, „Oil palm plantations in Colombia: a model of future expansion,“ *Environmental Science & Policy,* pp. 27: 172-183, 2013.

[105] C. Castiblanco, A. Etter und A. Ramirez, „Impacts of oil palm expansion in Colombia: What do socioeconomic indicators show?,“ *Land Use Policy,* pp. 44: 31-43, 2015.

[106] T. Selfa, C. Bain, R. Moreno, A. Eastmond, S. Sweitz, C. Bailey, G. Pereira, T. Souza und R. Medeiros, „Interrogating Social Sustainability in the Biofuels Sector in Latin America: Tensions Between Global Standards and Local Experiences in Mexico, Brazil, and Colombia,“ *Environmental Management,* pp. 56: 1315-1329, 2015.

[107] E. Castanheira, H. Acevedo und F. Freire, „Greenhouse gas intensity of palm oil produced in Colombia addressing alternative land use change and fertilization scenarios,“ *Applied Energy,* pp. 114: 958-967, 2014.

[108] M. Valencia-Botero, L. Rincón-Pérez und C. Cardona, „Effect of Change in Land Use due to Oil Palm Cultivation for Biodiesel Production in Colombia,“ *Ing.Univ.Bogotá (Colombia),* pp. 18(1): 91-102. doi:10.11144/Javeriana.IYU18-1.ecut, 2014.

[109] F. Boons und A. Mendoza, „Constructing sustainable palm oil: how actors define sustainability,“ *Journal of Cleaner Production,* pp. 18: 1686-1695, 2010.

[110] C. Castiblanco, A. Moreno und A. Etter, „Impact of policies and subsidies in agribusiness: The case of oil palm and biofuels in Colombia,“ *Energy Economics,* pp. 49: 676-686, 2015.

[111] J. Moncada, J. Tamayo und C. Cardona, „Evolution from biofuels to integrated biorefineries: techno-economic and environmental assessment of oil palm in Colombia,“ *Journal of Cleaner Production,* pp. 81: 51-59, 2014.

[112] L. Rincón, J. Moncada und C. Cardona, „Analysis of potential technological schemes for the development of oil palm industry in Colombia: A biorefinery point of view,“ *Industrial Crops and Products,* pp. 52: 457-465, 2014.

[113] E. Yánez Angarita, E. Lora, R. da Costa und E. Torres, „The energy balance in the Palm Oil-Derived Methyl Ester (PME) life cycle for the cases in Brazil and Colombia,“ *Renewable Energy,* pp. 34: 2905-2913, 2009.

[114] I. Macedo und R. Leal, „Sugar cane residues for power generation in the sugar/ethanol mills in Brazil,“ *Energy for Sustainable Development,* Nr. 5, pp. 77-82, 2001.

[115] F. Arrieta, F. Teixeira, E. Yánez, E. Lora und E. Castillo, „Cogeneration potential in the Columbian palm oil industry: Three case studies,“ *Biomass and Bioenergy,* pp. 31: 503-511, 2007.

[116] XM, "OpeSIN," 15 October 2013. [Online]. Available: http://www.xm.com.co/Pages/Home.aspx. [Accessed 15 October 2013].

[117] M. Salomón, M. Gomez und A. Martin, „Technical polygeneration potential in palm oil mills in Colombia: A case study,“ *Sustainable Energy Technologies and Assessments,* pp. 3: 40-52, 2013.

[118] A. Cuevas, "La madera que dejó de generar energía," 25 September 2013. [Online]. Available: http://www.elespectador.com/noticias/medio-ambiente/madera-dejo-de-generar-energia-articulo-448792. [Accessed 15 July 2014].

[119] A. Rosso-Cerón und V. Kafarov, „Barriers to social acceptance of renewable energy systems in Colombia,“ *Current Opinion in Chemical Engineering,* pp. 10: 103-110, 2015.

[120] G. Caspary, „Gauging the future competitiveness of renewable energy in Colombia,“ *Energy Economics,* pp. 31: 443-449, 2009.

[121] C. de Carvalho, S. Silveira, E. La Rovere und A. Iwama, „Deforested and degraded land available for the expansion of palm oil for biodiesel in the state of Pará in the Brazilian Amazon,“ *Renewable and Sustainable Energy Reviews,* Bd. 44, pp. 867-876, 2015.

[122] INPE-UNFCC, „Brazilian Amazon deforestation rates,“ Brazil's National Institute for Space Research (INPE) and United Nations Framework Convention on Climate Change (UNFCCC). https://unfccc.int/files/bodies/awg/application/pdf/s1_4_brazil.pdf, 2014.

[123] A. Walter, M. Galdos, F. Scarpare, R. Leal, J. Seabra, M. da Cunha, M. Picoli und C. de Oliveira, „Brazilian sugarcane ethanol: developments so far and challenges for the future,“ *WIREs Energy and Environment,* Bd. 3, Nr. 1, pp. 70-92. 10.1002/wene.87, 2013.

[124] MME, „Ten-year energy expansion plan 2024,“ Ministério de Minas e Energia. Government of Brazil. http://www.epe.gov.br/PDEE/Sum%C3%A1rio%20Executivo%20do%20PDE%202024.pdf, 2014.

[125] J. Puerto Rico, S. Mercedes und I. Sauer, „Genesis and consolidation of the Brazilian bioethanol: A review of policies and incentive mechanisms,“ *Renewable and Sustainable Energy Reviews,* Bd. 14, pp. 1874-1887, 2010.

[126] J. De Azevedo und F. Galiana, „The sugarcane ethanol power industry in Brazil: obstacles, success and perspectives,“ in *IEEE Electrical Power & Energy Conference*, 2009.

[127] MinAmbiente, „En 2020 tendremos cero deforestación en la Amazonía,“ 13 February 2015. [Online]. Available: https://www.minambiente.gov.co/index.php/component/content/article?id=1667:en-2020-tendremos-cero-deforestacion-en-la-amazonia-minambiente.

[128] A. Castro-Nunez, O. Mertz und M. Quintero, „Propensity of farmers to conserve forest within REDD+ projects in areas affected by armed-conflict,“ *Forest Policy and Economics,* Bd. 66, pp. 22-30, 2016.

[129] I. Flachsbarth, B. Willaarts, H. Xie, G. Pitois, N. Mueller, C. Ringler und A. Garrido, „The Role of Latin America's Land and Water Resources for Global Food Security: Environmental Trade-Offs of future Food Production Pathways,“ *PLos ONE,* Bd. 1. doi:10.1371/journal.pone.0116733, pp. 1-24, 2015.

[130] G. Nelson, M. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu, T. Sulser, C. Ringler, S. Msangi und L. You, „Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options,“ International Food Policy Research Institute (IFPRI), Washington, 2010.

[131] J. Burney, S. Davis und D. Lobell, „Greenhouse gas mitigation by agricultural intensification,“ *Proceedings of the National Academy of Sciences of the United States of America (PNAS),* Bd. 107, Nr. 26, pp. 12052-12057. www.pnas.org/cgi/doi/10.1073/pnas.0914216107, 2010.

[132] T. Rudel, L. Schneider, M. Urlarte, B. Turner, R. DeFries, D. Lawrence, J. Geoghegan, S. Hecht, A. Ickowitz, E. Lambin, T. Birkenholtz, S. Baptista und R. Grau, „Agricultural intensification and changes in cultivated areas,

1970-2005,“ *Proceedings of the National Academy of Sciences of the United States of America (PNAS),* Bd. 106, Nr. 49, pp. 20675-20680, 2009.

[133] DNP, „Estrategia Crecimiento Verde. Bases del Plan Nacional de Desarrollo 2014-2018,“ Departamento Nacional de Planeacion. https://colaboracion.dnp.gov.co/CDT/Consejo%20Nacional%20de%20Planeacin/Congreso%20SNP%20Estrategia%20Crec%20Verde%20(3).pdf, 2014.

[134] OECD, „Colombia. Policy Priorities for Inclusive Development,“ OECD. "Better Policies" Series, Paris, 2015.

[135] D. Connolly, H. Lund, B. Mathiesen and M. Leahy, "A review of computer tools for analysing the integration of renewable energy into various energy systems," *Applied Energy,* vol. 87, pp. 1059-1082, 2010.

[136] S. Bhattacharyya, „Energy Economics. Concepts, Issues, Markets and Governance,“ Springer-Verlag London. DOI 10.1007/978-0-85729-268-1, London, 2011.

[137] C. Heaps, „Long-range Energy Alternatives Planning (LEAP) system,“ Somerville, MA, USA, 2012.

[138] M. Howells, H. Rogner, N. Strachan, C. Heaps, H. Huntington, S. Kypreos, A. Hughes, S. Silveira, J. DeCarolis, M. Bazillian and A. Roehr, "OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development," *Energy Policy,* vol. 39, no. 10, pp. 5850-5870, 2011.

[139] IPCC, "IPCC Guidelines for National Greenhouse Gas Inventories," Intergovernmental Panel on Climate Change (IPCC), Task Force on National Greenhouse Gas Inventories (TFI). IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html, 2006.

[140] F. Cherubini, N. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger and S. Woess-Gallasch, "Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations," *Resources, Conservation and Recycling,* vol. 53, pp. 434-447, 2009.

[141] S. Gerssen-Gondelach, D. Saygin, B. Wicke, M. Patel and A. Faaij, "Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials," *Renewable and Sustainable Energy Reviews,* vol. 40, pp. 964-998, 2014.