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Title: FEASIBILITY ANALYSIS OF GAS TURBINE INLET AIR COOLING BY MEANS OF LIQUID NITROGEN EVAPORATION FOR IGCC POWER AUGMENTATION

Article Type: Research Paper

Keywords: IGCC, power augmentation, syngas

Corresponding Author: Dr. Mirko Morini, PhD

Corresponding Author's Institution: University of Parma

First Author: Mirko Morini, PhD

Order of Authors: Mirko Morini, PhD; Michele Pinelli; Pier Ruggero Spina; Anna Vaccari; Mauro Venturini

Abstract: Integrated Gasification Combined Cycles (IGCC) are energy systems mainly composed of a gasifier and a combined cycle power plant. Since the gasification process usually requires oxygen as the oxidant, an Air Separation Unit (ASU) is also part of the plant.
In this paper, a system for power augmentation in IGCC is evaluated. The system is based on gas turbine inlet air cooling by means of liquid nitrogen spray. In fact, nitrogen is a product of the ASU, but is not always exploited. In the proposed plant, the nitrogen is first liquefied to be used for inlet air cooling or stored for later use. This system is not characterized by the limits of water evaporative cooling systems (the lower temperature is limited by air saturation) and refrigeration cooling (the effectiveness is limited by the pressure drop in the heat exchanger).
A thermodynamic model of the system is built by using a commercial code for energy conversion system simulation. A sensitivity analysis on the main parameters is presented. Finally the model is used to study the capabilities of the system by imposing the real temperature profiles of different sites for a whole year and by comparing to traditional inlet air cooling strategies.

Reviewers' comments:	
Reviewer #1: This article is of interest but needs still some attention before it could be accepted. The subject of the article is meaningful for this journal and is original. It is of certain interest in the thermal engineering world But special attention should be given to the following points:	
- The INTRODUCTION section is a little bit disorganized and with certain lack of continuity. For instance:	
o At the end of the second paragraph some comments have to be done in order to connect with the Item 1.1 Air separation technologies. At that point nothing has been said about the nitrogen and why it has to be obtained from the air. It would be useful to explain to the reader some more about this question.	A paragraph has been added.
o The item 1. 1. 1. has thirty one lines and the Item 1. 1. 2 only three. I tend to think that some more explanation is needed in the last one or less in the first one.	Item 1.1.2 has been extended.
Also some more text is needed to explain why that second technology is not used in this paper.	Text has been added in Item 1.1.
o Also, the first sentence of the Item 1.2. is completely decoupled with the second sentence. I think it's better write that sentence in a clearer and more orderly form.	The sentence has been moved.
o The last sentence before the Item 2 is also decoupled with the previous one. I believe that greater continuity in the writing is required	The paragraph which outlines the work will be presented in the paper has been changed.
- A small explanation of the Thermoflex code and the advantages in this type of simulations would be welcome.	The explanation and some references have been added.
- First sentence of Item 2: It is worth to comment how or from where the values of the different	These are common value for a combined cycle.

magnitudes and data for the combined cycle are obtained.	
- Please explain more deeply why the ASU is designed to produce 100 kg/s of nitrogen. Why 100 kg/s?	As already stated in the paper “This does not significantly increase the size of the ASU with respect to a traditional design, since this stream is mostly recuperated from the gases usually discharged by the ASU when the only products are (i) a stream of oxygen sent to the gasifier and (ii) a small amount of nitrogen for NOx control (see the discussion in [6])”. In [6] it can be seen that the nitrogen discharged in atmosphere from the ASU is about 85 kg/s, 100 kg/s is a rounding of that value. This data has been added in the paper.
- The first three sentences of the Item 2.2 are difficult to be understood. Please rewrite them in a more clear form.	They have been rephrased.
- Actually the production of nitrogen consumes 120 MW? Some more comments on the significance of such a large amount of power in the "IGCC Power Augmentation" related to the output of the combined cycle are needed.	As stated in the paper the evaporation of the liquid nitrogen provide the power augmentation, but the production of the liquid nitrogen needs power. The system operates as a storage, as is the case of systems based on ice production.
- The fourth paragraph of the Item 2 says: "… in the next two paragraphs ..", which paragraphs?	Corrected.
- In my point of view the APPENDIX and the related figures a1 to a4 are not necessary in this paper. There are other papers of the authors including such results, but in this paper do not add anything useful.	The Appendix has been removed.
Reviewer #3: The paper is interesting due to two aspects; Air Separation Unit (ASU) as a part of the plant and using liquid nitrogen spray for inlet air cooling. The system considers existing technologies for gasification, air separation and liquification of nitrogen.	
It is claimed that system uses the nitrogen which otherwise not used but the benefits are not made clear.	The analyses presented in the paper shows that the benefits are strictly related to the climatic conditions, the costs of electricity and of the coal.
Also the impact of additional plant to do this is not discussed.	The aim of the paper is a thermodynamic analysis. In order to clarify this Item 1.2 has been modified.

There are some scientific and technical gaps in the description provided in the paper. Authors pointed out that the system is not profitable however technical merits of this technology could be discussed.	
The scientific justification various assumption and the process should be explained in more detail. Assumption that the condensation of the water content in the air can form a fine dispersed fog which enters into the gas turbine and operates as wet compression for further power augmentation. This assumption does not have any thermodynamic proof.	This is not an assumption, but a result of the simulation. The simulation model evidences the presence of liquid water downstream the nitrogen injection. This liquid water enters the gas turbine and operates as the water injected for wet compression.
Thermodynamic performance of the integrated system is analysed using commercial code.The system performance is analysed for real temperature profiles of different sites for a whole year and compared comparing to traditional inlet air cooling strategies. Sensitivity analysis is only done for the financial profits.	
In order to make the paper more suitable for other researchers and practising engineers scientific and technical details of the whole system and implications of alternative solution should be discussed.	As stated in the paper, the aim is the thermodynamic analysis of the system. Details cannot be discussed since the system is currently in a concept stage.
Comments from the Editor Some general comments to be dealt with:	
Would you submit revised version clearly mark all improvements/correction in the manuscript by using TRACK CHANGES or by coloured font/background?	All modifications are highlighted in yellow.
When reviewing the references a strong impression can be created that the manuscript should be submitted to another journal: In order to give our readers a sense of continuity, we encourage you to identify ATE publications of similar research in your papers. Please, do a literature check of the papers published in recent	The references are updated. Some references regarding IGCC modelling from Applied Thermal Engineering are added.

years (2013 and even 2014) and relate the content of relevant papers to the results and findings presented in your publication. You can also reference articles in print using their doi: Please be aware that, although Articles in Press do not have all bibliographic details available yet, they can already be cited using the year of online publication and the DOI , as follows: author(s), article title, journal (year), DOI Also recent papers should be included into the state of the art - the present lack of recent references creates a wrong impression that the authors are not aware about the most recent development The hyperlinks (blue colour and underlining) should be removed from email addresses and web references. You do not need to repeat http:// as modern browsers do not require it. However the full date (dd/mm/yyyy) of the last access should be always provided. For books, thesis, reports etc. - would you provide both the place and country where the book was published?	

Highlights (for review)

- Gas turbine inlet air cooling by means of liquid nitrogen spray
- Humidity condensation may form a fog which provides further power augmentation
- High peak and off peak electric energy price ratios make the system profitable

FEASIBILITY ANALYSIS OF GAS TURBINE INLET AIR COOLING BY MEANS OF LIQUID NITROGEN EVAPORATION FOR IGCC POWER AUGMENTATION

Mirko Morini[1]

Dipartimento di Ingegneria Industriale, Università degli Studi di Parma, Parma, Italy

Michele Pinelli, Pier Ruggero Spina, Anna Vaccari, Mauro Venturini

Dipartimento di Ingegneria, Università degli Studi di Ferrara, Ferrara, Italy

ABSTRACT

Integrated Gasification Combined Cycles (IGCC) are energy systems mainly composed of a gasifier and a combined cycle power plant. Since the gasification process usually requires oxygen as the oxidant, an Air Separation Unit (ASU) is also part of the plant.

In this paper, a system for power augmentation in IGCC is evaluated. The system is based on gas turbine inlet air cooling by means of liquid nitrogen spray. In fact, nitrogen is a product of the ASU, but is not always exploited. In the proposed plant, the nitrogen is first liquefied to be used for inlet air cooling or stored for later use. This system is not characterized by the limits of water evaporative cooling systems (the lower temperature is limited by air saturation) and refrigeration cooling (the effectiveness is limited by the pressure drop in the heat exchanger).

A thermodynamic model of the system is built by using a commercial code for energy conversion system simulation. A sensitivity analysis on the main parameters is presented. Finally the model is used to study the capabilities of the system by imposing the real temperature profiles of different sites for a whole year and by comparing to traditional inlet air cooling strategies.

Keywords: IGCC, power augmentation, syngas

NOMENCLATURE

Symbols

p	price

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[1] corresponding author, mirko.morini@unipr.it, +39 0521905714

Abbreviations

ASU	air separation unit
CCC	continuous compression cooling
COP	coefficient of performance
EC	electric chiller
G	gasifier
GC	gas cleaning system
GT	gas turbine
HPF	high pressure fogging
IACS	inlet air cooling system
IGCC	integrated gasification combined cycle
ISO	International Organization for Standardization
NC	air cooling by means of nitrogen
OS	overspray
RH	relative humidity
SS	steam section
ST	storage tank
TEC	traditional evaporative cooling

Subscripts

coal	coal
el	electrical energy
op	off peak hours
p	peak hours

1. INTRODUCTION

IGCC technology uses solid and/or liquid fuels – typically coal, petroleum coke, petroleum residue, biomass or a blend of these fuels – in a power plant that leverages the environmental benefits and thermal performance of a gas-fired combined cycle. In an IGCC gasifier, a solid or liquid feed is partially oxidized with air or high-purity oxygen. The resulting hot, raw “syngas” – an abbreviation for synthesis gas – consists of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen gas (H_2), water (H_2O), methane (CH_4), hydrogen sulphide (H_2S) and other sulphur compounds, nitrogen gas (N_2) and argon (Ar). After it is cooled and cleaned of particulate matter and sulphur species, the syngas is fired in a combustion turbine. The hot exhaust from the gas turbine passes to a heat recovery steam generator where it produces steam that drives a steam turbine.

The use of a gas turbine/steam turbine combined cycle helps gasification-based power systems achieve competitive power generation efficiencies, despite energy losses during fuel conversion in the gasification system and in the air separation unit (ASU) in oxygen-blown systems.

The perspectives for IGCC technological progress can be (i) the increase of cycle efficiency (through the increase of maximum allowable turbine inlet temperature) and (ii) the search for new methods to reduce power requirements associated with oxygen production (e.g. through a more advanced level of integration among IGCC main components). It was observed that, to optimize the operation and performance of IGCC power plants, the highest possible level of integration among processes and components is required. Different strategies can be adopted, as for instance, (i) the use of byproduct nitrogen from ASU in gas turbine combustor, (ii) the supply of compressed air extracted from the gas turbine to the ASU or to the gasifier, (iii) the firing of the syngas with pure oxygen and (iv) the integration of the IGCC plant with other energy systems (e.g. fuel cells or organic Rankine cycles).

Moreover, it was highlighted in literature that at present the cryogenic air separation unit is the Achille's heel of IGCC plants, since it parasitizes some percentage points of the gross power produced by the gas-steam combined cycle [1].

1.1 Air separation technologies

Dry air is a mixture of nitrogen (78 % v/v), oxygen (21 % v/v) and argon (1 % v/v), which together constitute the main gases of the atmosphere. The remaining gases are carbon dioxide, methane, nitrous oxide and ozone. Water vapor at sea level can be estimated as 1 % to 4 % of dry air. Different technologies were developed in the past in order to separate the different gases which air is composed of. A comprehensive review is presented in [2]. These technologies can be grouped in two categories: cryogenic and non-cryogenic processes. Cryogenic distillation seems to be the only commercially available technology today to produce large quantities of oxygen economically and at high purity [3]. Within the non-cryogenic processes, ion transport membranes integration with gas turbine is more complicated due to request of a much larger volume of feed air compared to cryogenic ASUs. Nevertheless, ion transport membranes are foreseen as the best candidate for high tonnage oxygen production [4,5], since they are associated with significantly lower power consumption than cryogenic processes.

1.1.1 Cryogenic air separation technologies

Cryogenic air separation is currently the most efficient and cost-effective technology for producing large quantities of oxygen, nitrogen and argon as gaseous or liquid products [2]. This characteristic makes the cryogenic process more suitable than the others for the supply of oxygen to the gasifier in IGCC power plants.

An air separation unit is usually composed of a multi-column cryogenic distillation process and produces high-purity oxygen from compressed air (up to 99 % v/v [6,7]).

Cryogenic technology can also produce high-purity nitrogen as a useful byproduct stream at a relatively low incremental cost [2]. Moreover, a liquefaction section can be added in order to produce liquid oxygen or nitrogen and store them at low incremental capital and power costs [2].

Most of the facilities use traditional electric motor-driven equipment to compress the feeding air, as well as the oxygen and other product streams. Cryogenic ASUs operating in the framework of IGCC facilities usually receive the feeding air by an air bleeding from the gas turbine compressor.

Downstream of the air compression and aftercooling, the process provides an air pre-treatment section which removes contaminants, such as water, carbon dioxide and hydrocarbons. The air is then cooled to cryogenic temperatures and distilled into oxygen, nitrogen, and, optionally, argon gaseous streams. These products cool down the incoming air in order to reduce the energy needed for refrigeration.

The characterization of the types of cryogenic processes used for air separation can be based on the method of pressurizing the product streams or on the air feed pressure to the ASU [2,6]:

- Low-Pressure Cryogenic ASU. Conventional cryogenic ASUs operate at low pressure, meaning that the feed air is compressed just enough to allow the nitrogen by-product to be discharged at atmospheric pressure. Depending on the oxygen purity specification and the extent of efficiency optimization, absolute air feed pressures to low-pressure cryogenic ASUs are typically 4.4 bar to 7.2 bar [6]. Product streams typically leave the ASU in gaseous form near ambient temperature and pressure. If liquid products are desired, additional refrigeration is required.
- Elevated-Pressure Cryogenic ASU. These cryogenic plants operate at much higher pressures (close to discharge pressures of gas turbine compressors) than the Low-Pressure Cryogenic ASU due to improvements in manufacturing technology that increase the maximum operating pressure rating of cryogenic heat exchangers [6]. Elevated-pressure ASUs are typically favored for systems that supply the ASU with air extracted from the gas turbine compressor. An elevated inlet pressure causes higher suction pressures for the pumps and compressors that boost oxygen and nitrogen products to their final delivery pressures, reducing

power consumption. Another important benefit of operating at elevated pressure is that more compact equipment can be used, reducing the capital cost of the ASU.

1.1.2 Non-cryogenic air separation technologies

Non-cryogenic processes can be classified into four different subcategories [2]:

- Adsorption processes: these processes are based on the property of some natural and synthetic materials to differentially adsorb gases. Pressurized air enters a vessel containing the adsorbent (usually zeolites [8]). Nitrogen is adsorbed and an oxygen-rich effluent stream is produced. When the bed has been saturated with nitrogen, the feed air is switched to a fresh vessel and regeneration of the first bed is accomplished by heating the bed (TSA - Temperature Swing Adsorption) or by reducing its pressure (PSA - Pressure Swing Adsorption and VPSA – Vacuum Pressure Swing Adsorption). Oxygen purity is typically 93–95 % v/v [2].
- Ion transport membrane: membrane based air separation technology separates oxygen from air by transporting oxygen ions across a nonporous ceramic membrane (high oxygen ion conductivity has been found in particular in fluorite and related types, perovskite and related types and Aurivillius type phases [9]). The membrane operates at high temperature (800–900 °C). Pure oxygen emerges from the membrane at a very low pressure and can be removed by a stream of purge gas (usually steam) or by compressors [6]. Unlike cryogenic processes, which routinely recover nearly 100% of the oxygen from the feed air stream [7], ion transport membrane ASUs assure a much lower oxygen recovery rate (10 % to 75 % [6]). Therefore, ion transport membrane ASUs require a much larger volume of feed air compared to cryogenic ASUs and this makes the integration with gas turbine more complicated. These technologies can achieve a theoretical value of oxygen purity of 100 %, but the presence of leakage in the plant reduces this value to 95 % [6].
- Chemical processes: these processes are based on the capability of liquids to absorb oxygen at one set of pressure and temperature conditions, and desorb the oxygen at a different set of conditions. An application with molten salt can be found in [10] and allows the achievement of 99.9 % oxygen purity [2];
- Polymeric membrane processes: these processes are based on the difference in rates of diffusion of oxygen and nitrogen through a polymeric membrane which separates high-pressure and low-pressure streams. They are usually limited to the production of oxygen enriched air (25–50% oxygen) [2].

1.2 Problem statement and aim of this paper

In this paper, a system for power augmentation in IGCC plants is evaluated through a thermodynamic model. The system consists of the liquefaction of the nitrogen stream which is usually discharged by the ASU by using an electric chiller. The liquefied nitrogen can be stored and then sprayed into the inlet duct of the gas turbine (in a similar way as for industrial fast freezing and chilling) when the remuneration of the produced electrical energy is higher.

This system does not present the drawbacks which characterize state-of-the-art cooling technologies: (i) the cooling temperature is not limited to the wet bulb temperature as for evaporative cooling and (ii) no pressure losses are generated at the compressor inlet, as for the heat exchanger in refrigeration cooling. Moreover, unlike current thermal storage systems, it does not require a large amount of water.

A thermodynamic model of the system is built by using a commercial code to perform a technical analysis. In order to assess the energy and economic feasibility of the proposed system, real temperature profiles of different sites for a whole year have been imposed on the model and the results of the proposed system are compared to traditional inlet air cooling strategies.

2. PLANT OVERALL ANALYSIS

Many studies dealing with the thermodynamic analysis of IGCC power plants by means of computational models are reported in literature [11, 12]. A simulation model of an IGCC power plant was developed by using Thermoflex [13]. Thermoflex is a flexible program for design and off-design steady-state simulation of thermal systems with a strong emphasis on combined cycle and conventional steam plants. For its extensive library of components it is widely used in literature for thermal system analysis [14,15].

The considered gas turbine is a Mitsubishi 701 F (rated power equal to 271.69 MW, rated LHV efficiency equal to 38.4 %) and the steam section is characterized by three pressure levels at 124.0 bar, 23.6 bar and 2.4 bar. The same performances are considered for operation in both 50 Hz and 60 Hz areas. A condensation pressure of 0.05 bar is imposed at design conditions. The cooling water (of which the temperature increases by 10 °C through the condenser) is cooled in a cooling tower with a pinch point temperature difference equal to 5 °C with respect to the dew point temperature.

The considered gasifier technology is Texaco (General Electric), which is an entrained flow gasifier fed by coal. For gas clean up, no gas shift is considered and therefore there is no CO_2 removal. The ASU working pressure is assumed equal to 5 bar.

In order to implement the power augmentation system it has to take into consideration that:

- the ASU is designed in order to allow the production of a stream of 100 kg/s of high pressure (10 bar) nitrogen. This does not significantly increase the size of the ASU with respect to a traditional design, since this stream is mostly recuperated from the gases usually discharged by the ASU (e.g. 85 kg/s, as reported in [6] for a similar plant) when the only products are (i) a stream of oxygen sent to the gasifier and (ii) a small amount of nitrogen for NOx control;

- an electric chiller is added in order to liquefy the high pressure nitrogen. A COP equal to 0.4 is imposed by considering the cold source (i.e. -170 °C) and hot sink (i.e. ambient conditions) temperature and an exergy efficiency of about 65 % [16]. In order to correctly calculate the thermodynamic properties of the nitrogen stream during liquefaction, the "gas stream" is converted into a "refrigerant stream" [13], so that the NIST database [17] can be used for calculation;
- a mixer is added to the gas turbine inlet in order to allow the ambient air to be mixed with the nitrogen when the cooling system is switched on.

The results of the characterization of the simulation model at ISO conditions are reported in Table 1 in terms of plant main energy features and in Fig. 1 in terms of main component interactions through gaseous streams. In this case the nitrogen is liquefied by the electric chiller and then stored. Inlet air cooling can be performed by using the stored nitrogen, as shown in Fig. 2.

2.1 Plant overall performance

Plant performance maps for (i) IGCC normal operation, (ii) liquid nitrogen production and storage and (iii) inlet air cooling with stored liquid nitrogen to 15 °C are built. Three properties are mapped as a function of the ambient temperature and relative humidity: (i) plant net power output, (ii) plant coal requirement and (iii) liquid nitrogen consumption for inlet air cooling.

2.2 Effect of ambient temperature and relative humidity on the plant performance

Figure 3 reports the net power output. It shows the behavior of the IGCC during normal operation (black lines): it can be noticed that the net power output decreases as the ambient temperature and ambient relative humidity increase. This is due to the fact that (i) the gas turbine suffers a derating when the ambient temperature increases due to the reduction in the inlet mass flow rate, and (ii) the increase in ambient temperature and relative humidity causes an increase in the ambient dew point temperature and, therefore, in the cooling water at the condenser inlet, causing an increase in condensation pressure and a reduction in the specific work of the steam section.

Figure 3 also shows the effect of the production and storage of liquid nitrogen (blue lines). It can be highlighted that the production of 100 kg/s of liquid nitrogen causes a reduction of about 120 MW for the whole investigated range.

Finally, Fig. 3 shows the effect of the air cooling to 15 °C (red lines). It can be seen that there is a clear effect of power augmentation, and the power output is almost constant when the air cooling system is turned on. A reduction in the power can be seen for high temperature and high humidity. This is due to the fact that the system cannot reach the target temperature since the imposed maximum nitrogen mass flow rate (i.e. 100 kg/s, see Fig. 4) is not enough to reduce air temperature and condense all the water vapor in the humid air.

This aspect will be further analyzed in paragraphs 2.3 and 2.4 focusing on the inlet air properties change and on gas turbine behavior.

The maps of the coal requirements are trivial and are not presented in this paper. In fact, since the nitrogen production and its use for air cooling do not affect the gas turbine efficiency, the coal requirements are proportional to the gas turbine power which decreases as the ambient temperature increases. The only effect on the gas turbine efficiency is when liquid water is present at the compressor inlet: in this case the coal specific consumption slightly decreases.

2.3 Effect of spraying liquid nitrogen at compressor inlet

The effect of the liquid nitrogen injection on the inlet air properties is analyzed in this paragraph. Simulations are carried out by varying the liquid nitrogen mass flow rate for a given ambient condition (i.e. ambient temperature equal to 45°C, ambient pressure equal to 1.013 bar and ambient relative humidity equal to 60 %). Figure 5 shows the results of the simulation in terms of oxygen molar fraction of the ambient air, of the gas turbine inlet air (i.e. downstream of the nitrogen injection) and of the gas turbine exhaust gas. It can be highlighted that the air composition changes, though not considerably, after nitrogen injection. The oxygen content seems always high enough to allow a regular combustion. Local effects will be further investigated in [18].

Figure 6 shows the effect of the nitrogen injection on the gas turbine inlet temperature. The trend is not linear in the whole investigated range of nitrogen mass flow rate. This is due to the fact that when the temperature decreases under the dew point temperature part of the liquid nitrogen is used for water condensation. For this reason, the rate of temperature reduction decreases after this temperature.

Figures 7 and 8 show the effect of the change in composition and temperature of the inlet air on gas turbine inlet mass flow rate and compressor pressure ratio. The overall effect consists of a move towards higher mass flow rate and higher pressure ratio of the operating point. This behavior is consistent with a reduction of the inlet temperature.

2.4 Effect of water condensation at compressor inlet

As stated above, when warm humid air is cooled by spraying liquid nitrogen, the air can saturate by forming liquid water. This fine dispersed fog enters the gas turbine and contributes to a further gas turbine power augmentation as wet compression or overspray [19,20]. The model takes this possibility into consideration.

Figure 9 shows the behavior of the gas turbine in the case of air cooling as a function of the ambient temperature and the relative humidity.

It can be highlighted that formation of liquid water increases the power output of the gas turbine for a given cooling level when the relative humidity is high. The curves at each different humidity diverge. When the water content in the air is high enough to prevent the achievement of the target inlet air temperature with the imposed maximum liquid nitrogen mass flow rate (i.e. 100 kg/s), the gas turbine power decreases by increasing the ambient temperature as the gas turbine inlet air increases.

3. ENERGY AND ECONOMIC ANALYSIS

3.1 IGCC plant site characteristics

Four different sites (Darwin, Australia; Dubai, UAE; Ferrara, Italy; Johannesburg, South Africa) have been chosen in order to evaluate the performance of the cooling system in different climatic conditions.

The model presented in [21] is used to calculate the ambient temperature on an hourly basis by starting from (i) the maximum temperature of the considered day, (ii) the minimum temperature of the considered day and the following day and (iii) sunrise and sunset. According to literature, the water content in the air can be considered constant during the day [22,23]. Climatic data are collected from [24] while sunrise and sunset are calculated by starting from the city coordinates with a standard astronomic algorithm.

Figure 10 reports the profiles of the dew point temperature for the four locations. Dew point temperature can be considered as an index of the limit temperature for evaporative cooling. For some localities (Darwin and Dubai), the dew point temperature in summer time is always higher than 15 °C (black dotted line), and, therefore, evaporative cooling cannot provide suitable power augmentation.

The results of the elaboration are shown in Figs. 11-14 in terms of distributions. Darwin and Dubai are the hottest localities. Darwin is characterized by a higher level of humidity than Dubai. Johannesburg and Ferrara are the coldest sites.

3.2 IGCC plant operating mode

It is assumed that the plant is operated as follows:

- base mode (IGCC): this is the IGCC normal operation without liquid nitrogen production and without inlet air cooling;
- thermal energy storage and air cooling to 15 °C (NC): during peak hours the inlet air is cooled to 15 °C by using the liquid nitrogen stored during off peak hours. The maximum consumption of nitrogen for cooling is equal to 100 kg/s. The production rate, on the other hand, is established at 100 kg/s and the number of hours of production is calculated by guaranteeing the amount of nitrogen necessary for cooling during the successive peak hour period.

Moreover, traditional power augmentation technologies such as traditional evaporative cooling (TEC), high pressure fogging (HPF), overspray (OS) and continuous compression cooling (CCC) [25] are also considered in order to evaluate the proposed system.

3.3 Economic assumptions

In order to draw some economic considerations about the profitability of the system, it is assumed that:

- peak hours run from 8 a.m. to 7 p.m. Monday to Friday;
- the value of electrical energy during peak hours is 100 €/MWh, while during off peak hours it is 50 €/MWh;
- the price of coal is equal to 100 €/t;
- extra costs for maintenance are not considered.

3.4 Results

The maps presented in section 2.2 are used in order to calculate the performance (net power output, coal consumption and liquid nitrogen requirements) of the plant in the four different locations for an entire year.

The overall results are summarized in Tab. 2 in terms of the net electrical energy produced. It can be noticed that the power augmentation strategy proposed leads to an increase in the total electrical energy produced, while the off peak production decreases.

The higher increase is achieved in the locations characterized by the higher temperature and the longer hot period (e.g. Darwin and Dubai).

Table 3 reports the annual consumption of coal and the annual average plant efficiency. It can be noted that the increase in electrical energy production is obtained through higher coal consumption, with the annual average efficiency decreasing. However, the efficiency calculated for the peak hours remains almost constant.

Figures 15 shows the annual hourly profile of the difference between (i) the power when the production of liquid nitrogen at night and its use during peak hours for inlet air cooling to 15 °C is considered and (ii) the power for IGCC normal operation in the location where the highest increase in peak hour electricity production is achieved, i.e. Dubai. IGCC normal operation leads the power profile to follow the ambient condition variation: the maximum power is achieved in the winter period during the night, while the minimum is in the summer period during the day (i.e. when the electrical energy demand and price are higher).

By considering the case of production of liquid nitrogen at night and its use during peak hours for inlet air cooling, it can be seen that the production during peak hours increases: the magnitude of this augmentation is obviously higher in summer period than in winter period. The main effect is that the net power is kept almost constant by air cooling. During off peak hours a reduction in the net power can be noted: nitrogen production lasts for a longer period during the summer, while the production hours decrease during the winter.

Table 4 shows the cash flows of the base case and the cash flow variation when the power augmentation strategies are considered. In the case of the proposed inlet air cooling strategy NC, negative differences can be highlighted for all four locations. The lowest value is achieved in Darwin and is equal to -4.5 M€. Higher differential cash flows can be obtained when residues of the petroleum refinery process (e.g. visbreaking tar, etc.) are of concern instead of coal. In this case, the cooling system provides a higher annual capability of the IGCC to exploit the residues. The performance of the proposed inlet air cooling system is not comparable with traditional power augmentation technologies such as TEC, HPF, CCC and OS (which outperforms all the others).

3.5 Sensitivity analysis

A sensitivity analysis of the profitability of the system has been carried out. The differential cash flow for the four location has been calculated by varying (i) the ratio between the price of the electrical energy during peak hours and the price of coal and (ii) the ratio between the prices of electrical energy during peak hours and during off peak hours. The results are reported in Fig. 16 as contour lines. A red circle represents the assumptions reported in paragraph 3.3 (i.e. the worth of the electrical energy in peak hours equal to 100 €/MWh, the worth of the electrical energy in off peak hours equal to 50 €/MWh and coal price equal to 100 €/t): from this point moving towards higher y-axis values means a decrease in coal price (down to 33 €/t) while moving towards higher x-axis values means a decrease in electrical energy off peak worth (down to 33 €/t). Nevertheless, the reorganization of the three economic parameters as mutual ratios allows the generalization of the results by unlinking them from the base case assumptions.

It can be highlighted that by increasing both the ratio between the prices of electrical energy during peak and of peak hours and the ratio between the electrical energy price during peak hours and the coal price the differential cash flow increases and reaches positive values. The hotter the locality, the faster the transition towards positive values.

4. CONCLUSIONS

In this paper, a system for power augmentation of integrated gasification combined cycle (IGCC) plants has been evaluated. The system consists of the liquefaction by means of an electric chiller of the nitrogen stream which is usually discharged by the air separation unit when the oxygen for the gasification process is produced.

The system is studied by means of a thermodynamic model of an IGCC developed in a commercial code. The model is applied to a whole year on an hourly basis for four different locations with different temperature and humidity profiles.

The system did not prove to be profitable, but, since it uses low remunerated energy during the night to produce high remunerated energy during the day an increase of the ratio between the prices of electrical energy during peak and off peak hours can make the system profitable. Obviously this is most advantageous in locations with higher temperatures and longer hot periods. The humidity increases the amount of liquid nitrogen needed to achieve the target inlet temperature (this even prevents the target temperature being reached at high ambient temperature and high humidity). The condensation of the water content in the air can form a fine dispersed fog which enters into the gas turbine and operates as wet compression for further power augmentation.

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The authors wish to dedicate this paper to Prof. Roberto Bettocchi, who was one of the pioneers of the study of combined cycle power plants.

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Table Captions

Table 1 Plant energy features

Table 2 Annual electrical energy produced

Table 3 Annual coal needs and average overall efficiency

Table 4 Economic results

Figure Captions

Figure 1 Plant component interaction during off-peak operation (nitrogen production and storage)

Figure 2 Plant component interaction during peak operation (inlet air cooling by means of stored nitrogen)

Figure 3 Plant net power as a function of ambient temperature and relative humidity

Figure 4 Nitrogen mass flow rate for air cooling as a function of ambient temperature and relative humidity

Figure 5 Effect of nitrogen injection on inlet air and exhaust gas composition

Figure 6 Effect of nitrogen injection on inlet air temperature

Figure 7 Effect of nitrogen injection on inlet air mass flow rate

Figure 8 Effect of nitrogen injection on compressor pressure ratio

Figure 9 Gas turbine net power as a function of ambient temperature and relative humidity for air cooling to 15 °C

Figure 10 Dew point temperature profiles

Figure 11 Climatic data for Darwin (Australia)

Figure 12 Climatic data for Dubai (UAE)

Figure 13 Climatic data for Ferrara (Italy)

Figure 14 Climatic data for Johannesburg (South Africa)

Figure 15 Differential plant net power output profile in Dubai

Figure 16 Sensitivity analysis

Table 1 Plant energy features

Net fuel input	[kW]	844101
Coal mass flow	[kg/s]	39.6
Gross power	[kW]	409252
Gas turbine shaft	[kW]	234036
HP Steam turbine shaft	[kW]	44119
MP Steam turbine shaft	[kW]	68809
LP Steam turbine shaft	[kW]	67446
Total auxiliaries	[kW]	186318
ASU	[kW]	39848
Electric chiller	[kW]	127978
Gas clean up	[kW]	4833
Gasifier	[kW]	3142
Cooling tower	[kW]	2174
Net power	[kW]	222933
Gross electric efficiency (LHV basis)	[%]	48.5
Net electric efficiency (LHV basis)	[%]	26.4

Table 2 Annual electrical energy produced

	Electrical energy [TWh/yr]					
	Peak	Off Peak	Tot.	Peak	Off Peak	Tot.
	IGCC			NC		
Darwin	0.99	2.08	3.07	1.08	1.87	2.95
Dubai	0.97	2.05	3.02	1.07	1.85	2.92
Ferrara	1.07	2.25	3.31	1.10	2.16	3.26
Johannesburg	1.05	2.24	3.29	1.08	2.17	3.25

Table 3 Annual coal needs and average overall efficiency

	Coal	Efficiency [%]			Coal	Efficiency [%]		
	[Mt/yr]	Peak	Off Peak	Tot.	[Mt/yr]	Peak	Off Peak	Tot.
	IGCC				NC			
Darwin	1.19	41.3	41.5	41.5	1.23	41.3	37.4	38.7
Dubai	1.17	41.4	41.5	41.5	1.21	41.4	37.7	39.0
Ferrara	1.27	42.1	42.2	42.2	1.28	42.0	40.6	41.1
Johannesburg	1.26	42.1	42.3	42.2	1.27	42.1	41.0	41.3

Table 4 Economic results

	IGCC	NC	TEC	HPF	OS	CCC
	Cash Flow [M€/yr]	Diff. [M€/yr]	Diff. [M€/yr]	Diff. [M€/yr]	Diff. [M€/yr]	Diff. [M€/yr]
Darwin	83.3	-4.5	2.8	3.2	9.9	3.3
Dubai	82.1	-3.1	1.6	1.9	2.7	3.1
Ferrara	92.4	-2.2	0.5	0.7	4.8	0.6
Johannesburg	91.6	-1.6	0.8	1.1	7.0	0.5

FEASIBILITY ANALYSIS OF GAS TURBINE INLET AIR COOLING BY MEANS OF LIQUID NITROGEN EVAPORATION FOR IGCC POWER AUGMENTATION

Mirko Morini[1]

Dipartimento di Ingegneria Industriale, Università degli Studi di Parma, Parma, Italy

Michele Pinelli, Pier Ruggero Spina, Anna Vaccari, Mauro Venturini

Dipartimento di Ingegneria, Università degli Studi di Ferrara, Ferrara, Italy

ABSTRACT

Integrated Gasification Combined Cycles (IGCC) are energy systems mainly composed of a gasifier and a combined cycle power plant. Since the gasification process usually requires oxygen as the oxidant, an Air Separation Unit (ASU) is also part of the plant.

In this paper, a system for power augmentation in IGCC is evaluated. The system is based on gas turbine inlet air cooling by means of liquid nitrogen spray. In fact, nitrogen is a product of the ASU, but is not always exploited. In the proposed plant, the nitrogen is first liquefied to be used for inlet air cooling or stored for later use. This system is not characterized by the limits of water evaporative cooling systems (the lower temperature is limited by air saturation) and refrigeration cooling (the effectiveness is limited by the pressure drop in the heat exchanger).

A thermodynamic model of the system is built by using a commercial code for energy conversion system simulation. A sensitivity analysis on the main parameters is presented. Finally the model is used to study the capabilities of the system by imposing the real temperature profiles of different sites for a whole year and by comparing to traditional inlet air cooling strategies.

Keywords: IGCC, power augmentation, syngas

NOMENCLATURE

Symbols

p	price

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[1] corresponding author, mirko.morini@unipr.it, +39 0521905714

Abbreviations

ASU	air separation unit
CCC	continuous compression cooling
COP	coefficient of performance
EC	electric chiller
G	gasifier
GC	gas cleaning system
GT	gas turbine
HPF	high pressure fogging
IACS	inlet air cooling system
IGCC	integrated gasification combined cycle
ISO	International Organization for Standardization
NC	air cooling by means of nitrogen
OS	overspray
RH	relative humidity
SS	steam section
ST	storage tank
TEC	traditional evaporative cooling

Subscripts

coal	coal
el	electrical energy
op	off peak hours
p	peak hours

1. INTRODUCTION

IGCC technology uses solid and/or liquid fuels – typically coal, petroleum coke, petroleum residue, biomass or a blend of these fuels – in a power plant that leverages the environmental benefits and thermal performance of a gas-fired combined cycle. In an IGCC gasifier, a solid or liquid feed is partially oxidized with air or high-purity oxygen. The resulting hot, raw “syngas” – an abbreviation for synthesis gas – consists of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen gas (H_2), water (H_2O), methane (CH_4), hydrogen sulphide (H_2S) and other sulphur compounds, nitrogen gas (N_2) and argon (Ar). After it is cooled and cleaned of particulate matter and sulphur species, the syngas is fired in a combustion turbine. The hot exhaust from the gas turbine passes to a heat recovery steam generator where it produces steam that drives a steam turbine.

The use of a gas turbine/steam turbine combined cycle helps gasification-based power systems achieve competitive power generation efficiencies, despite energy losses during fuel conversion in the gasification system and in the air separation unit (ASU) in oxygen-blown systems.

The perspectives for IGCC technological progress can be (i) the increase of cycle efficiency (through the increase of maximum allowable turbine inlet temperature) and (ii) the search for new methods to reduce power requirements associated with oxygen production (e.g. through a more advanced level of integration among IGCC main components). It was observed that, to optimize the operation and performance of IGCC power plants, the highest possible level of integration among processes and components is required. Different strategies can be adopted, as for instance, (i) the use of byproduct nitrogen from ASU in gas turbine combustor, (ii) the supply of compressed air extracted from the gas turbine to the ASU or to the gasifier, (iii) the firing of the syngas with pure oxygen and (iv) the integration of the IGCC plant with other energy systems (e.g. fuel cells or organic Rankine cycles).

Moreover, it was highlighted in literature that at present the cryogenic air separation unit is the Achille's heel of IGCC plants, since it parasitizes some percentage points of the gross power produced by the gas-steam combined cycle [1].

1.1 Air separation technologies

Dry air is a mixture of nitrogen (78 % v/v), oxygen (21 % v/v) and argon (1 % v/v), which together constitute the main gases of the atmosphere. The remaining gases are carbon dioxide, methane, nitrous oxide and ozone. Water vapor at sea level can be estimated as 1 % to 4 % of dry air. Different technologies were developed in the past in order to separate the different gases which air is composed of. A comprehensive review is presented in [2]. These technologies can be grouped in two categories: cryogenic and non-cryogenic processes. Cryogenic distillation seems to be the only commercially available technology today to produce large quantities of oxygen economically and at high purity [3]. Within the non-cryogenic processes, ion transport membranes integration with gas turbine is more complicated due to request of a much larger volume of feed air compared to cryogenic ASUs. Nevertheless, ion transport membranes are foreseen as the best candidate for high tonnage oxygen production [4,5], since they are associated with significantly lower power consumption than cryogenic processes.

1.1.1 Cryogenic air separation technologies

Cryogenic air separation is currently the most efficient and cost-effective technology for producing large quantities of oxygen, nitrogen and argon as gaseous or liquid products [2]. This characteristic makes the cryogenic process more suitable than the others for the supply of oxygen to the gasifier in IGCC power plants.

An air separation unit is usually composed of a multi-column cryogenic distillation process and produces high-purity oxygen from compressed air (up to 99 % v/v [6,7]).

Cryogenic technology can also produce high-purity nitrogen as a useful byproduct stream at a relatively low incremental cost [2]. Moreover, a liquefaction section can be added in order to produce liquid oxygen or nitrogen and store them at low incremental capital and power costs [2].

Most of the facilities use traditional electric motor-driven equipment to compress the feeding air, as well as the oxygen and other product streams. Cryogenic ASUs operating in the framework of IGCC facilities usually receive the feeding air by an air bleeding from the gas turbine compressor.

Downstream of the air compression and aftercooling, the process provides an air pre-treatment section which removes contaminants, such as water, carbon dioxide and hydrocarbons. The air is then cooled to cryogenic temperatures and distilled into oxygen, nitrogen, and, optionally, argon gaseous streams. These products cool down the incoming air in order to reduce the energy needed for refrigeration.

The characterization of the types of cryogenic processes used for air separation can be based on the method of pressurizing the product streams or on the air feed pressure to the ASU [2,6]:

- Low-Pressure Cryogenic ASU. Conventional cryogenic ASUs operate at low pressure, meaning that the feed air is compressed just enough to allow the nitrogen by-product to be discharged at atmospheric pressure. Depending on the oxygen purity specification and the extent of efficiency optimization, absolute air feed pressures to low-pressure cryogenic ASUs are typically 4.4 bar to 7.2 bar [6]. Product streams typically leave the ASU in gaseous form near ambient temperature and pressure. If liquid products are desired, additional refrigeration is required.
- Elevated-Pressure Cryogenic ASU. These cryogenic plants operate at much higher pressures (close to discharge pressures of gas turbine compressors) than the Low-Pressure Cryogenic ASU due to improvements in manufacturing technology that increase the maximum operating pressure rating of cryogenic heat exchangers [6]. Elevated-pressure ASUs are typically favored for systems that supply the ASU with air extracted from the gas turbine compressor. An elevated inlet pressure causes higher suction pressures for the pumps and compressors that boost oxygen and nitrogen products to their final delivery pressures, reducing

power consumption. Another important benefit of operating at elevated pressure is that more compact equipment can be used, reducing the capital cost of the ASU.

1.1.2 Non-cryogenic air separation technologies

Non-cryogenic processes can be classified into four different subcategories [2]:

- Adsorption processes: these processes are based on the property of some natural and synthetic materials to differentially adsorb gases. Pressurized air enters a vessel containing the adsorbent (usually zeolites [8]). Nitrogen is adsorbed and an oxygen-rich effluent stream is produced. When the bed has been saturated with nitrogen, the feed air is switched to a fresh vessel and regeneration of the first bed is accomplished by heating the bed (TSA - Temperature Swing Adsorption) or by reducing its pressure (PSA - Pressure Swing Adsorption and VPSA – Vacuum Pressure Swing Adsorption). Oxygen purity is typically 93–95 % v/v [2].
- Ion transport membrane: membrane based air separation technology separates oxygen from air by transporting oxygen ions across a nonporous ceramic membrane (high oxygen ion conductivity has been found in particular in fluorite and related types, perovskite and related types and Aurivillius type phases [9]). The membrane operates at high temperature (800–900 °C). Pure oxygen emerges from the membrane at a very low pressure and can be removed by a stream of purge gas (usually steam) or by compressors [6]. Unlike cryogenic processes, which routinely recover nearly 100% of the oxygen from the feed air stream [7], ion transport membrane ASUs assure a much lower oxygen recovery rate (10 % to 75 % [6]). Therefore, ion transport membrane ASUs require a much larger volume of feed air compared to cryogenic ASUs and this makes the integration with gas turbine more complicated. These technologies can achieve a theoretical value of oxygen purity of 100 %, but the presence of leakage in the plant reduces this value to 95 % [6].
- Chemical processes: these processes are based on the capability of liquids to absorb oxygen at one set of pressure and temperature conditions, and desorb the oxygen at a different set of conditions. An application with molten salt can be found in [10] and allows the achievement of 99.9 % oxygen purity [2];
- Polymeric membrane processes: these processes are based on the difference in rates of diffusion of oxygen and nitrogen through a polymeric membrane which separates high-pressure and low-pressure streams. They are usually limited to the production of oxygen enriched air (25–50% oxygen) [2].

1.2 Problem statement and aim of this paper

In this paper, a system for power augmentation in IGCC plants is evaluated through a thermodynamic model. The system consists of the liquefaction of the nitrogen stream which is usually discharged by the ASU by using an electric chiller. The liquefied nitrogen can be stored and then sprayed into the inlet duct of the gas turbine (in a similar way as for industrial fast freezing and chilling) when the remuneration of the produced electrical energy is higher.

This system does not present the drawbacks which characterize state-of-the-art cooling technologies: (i) the cooling temperature is not limited to the wet bulb temperature as for evaporative cooling and (ii) no pressure losses are generated at the compressor inlet, as for the heat exchanger in refrigeration cooling. Moreover, unlike current thermal storage systems, it does not require a large amount of water.

A thermodynamic model of the system is built by using a commercial code to perform a technical analysis. In order to assess the energy and economic feasibility of the proposed system, real temperature profiles of different sites for a whole year have been imposed on the model and the results of the proposed system are compared to traditional inlet air cooling strategies.

2. PLANT OVERALL ANALYSIS

Many studies dealing with the thermodynamic analysis of IGCC power plants by means of computational models are reported in literature [11, 12]. A simulation model of an IGCC power plant was developed by using Thermoflex [13]. Thermoflex is a flexible program for design and off-design steady-state simulation of thermal systems with a strong emphasis on combined cycle and conventional steam plants. For its extensive library of components it is widely used in literature for thermal system analysis [14,15].

The considered gas turbine is a Mitsubishi 701 F (rated power equal to 271.69 MW, rated LHV efficiency equal to 38.4 %) and the steam section is characterized by three pressure levels at 124.0 bar, 23.6 bar and 2.4 bar. The same performances are considered for operation in both 50 Hz and 60 Hz areas. A condensation pressure of 0.05 bar is imposed at design conditions. The cooling water (of which the temperature increases by 10 °C through the condenser) is cooled in a cooling tower with a pinch point temperature difference equal to 5 °C with respect to the dew point temperature.

The considered gasifier technology is Texaco (General Electric), which is an entrained flow gasifier fed by coal. For gas clean up, no gas shift is considered and therefore there is no CO_2 removal. The ASU working pressure is assumed equal to 5 bar.

In order to implement the power augmentation system it has to take into consideration that:

- the ASU is designed in order to allow the production of a stream of 100 kg/s of high pressure (10 bar) nitrogen. This does not significantly increase the size of the ASU with respect to a traditional design, since this stream is mostly recuperated from the gases usually discharged by the ASU (e.g. 85 kg/s, as reported in [6] for a similar plant) when the only products are (i) a stream of oxygen sent to the gasifier and (ii) a small amount of nitrogen for NOx control;

- an electric chiller is added in order to liquefy the high pressure nitrogen. A COP equal to 0.4 is imposed by considering the cold source (i.e. -170 °C) and hot sink (i.e. ambient conditions) temperature and an exergy efficiency of about 65 % [16]. In order to correctly calculate the thermodynamic properties of the nitrogen stream during liquefaction, the "gas stream" is converted into a "refrigerant stream" [13], so that the NIST database [17] can be used for calculation;
- a mixer is added to the gas turbine inlet in order to allow the ambient air to be mixed with the nitrogen when the cooling system is switched on.

The results of the characterization of the simulation model at ISO conditions are reported in Table 1 in terms of plant main energy features and in Fig. 1 in terms of main component interactions through gaseous streams. In this case the nitrogen is liquefied by the electric chiller and then stored. Inlet air cooling can be performed by using the stored nitrogen, as shown in Fig. 2.

2.1 Plant overall performance

Plant performance maps for (i) IGCC normal operation, (ii) liquid nitrogen production and storage and (iii) inlet air cooling with stored liquid nitrogen to 15 °C are built. Three properties are mapped as a function of the ambient temperature and relative humidity: (i) plant net power output, (ii) plant coal requirement and (iii) liquid nitrogen consumption for inlet air cooling.

2.2 Effect of ambient temperature and relative humidity on the plant performance

Figure 3 reports the net power output. It shows the behavior of the IGCC during normal operation (black lines): it can be noticed that the net power output decreases as the ambient temperature and ambient relative humidity increase. This is due to the fact that (i) the gas turbine suffers a derating when the ambient temperature increases due to the reduction in the inlet mass flow rate, and (ii) the increase in ambient temperature and relative humidity causes an increase in the ambient dew point temperature and, therefore, in the cooling water at the condenser inlet, causing an increase in condensation pressure and a reduction in the specific work of the steam section.

Figure 3 also shows the effect of the production and storage of liquid nitrogen (blue lines). It can be highlighted that the production of 100 kg/s of liquid nitrogen causes a reduction of about 120 MW for the whole investigated range.

Finally, Fig. 3 shows the effect of the air cooling to 15 °C (red lines). It can be seen that there is a clear effect of power augmentation, and the power output is almost constant when the air cooling system is turned on. A reduction in the power can be seen for high temperature and high humidity. This is due to the fact that the system cannot reach the target temperature since the imposed maximum nitrogen mass flow rate (i.e. 100 kg/s, see Fig. 4) is not enough to reduce air temperature and condense all the water vapor in the humid air.

This aspect will be further analyzed in paragraphs 2.3 and 2.4 focusing on the inlet air properties change and on gas turbine behavior.

The maps of the coal requirements are trivial and are not presented in this paper. In fact, since the nitrogen production and its use for air cooling do not affect the gas turbine efficiency, the coal requirements are proportional to the gas turbine power which decreases as the ambient temperature increases. The only effect on the gas turbine efficiency is when liquid water is present at the compressor inlet: in this case the coal specific consumption slightly decreases.

2.3 Effect of spraying liquid nitrogen at compressor inlet

The effect of the liquid nitrogen injection on the inlet air properties is analyzed in this paragraph. Simulations are carried out by varying the liquid nitrogen mass flow rate for a given ambient condition (i.e. ambient temperature equal to 45°C, ambient pressure equal to 1.013 bar and ambient relative humidity equal to 60 %). Figure 5 shows the results of the simulation in terms of oxygen molar fraction of the ambient air, of the gas turbine inlet air (i.e. downstream of the nitrogen injection) and of the gas turbine exhaust gas. It can be highlighted that the air composition changes, though not considerably, after nitrogen injection. The oxygen content seems always high enough to allow a regular combustion. Local effects will be further investigated in [18].

Figure 6 shows the effect of the nitrogen injection on the gas turbine inlet temperature. The trend is not linear in the whole investigated range of nitrogen mass flow rate. This is due to the fact that when the temperature decreases under the dew point temperature part of the liquid nitrogen is used for water condensation. For this reason, the rate of temperature reduction decreases after this temperature.

Figures 7 and 8 show the effect of the change in composition and temperature of the inlet air on gas turbine inlet mass flow rate and compressor pressure ratio. The overall effect consists of a move towards higher mass flow rate and higher pressure ratio of the operating point. This behavior is consistent with a reduction of the inlet temperature.

2.4 Effect of water condensation at compressor inlet

As stated above, when warm humid air is cooled by spraying liquid nitrogen, the air can saturate by forming liquid water. This fine dispersed fog enters the gas turbine and contributes to a further gas turbine power augmentation as wet compression or overspray [19,20]. The model takes this possibility into consideration.

Figure 9 shows the behavior of the gas turbine in the case of air cooling as a function of the ambient temperature and the relative humidity.

It can be highlighted that formation of liquid water increases the power output of the gas turbine for a given cooling level when the relative humidity is high. The curves at each different humidity diverge. When the water content in the air is high enough to prevent the achievement of the target inlet air temperature with the imposed maximum liquid nitrogen mass flow rate (i.e. 100 kg/s), the gas turbine power decreases by increasing the ambient temperature as the gas turbine inlet air increases.

3. ENERGY AND ECONOMIC ANALYSIS

3.1 IGCC plant site characteristics

Four different sites (Darwin, Australia; Dubai, UAE; Ferrara, Italy; Johannesburg, South Africa) have been chosen in order to evaluate the performance of the cooling system in different climatic conditions.

The model presented in [21] is used to calculate the ambient temperature on an hourly basis by starting from (i) the maximum temperature of the considered day, (ii) the minimum temperature of the considered day and the following day and (iii) sunrise and sunset. According to literature, the water content in the air can be considered constant during the day [22,23]. Climatic data are collected from [24] while sunrise and sunset are calculated by starting from the city coordinates with a standard astronomic algorithm.

Figure 10 reports the profiles of the dew point temperature for the four locations. Dew point temperature can be considered as an index of the limit temperature for evaporative cooling. For some localities (Darwin and Dubai), the dew point temperature in summer time is always higher than 15 °C (black dotted line), and, therefore, evaporative cooling cannot provide suitable power augmentation.

The results of the elaboration are shown in Figs. 11-14 in terms of distributions. Darwin and Dubai are the hottest localities. Darwin is characterized by a higher level of humidity than Dubai. Johannesburg and Ferrara are the coldest sites.

3.2 IGCC plant operating mode

It is assumed that the plant is operated as follows:

- base mode (IGCC): this is the IGCC normal operation without liquid nitrogen production and without inlet air cooling;
- thermal energy storage and air cooling to 15 °C (NC): during peak hours the inlet air is cooled to 15 °C by using the liquid nitrogen stored during off peak hours. The maximum consumption of nitrogen for cooling is equal to 100 kg/s. The production rate, on the other hand, is established at 100 kg/s and the number of hours of production is calculated by guaranteeing the amount of nitrogen necessary for cooling during the successive peak hour period.

Moreover, traditional power augmentation technologies such as traditional evaporative cooling (TEC), high pressure fogging (HPF), overspray (OS) and continuous compression cooling (CCC) [25] are also considered in order to evaluate the proposed system.

3.3 Economic assumptions

In order to draw some economic considerations about the profitability of the system, it is assumed that:

- peak hours run from 8 a.m. to 7 p.m. Monday to Friday;
- the value of electrical energy during peak hours is 100 €/MWh, while during off peak hours it is 50 €/MWh;
- the price of coal is equal to 100 €/t;
- extra costs for maintenance are not considered.

3.4 Results

The maps presented in section 2.2 are used in order to calculate the performance (net power output, coal consumption and liquid nitrogen requirements) of the plant in the four different locations for an entire year.

The overall results are summarized in Tab. 2 in terms of the net electrical energy produced. It can be noticed that the power augmentation strategy proposed leads to an increase in the total electrical energy produced, while the off peak production decreases.

The higher increase is achieved in the locations characterized by the higher temperature and the longer hot period (e.g. Darwin and Dubai).

Table 3 reports the annual consumption of coal and the annual average plant efficiency. It can be noted that the increase in electrical energy production is obtained through higher coal consumption, with the annual average efficiency decreasing. However, the efficiency calculated for the peak hours remains almost constant.

Figures 15 shows the annual hourly profile of the difference between (i) the power when the production of liquid nitrogen at night and its use during peak hours for inlet air cooling to 15 °C is considered and (ii) the power for IGCC normal operation in the location where the highest increase in peak hour electricity production is achieved, i.e. Dubai. IGCC normal operation leads the power profile to follow the ambient condition variation: the maximum power is achieved in the winter period during the night, while the minimum is in the summer period during the day (i.e. when the electrical energy demand and price are higher).

By considering the case of production of liquid nitrogen at night and its use during peak hours for inlet air cooling, it can be seen that the production during peak hours increases: the magnitude of this augmentation is obviously higher in summer period than in winter period. The main effect is that the net power is kept almost constant by air cooling. During off peak hours a reduction in the net power can be noted: nitrogen production lasts for a longer period during the summer, while the production hours decrease during the winter.

Table 4 shows the cash flows of the base case and the cash flow variation when the power augmentation strategies are considered. In the case of the proposed inlet air cooling strategy NC, negative differences can be highlighted for all four locations. The lowest value is achieved in Darwin and is equal to -4.5 M€. Higher differential cash flows can be obtained when residues of the petroleum refinery process (e.g. visbreaking tar, etc.) are of concern instead of coal. In this case, the cooling system provides a higher annual capability of the IGCC to exploit the residues. The performance of the proposed inlet air cooling system is not comparable with traditional power augmentation technologies such as TEC, HPF, CCC and OS (which outperforms all the others).

3.5 Sensitivity analysis

A sensitivity analysis of the profitability of the system has been carried out. The differential cash flow for the four location has been calculated by varying (i) the ratio between the price of the electrical energy during peak hours and the price of coal and (ii) the ratio between the prices of electrical energy during peak hours and during off peak hours. The results are reported in Fig. 16 as contour lines. A red circle represents the assumptions reported in paragraph 3.3 (i.e. the worth of the electrical energy in peak hours equal to 100 €/MWh, the worth of the electrical energy in off peak hours equal to 50 €/MWh and coal price equal to 100 €/t): from this point moving towards higher y-axis values means a decrease in coal price (down to 33 €/t) while moving towards higher x-axis values means a decrease in electrical energy off peak worth (down to 33 €/t). Nevertheless, the reorganization of the three economic parameters as mutual ratios allows the generalization of the results by unlinking them from the base case assumptions.

It can be highlighted that by increasing both the ratio between the prices of electrical energy during peak and of peak hours and the ratio between the electrical energy price during peak hours and the coal price the differential cash flow increases and reaches positive values. The hotter the locality, the faster the transition towards positive values.

4. CONCLUSIONS

In this paper, a system for power augmentation of integrated gasification combined cycle (IGCC) plants has been evaluated. The system consists of the liquefaction by means of an electric chiller of the nitrogen stream which is usually discharged by the air separation unit when the oxygen for the gasification process is produced.

The system is studied by means of a thermodynamic model of an IGCC developed in a commercial code. The model is applied to a whole year on an hourly basis for four different locations with different temperature and humidity profiles.

The system did not prove to be profitable, but, since it uses low remunerated energy during the night to produce high remunerated energy during the day an increase of the ratio between the prices of electrical energy during peak and off peak hours can make the system profitable. Obviously this is most advantageous in locations with higher temperatures and longer hot periods. The humidity increases the amount of liquid nitrogen needed to achieve the target inlet temperature (this even prevents the target temperature being reached at high ambient temperature and high humidity). The condensation of the water content in the air can form a fine dispersed fog which enters into the gas turbine and operates as wet compression for further power augmentation.

ACKNOWLEDGEMENTS

The authors wish to dedicate this paper to Prof. Roberto Bettocchi, who was one of the pioneers of the study of combined cycle power plants.

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Table Captions

Table 1 Plant energy features

Table 2 Annual electrical energy produced

Table 3 Annual coal needs and average overall efficiency

Table 4 Economic results

Figure Captions

Figure 1 Plant component interaction during off-peak operation (nitrogen production and storage)

Figure 2 Plant component interaction during peak operation (inlet air cooling by means of stored nitrogen)

Figure 3 Plant net power as a function of ambient temperature and relative humidity

Figure 4 Nitrogen mass flow rate for air cooling as a function of ambient temperature and relative humidity

Figure 5 Effect of nitrogen injection on inlet air and exhaust gas composition

Figure 6 Effect of nitrogen injection on inlet air temperature

Figure 7 Effect of nitrogen injection on inlet air mass flow rate

Figure 8 Effect of nitrogen injection on compressor pressure ratio

Figure 9 Gas turbine net power as a function of ambient temperature and relative humidity for air cooling to 15 °C

Figure 10 Dew point temperature profiles

Figure 11 Climatic data for Darwin (Australia)

Figure 12 Climatic data for Dubai (UAE)

Figure 13 Climatic data for Ferrara (Italy)

Figure 14 Climatic data for Johannesburg (South Africa)

Figure 15 Differential plant net power output profile in Dubai

Figure 16 Sensitivity analysis

Table 1 Plant energy features

Net fuel input	[kW]	844101
Coal mass flow	[kg/s]	39.6
Gross power	[kW]	409252
Gas turbine shaft	[kW]	234036
HP Steam turbine shaft	[kW]	44119
MP Steam turbine shaft	[kW]	68809
LP Steam turbine shaft	[kW]	67446
Total auxiliaries	[kW]	186318
ASU	[kW]	39848
Electric chiller	[kW]	127978
Gas clean up	[kW]	4833
Gasifier	[kW]	3142
Cooling tower	[kW]	2174
Net power	[kW]	222933
Gross electric efficiency (LHV basis)	[%]	48.5
Net electric efficiency (LHV basis)	[%]	26.4

Table 2 Annual electrical energy produced

	Electrical energy [TWh/yr]					
	Peak	Off Peak	Tot.	Peak	Off Peak	Tot.
	IGCC			NC		
Darwin	0.99	2.08	3.07	1.08	1.87	2.95
Dubai	0.97	2.05	3.02	1.07	1.85	2.92
Ferrara	1.07	2.25	3.31	1.10	2.16	3.26
Johannesburg	1.05	2.24	3.29	1.08	2.17	3.25

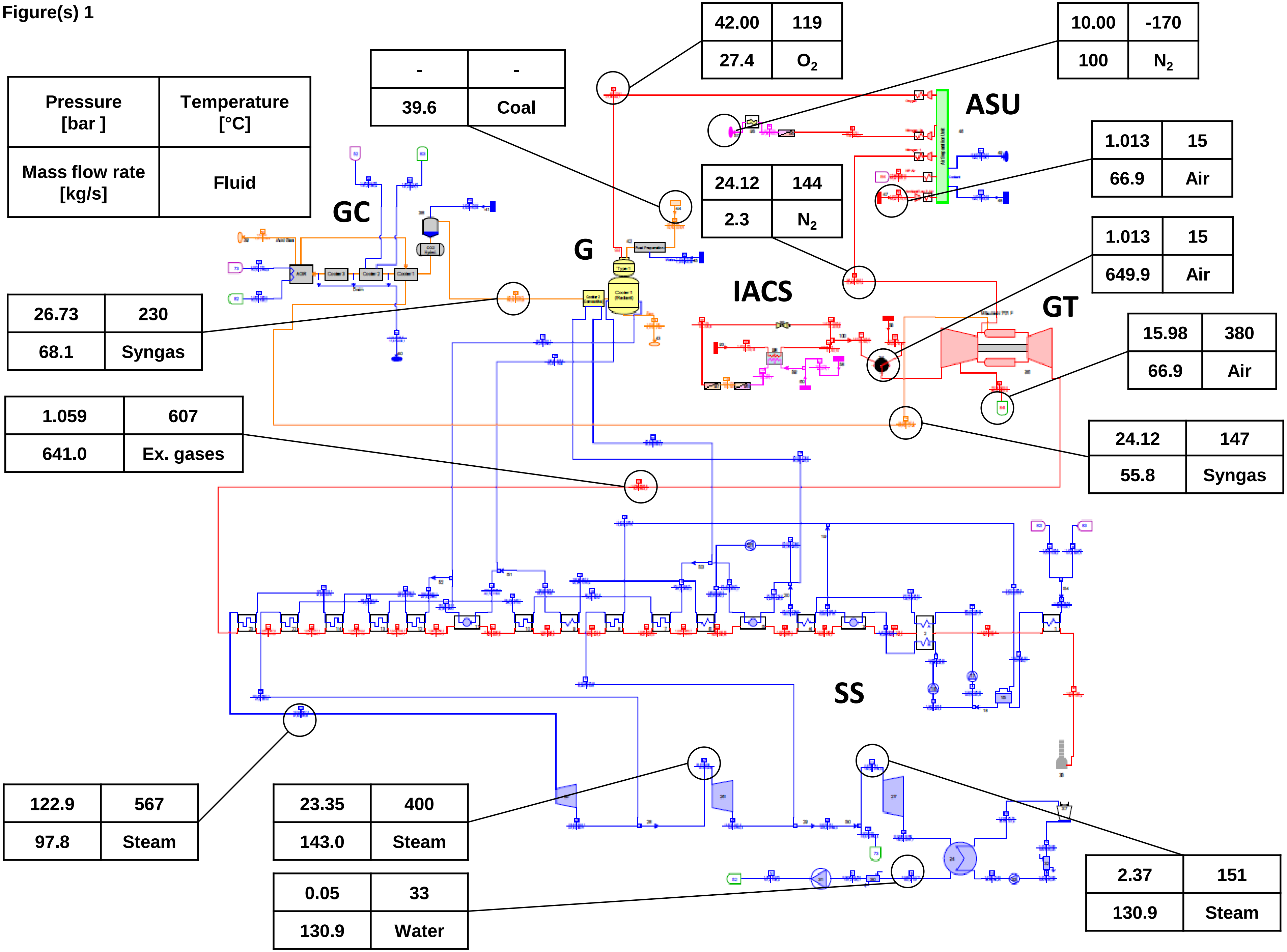
Table 3 Annual coal needs and average overall efficiency

	Coal	Efficiency [%]			Coal	Efficiency [%]		
	[Mt/yr]	Peak	Off Peak	Tot.	[Mt/yr]	Peak	Off Peak	Tot.
	IGCC				NC			
Darwin	1.19	41.3	41.5	41.5	1.23	41.3	37.4	38.7
Dubai	1.17	41.4	41.5	41.5	1.21	41.4	37.7	39.0
Ferrara	1.27	42.1	42.2	42.2	1.28	42.0	40.6	41.1
Johannesburg	1.26	42.1	42.3	42.2	1.27	42.1	41.0	41.3

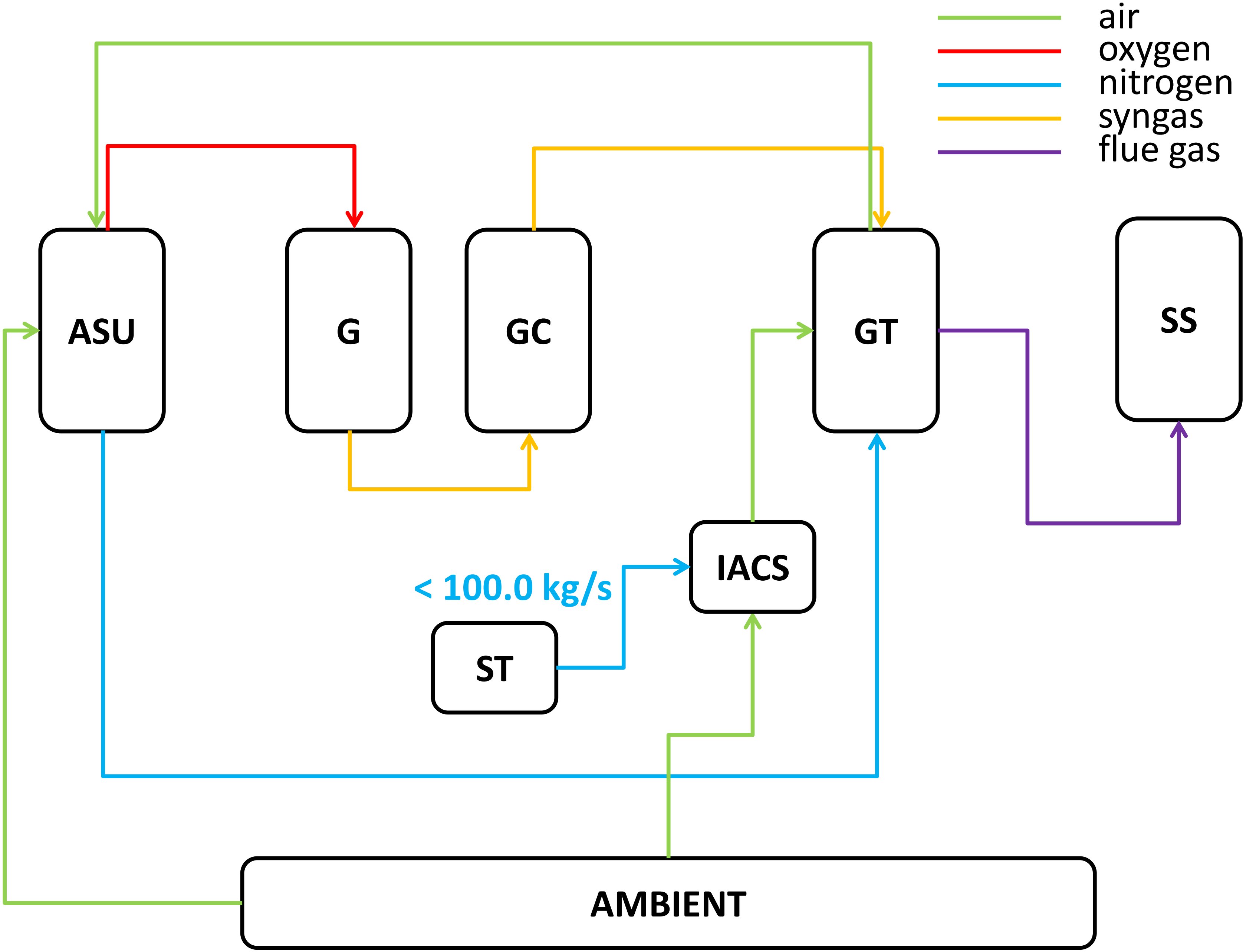
Table 4 Economic results

	IGCC	NC	TEC	HPF	OS	CCC
	Cash Flow [M€/yr]	Diff. [M€/yr]	Diff. [M€/yr]	Diff. [M€/yr]	Diff. [M€/yr]	Diff. [M€/yr]
Darwin	83.3	-4.5	2.8	3.2	9.9	3.3
Dubai	82.1	-3.1	1.6	1.9	2.7	3.1
Ferrara	92.4	-2.2	0.5	0.7	4.8	0.6
Johannesburg	91.6	-1.6	0.8	1.1	7.0	0.5

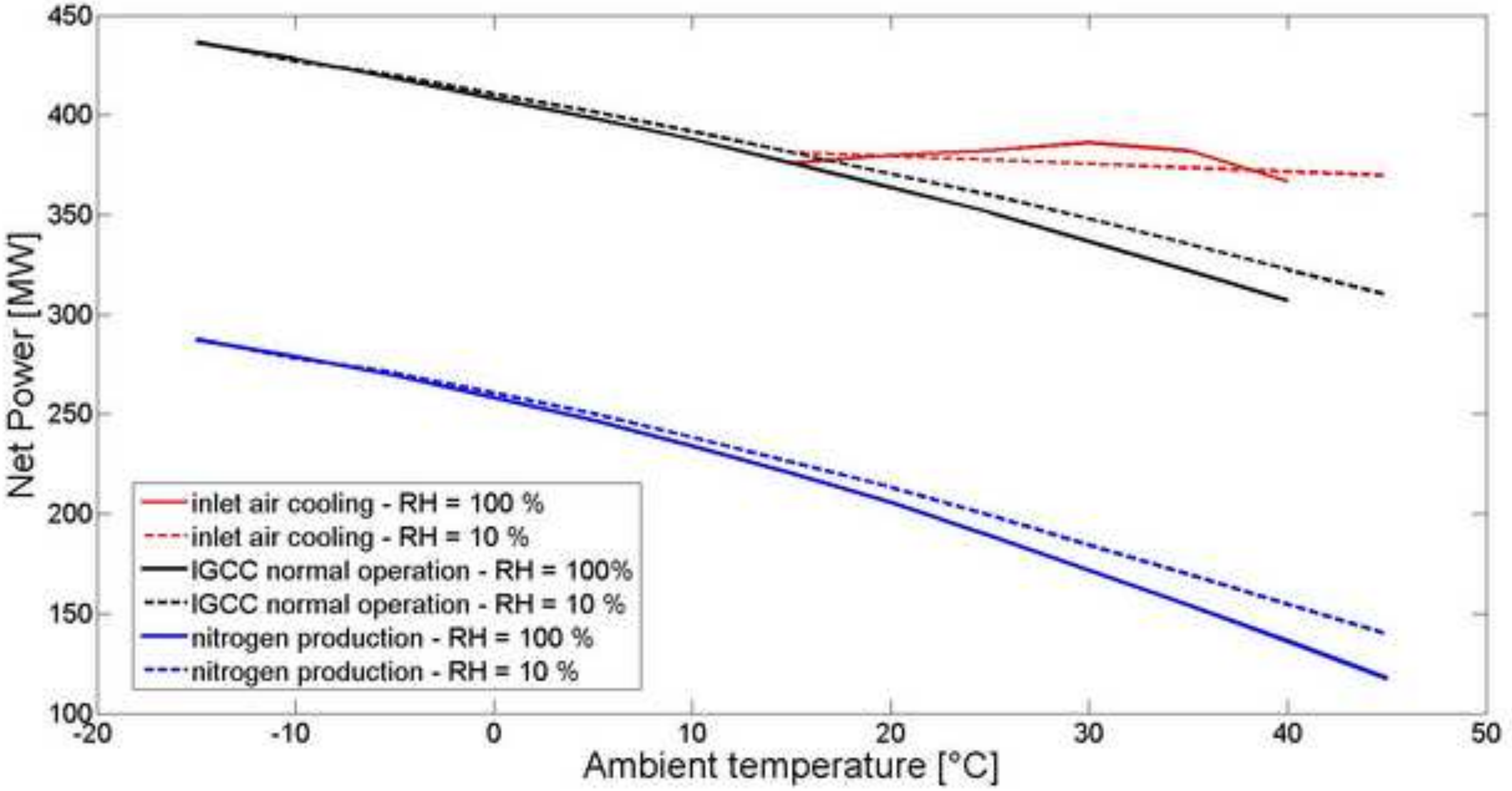
Figure(s) 1


Pressure [bar]
Temperature [°C]
Mass flow rate [kg/s]
Fluid
GC
G
ASU
IACS
GT
SS
- | -
39.6 | Coal
42.00 | 119
27.4 | O_2
10.00 | -170
100 | N_2
1.013 | 15
66.9 | Air
24.12 | 144
2.3 | N_2
1.013 | 15
649.9 | Air
15.98 | 380
66.9 | Air
26.73 | 230
68.1 | Syngas
1.059 | 607
641.0 | Ex. gases
24.12 | 147
55.8 | Syngas
122.9 | 567
97.8 | Steam
23.35 | 400
143.0 | Steam
0.05 | 33
130.9 | Water
2.37 | 151
130.9 | Steam

Figure(s) 2

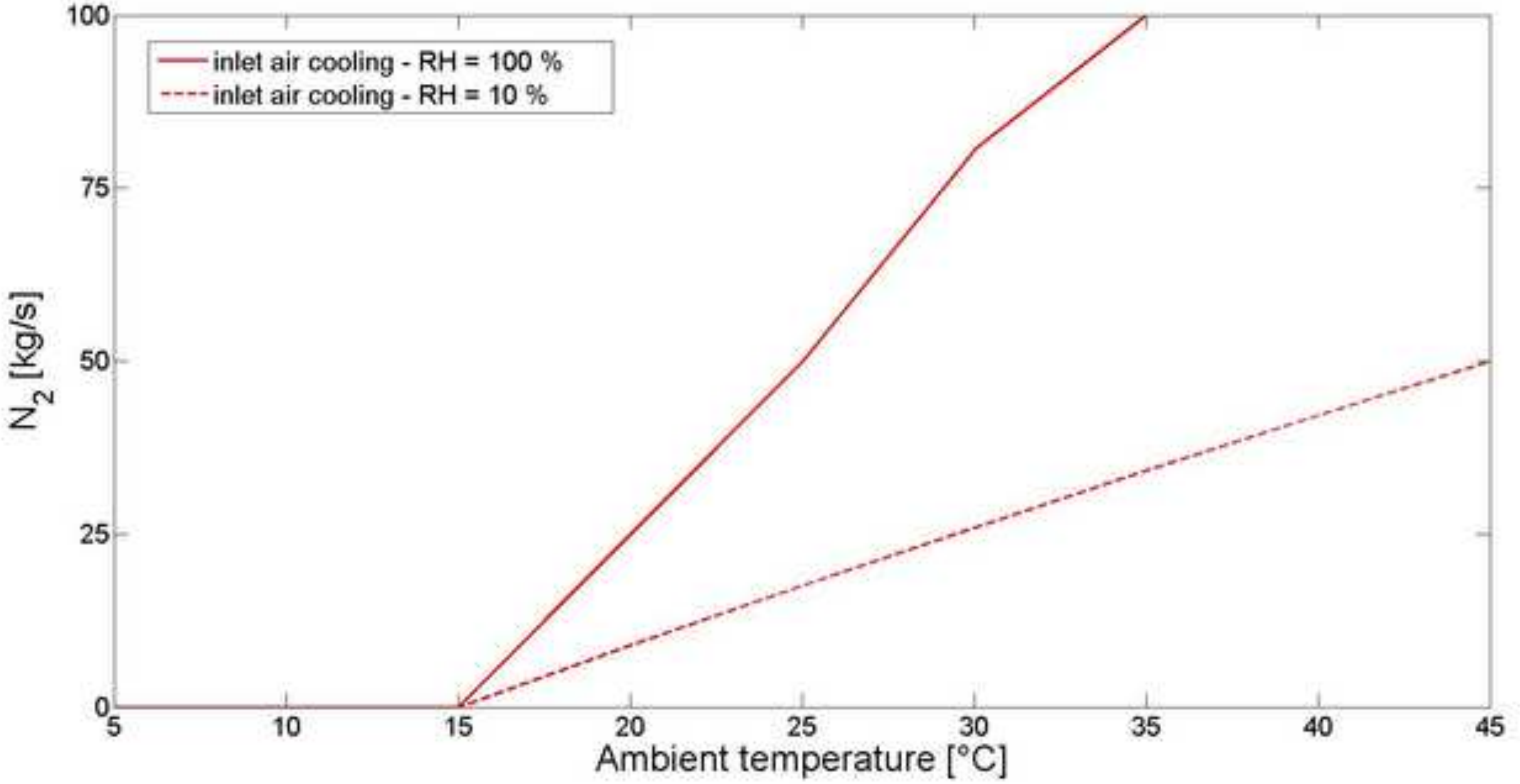

air
oxygen
nitrogen
syngas
flue gas
ASU
G
GC
GT
SS
IACS
< 100.0 kg/s
ST
AMBIENT

Figure(s) 3

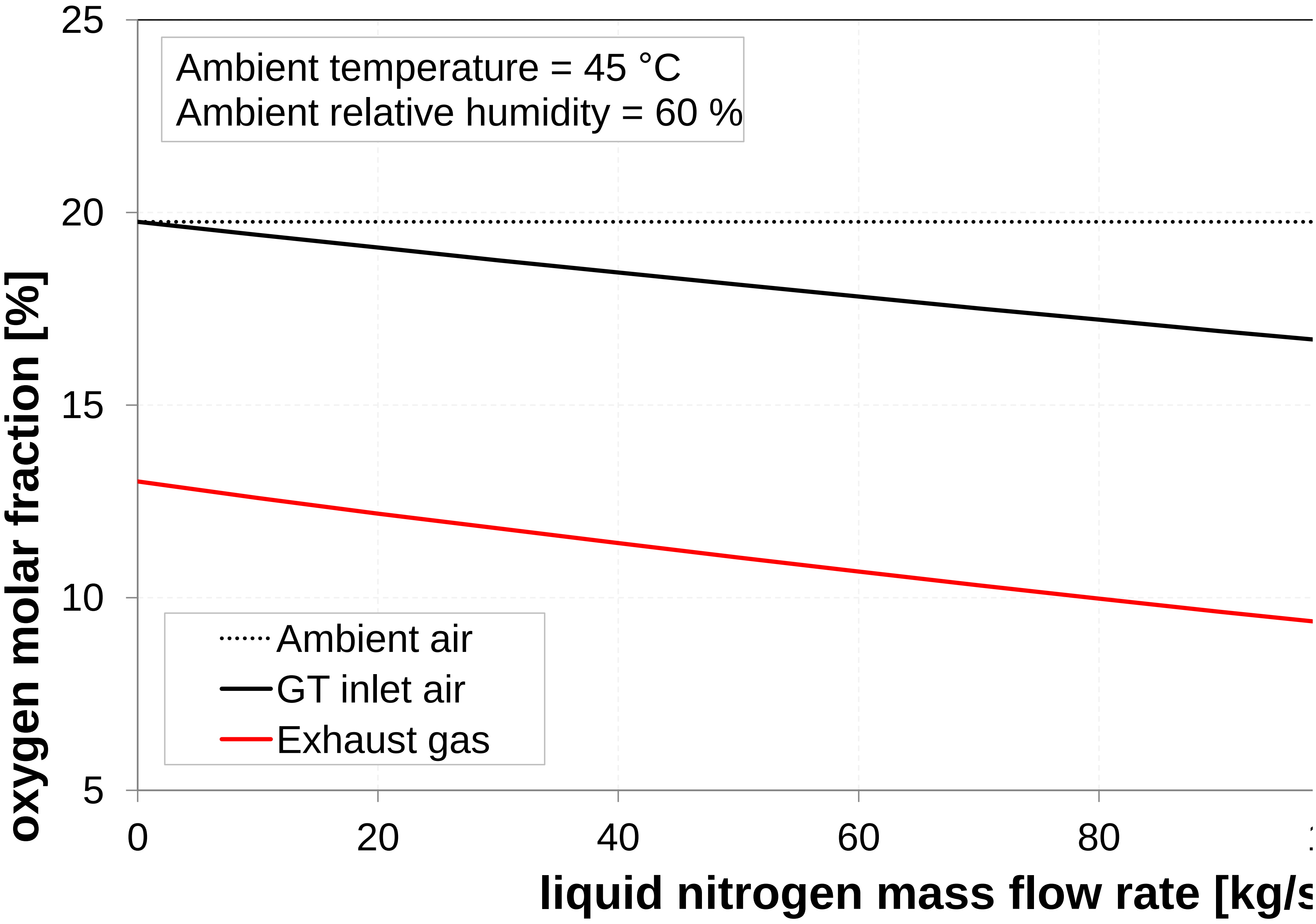


Net Power [MW]
450
400
350
300
250
200
150
100
-20
-10
0
10
20
30
40
50
Ambient temperature [°C]
inlet air cooling - RH = 100 %
inlet air cooling - RH = 10 %
IGCC normal operation - RH = 100%
IGCC normal operation - RH = 10 %
nitrogen production - RH = 100 %
nitrogen production - RH = 10 %

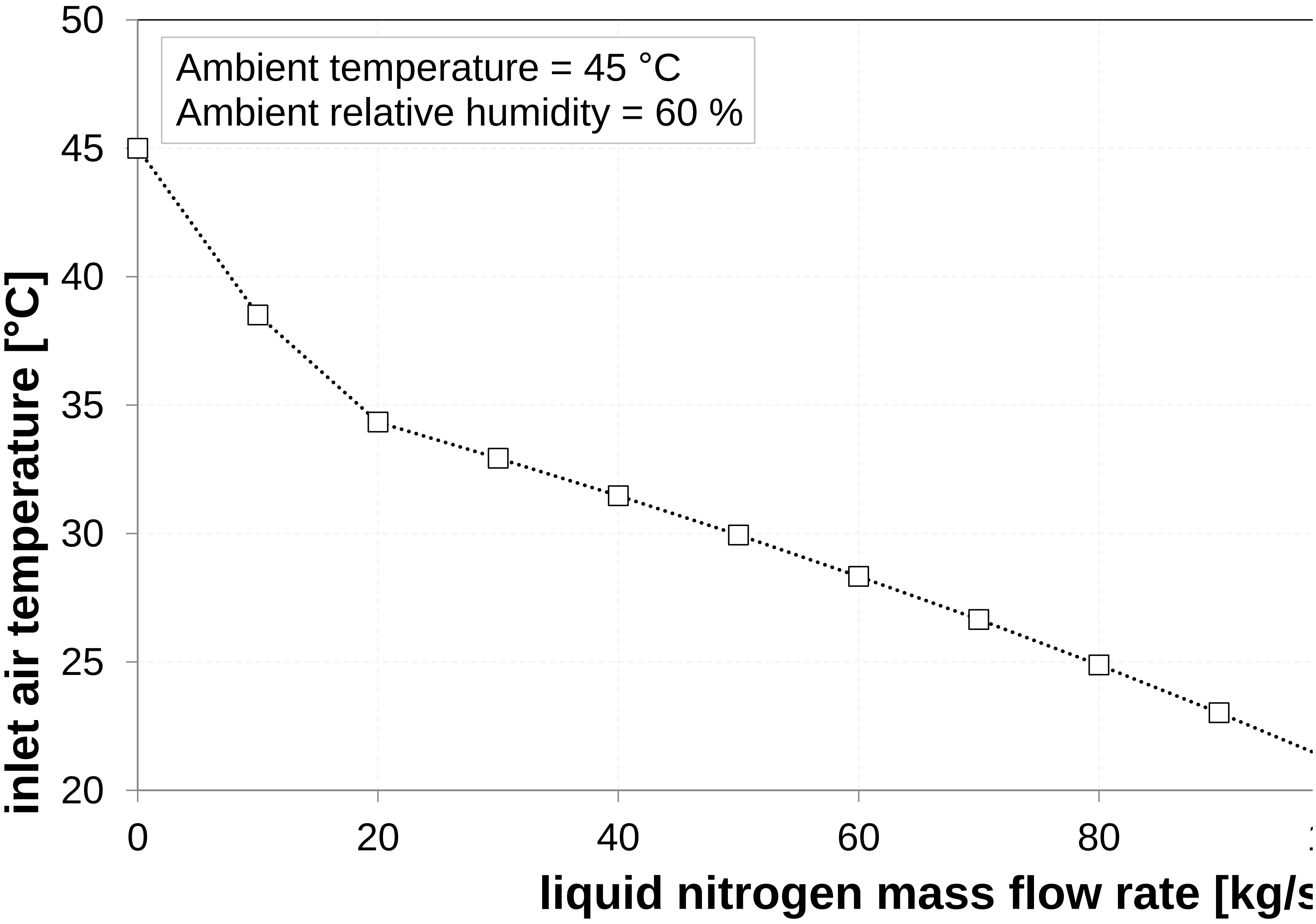
Figure(s) 4


inlet air cooling - RH = 100 %
inlet air cooling - RH = 10 %
N_2 [kg/s]
100
75
50
25
0
5
10
15
20
25
30
35
40
45
Ambient temperature [°C]

Figure(s) 5

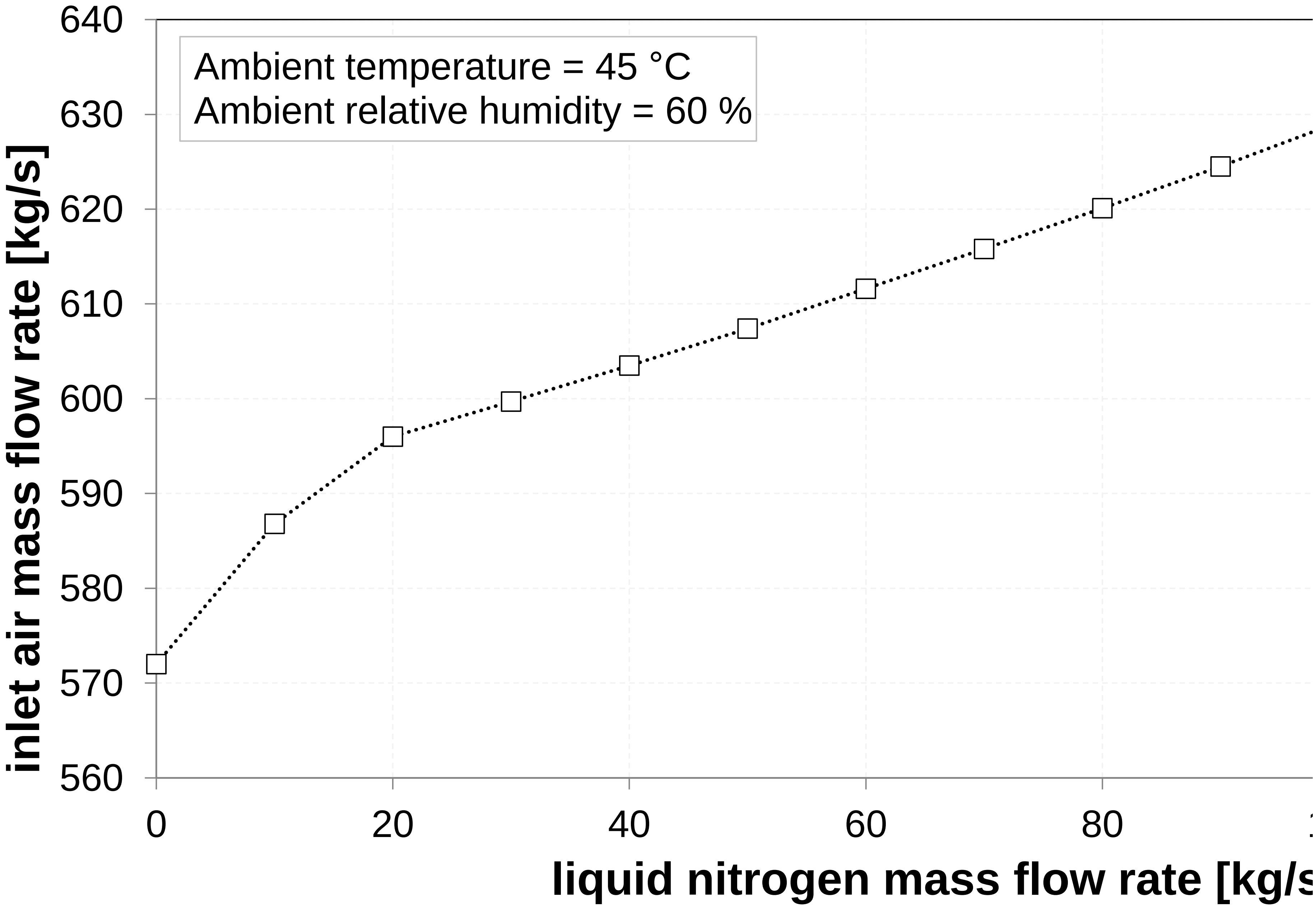

Ambient temperature = 45 °C
Ambient relative humidity = 60 %
Ambient air
GT inlet air
Exhaust gas
oxygen molar fraction [%]
25
20
15
10
5
0
20
40
60
80
liquid nitrogen mass flow rate [kg/s

Figure(s) 6



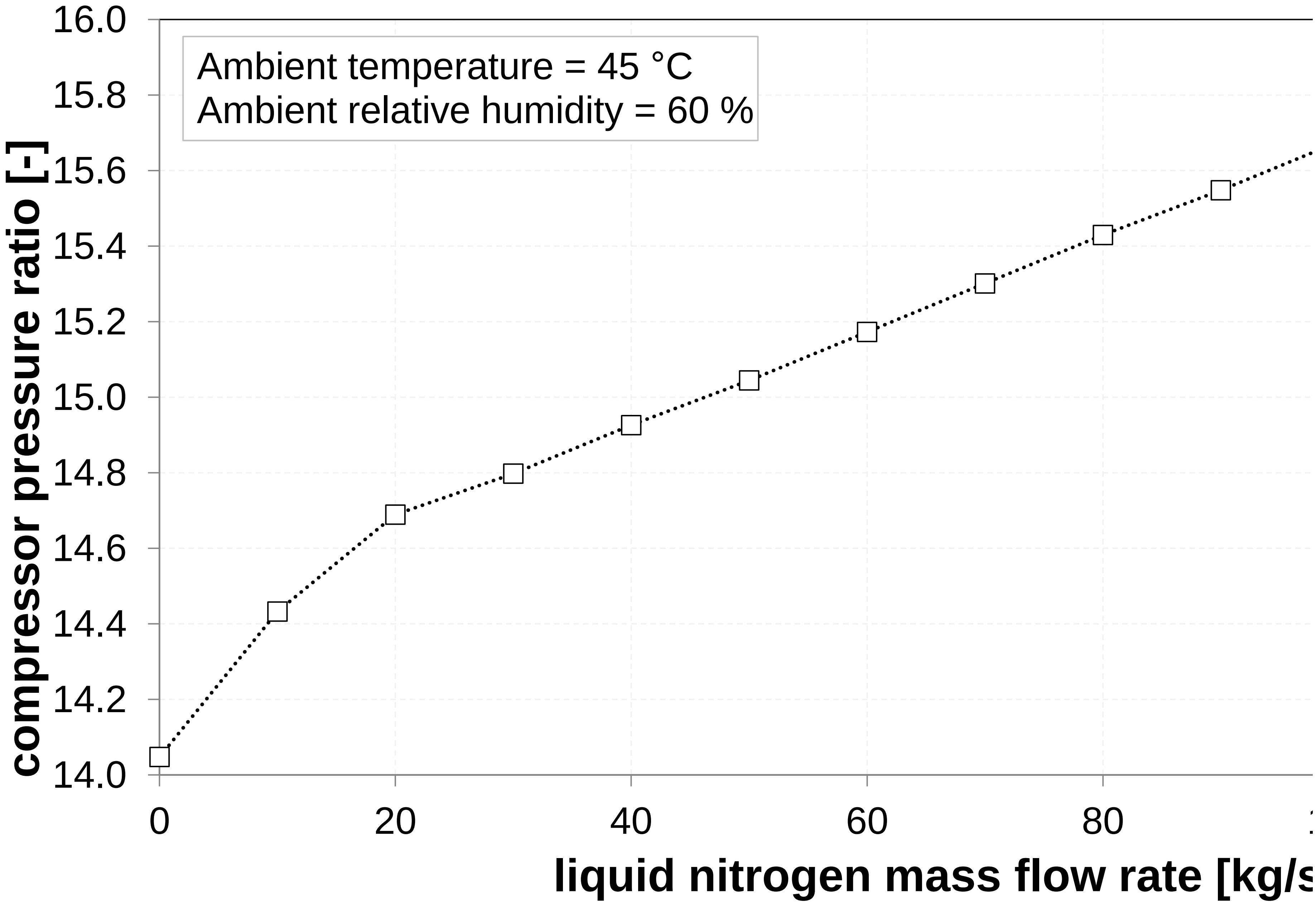
Ambient temperature = 45 °C
Ambient relative humidity = 60 %
inlet air temperature [°C]
50
45
40
35
30
25
20
0
20
40
60
80
liquid nitrogen mass flow rate [kg/s

Figure(s) 7



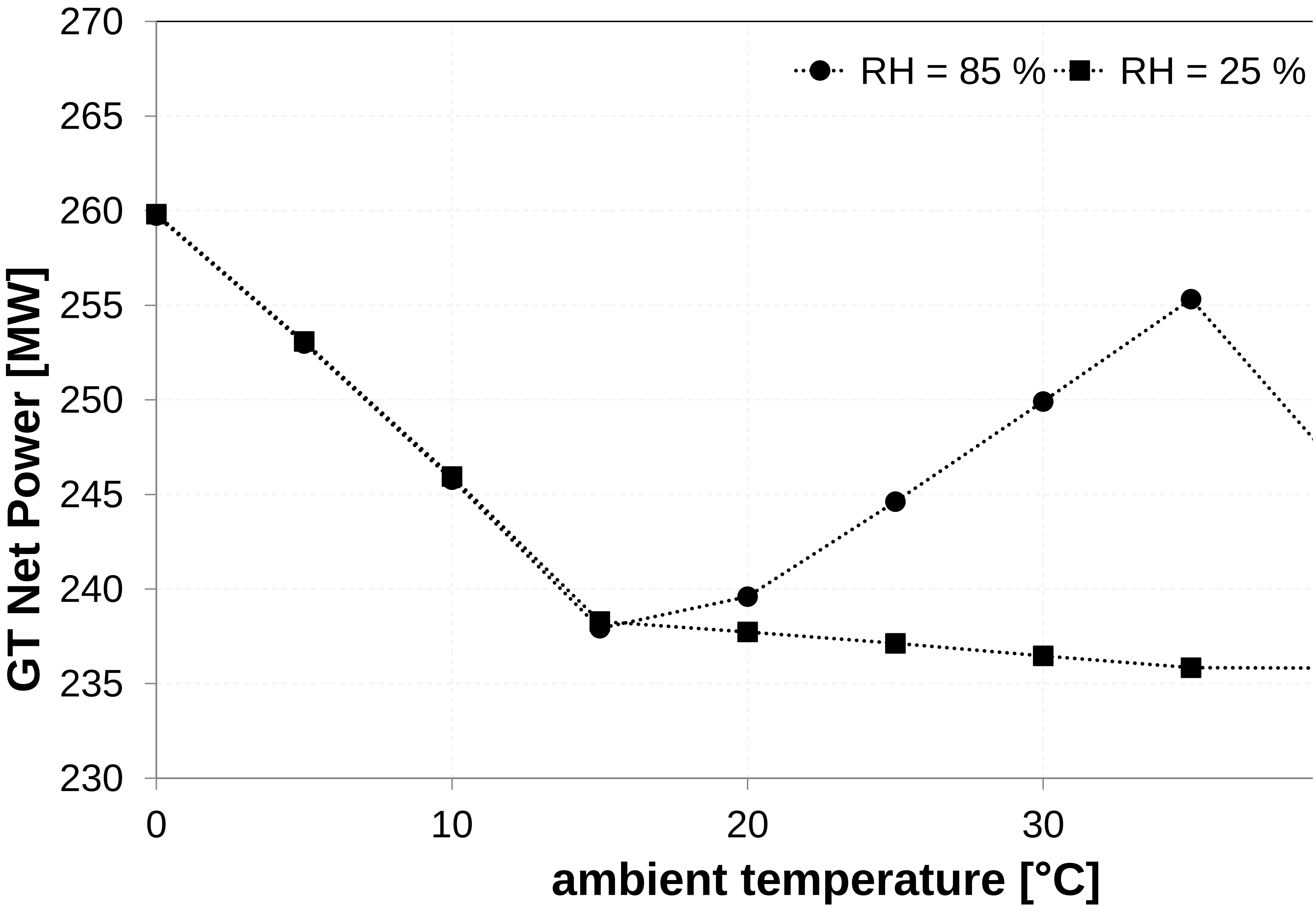
Ambient temperature = 45 °C
Ambient relative humidity = 60 %
inlet air mass flow rate [kg/s]
640
630
620
610
600
590
580
570
560
0
20
40
60
80
liquid nitrogen mass flow rate [kg/s

Figure(s) 8

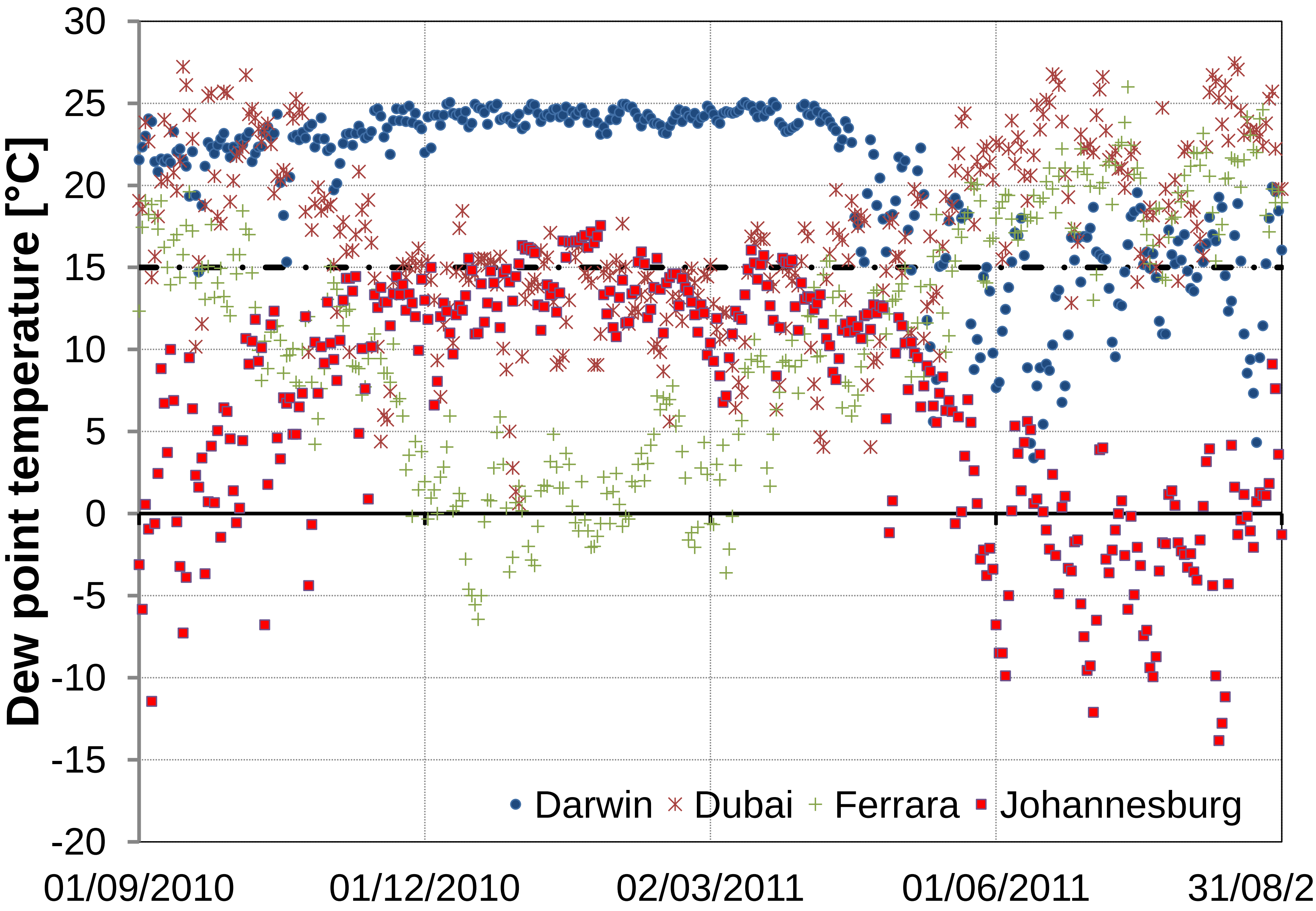


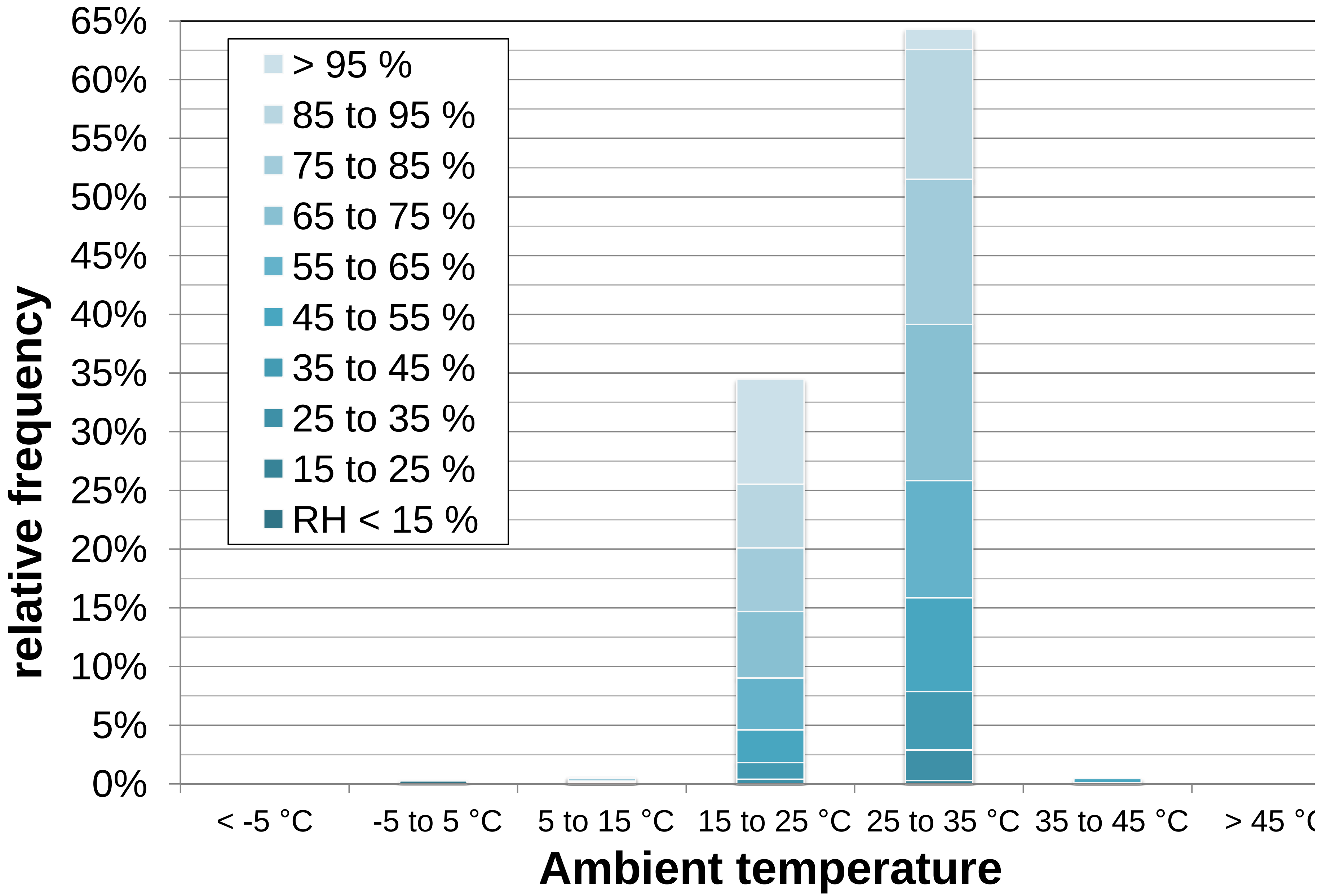
Ambient temperature = 45 °C
Ambient relative humidity = 60 %
compressor pressure ratio [-]
16.0
15.8
15.6
15.4
15.2
15.0
14.8
14.6
14.4
14.2
14.0
0
20
40
60
80
liquid nitrogen mass flow rate [kg/s

Figure(s) 9

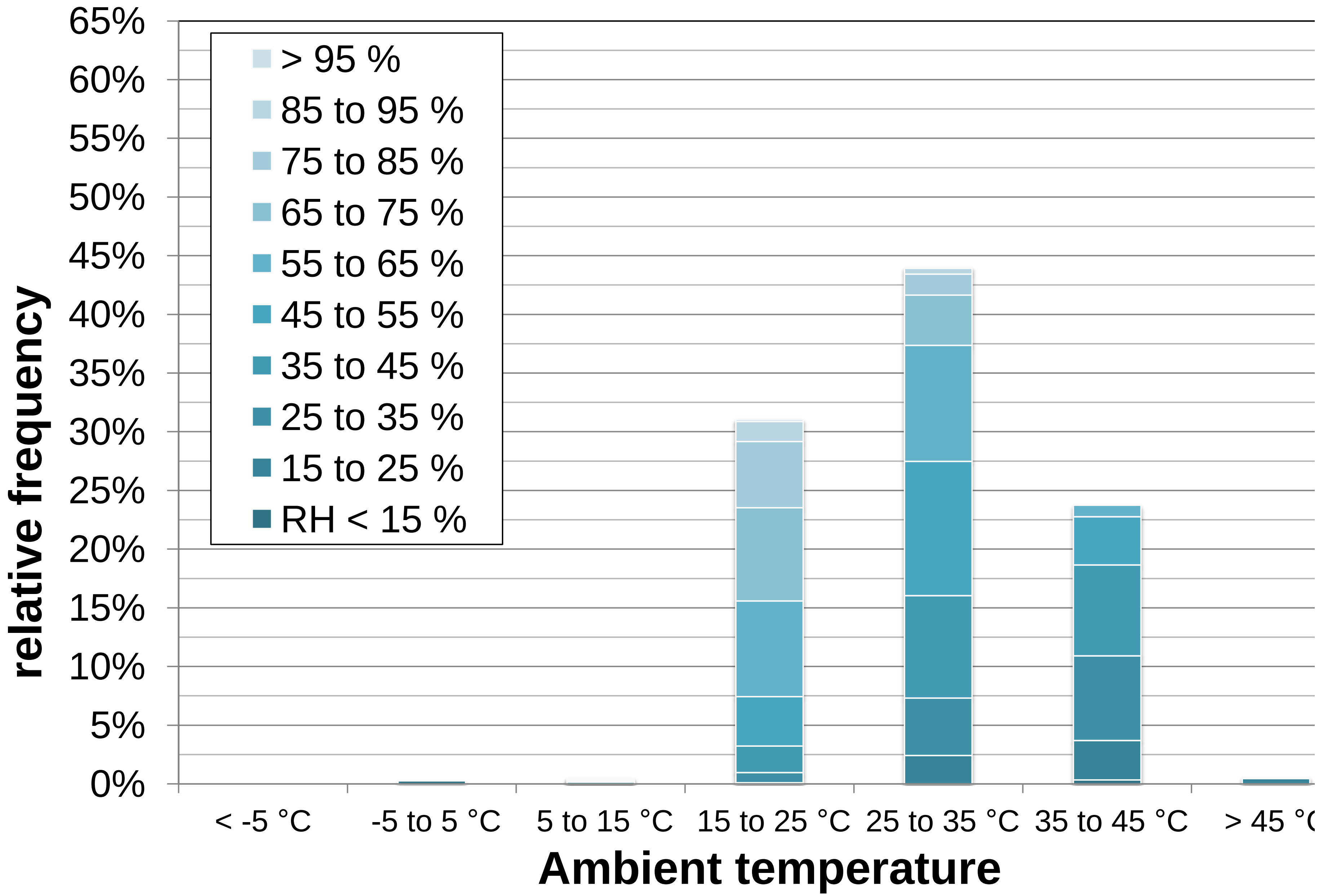

GT Net Power [MW]
270
265
260
255
250
245
240
235
230
0
10
20
30
ambient temperature [°C]
● RH = 85 %
■ RH = 25 %

Figure(s) 10

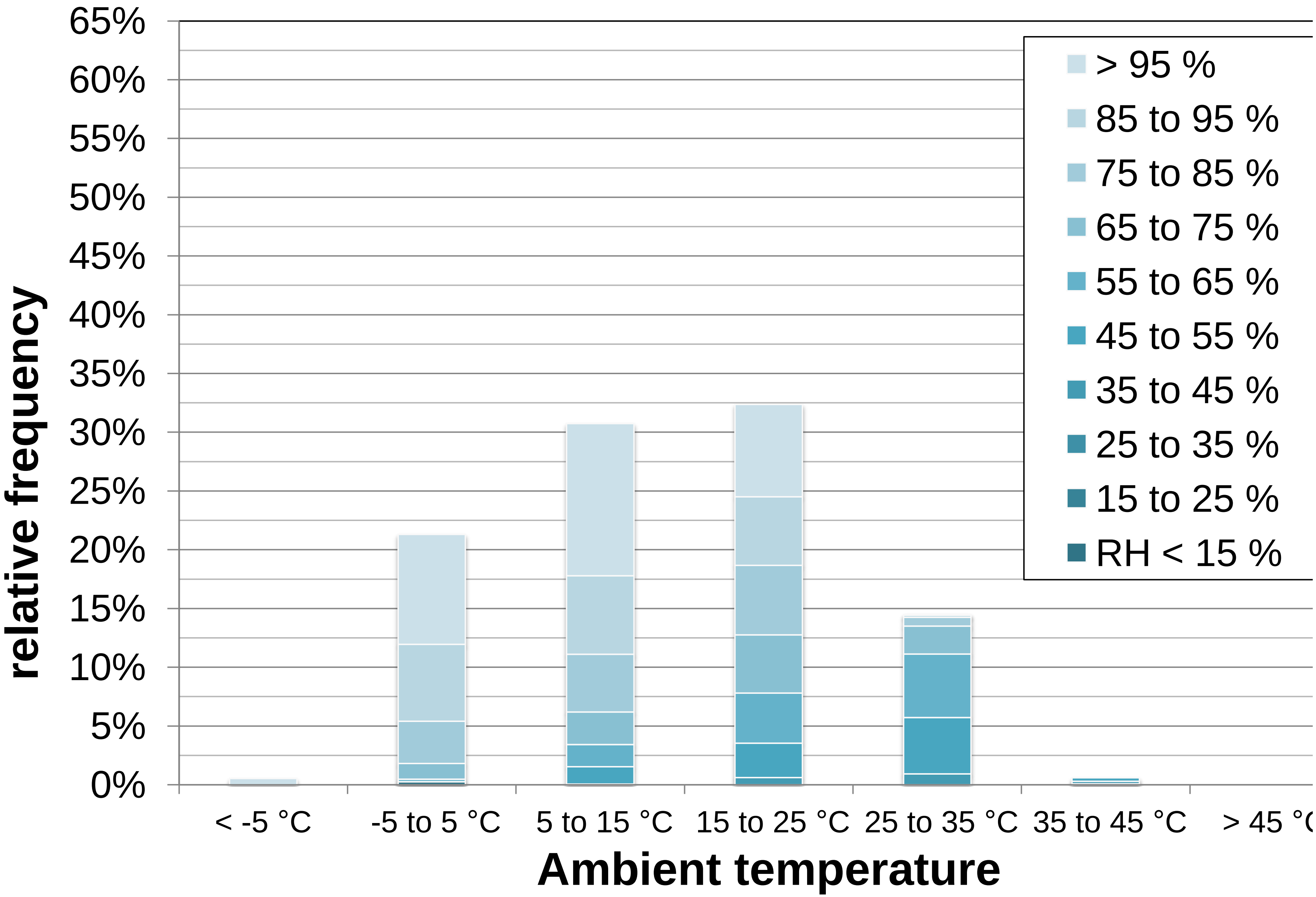

30
25
20
15
10
5
0
-5
-10
-15
-20
Dew point temperature [°C]
01/09/2010
01/12/2010
02/03/2011
01/06/2011
31/08/2
● Darwin
× Dubai
+ Ferrara
■ Johannesburg


65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
relative frequency
> 95 %
85 to 95 %
75 to 85 %
65 to 75 %
55 to 65 %
45 to 55 %
35 to 45 %
25 to 35 %
15 to 25 %
RH < 15 %
< -5 °C
-5 to 5 °C
5 to 15 °C
15 to 25 °C
25 to 35 °C
35 to 45 °C
> 45 °
Ambient temperature

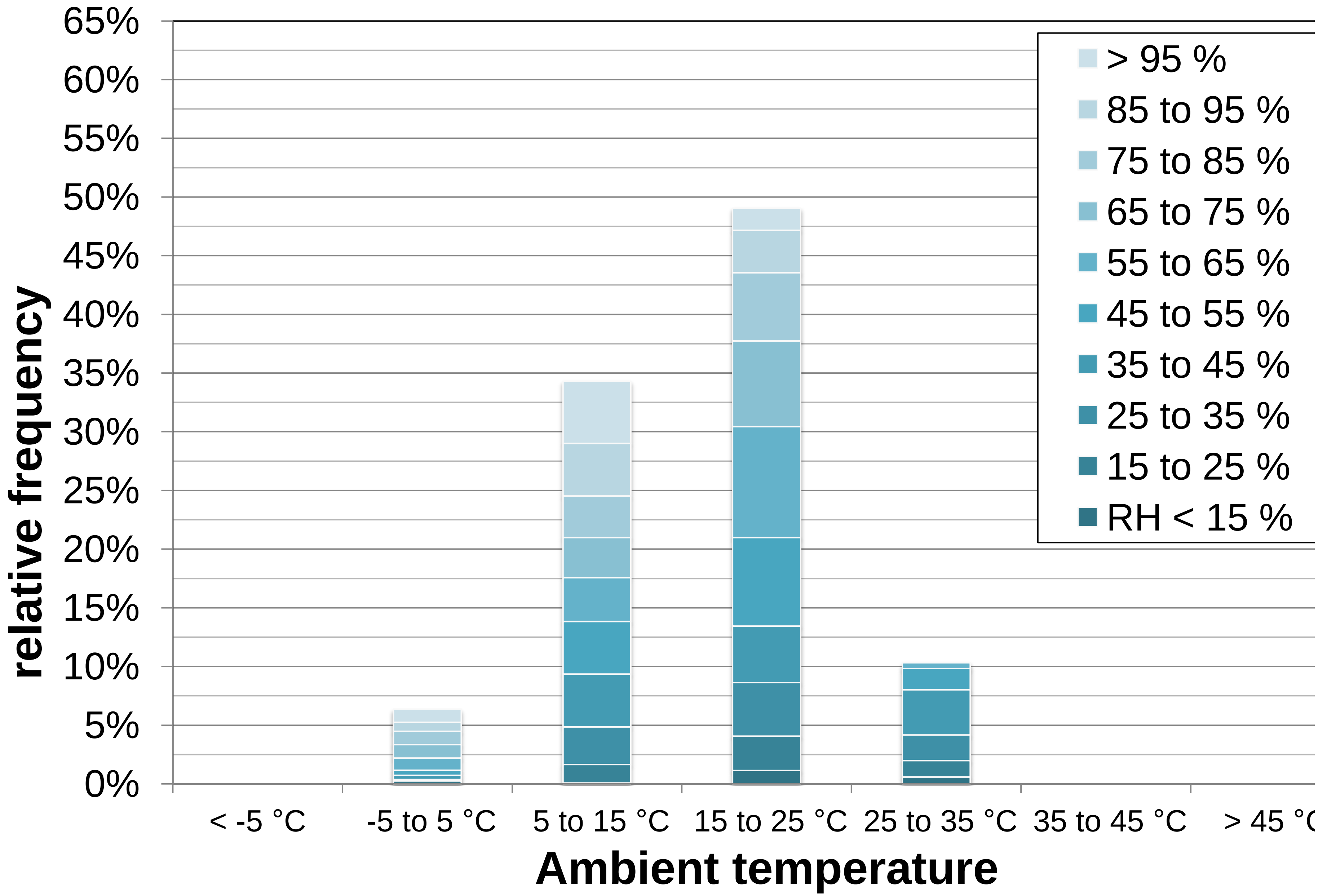
Figure(s) 12


65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
relative frequency
> 95 %
85 to 95 %
75 to 85 %
65 to 75 %
55 to 65 %
45 to 55 %
35 to 45 %
25 to 35 %
15 to 25 %
RH < 15 %
< -5 °C
-5 to 5 °C
5 to 15 °C
15 to 25 °C
25 to 35 °C
35 to 45 °C
> 45 °
Ambient temperature

Figure(s) 13


65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
relative frequency
> 95 %
85 to 95 %
75 to 85 %
65 to 75 %
55 to 65 %
45 to 55 %
35 to 45 %
25 to 35 %
15 to 25 %
RH < 15 %
< -5 °C
-5 to 5 °C
5 to 15 °C
15 to 25 °C
25 to 35 °C
35 to 45 °C
> 45 °
Ambient temperature

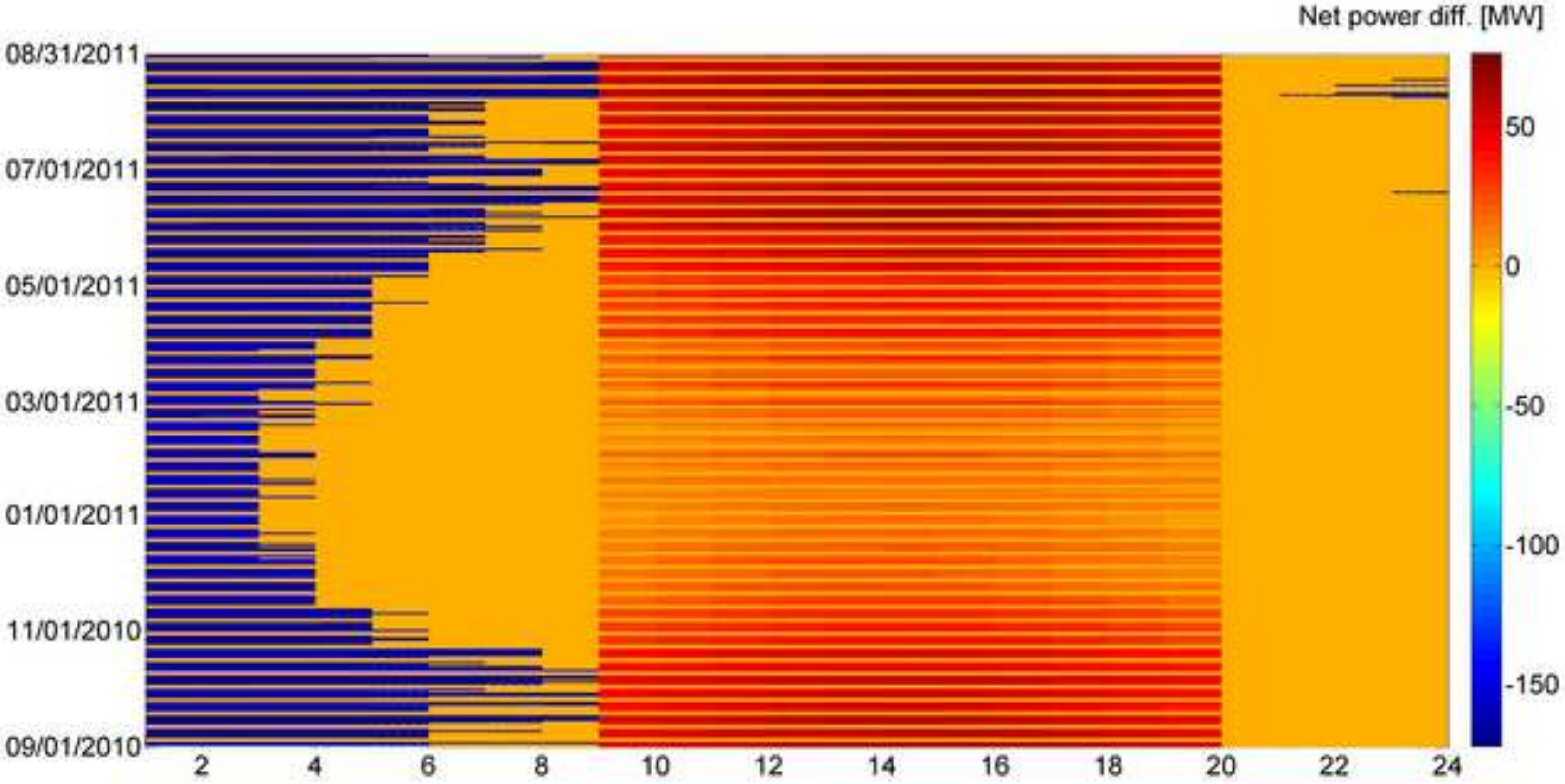
Figure(s) 14



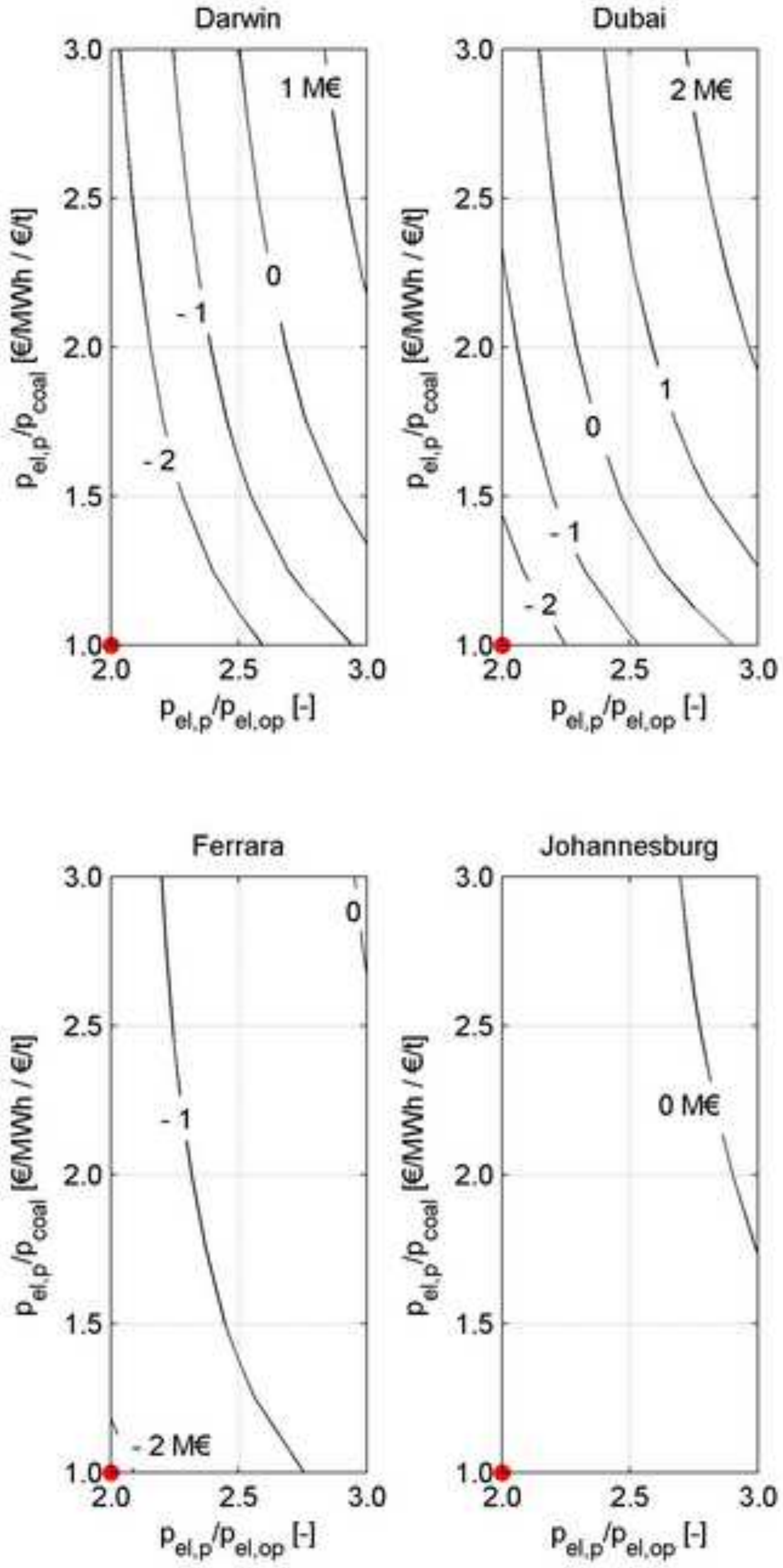
65%
60%
55%
50%
45%
40%
35%
30%
25%
20%
15%
10%
5%
0%
relative frequency
< -5 °C
-5 to 5 °C
5 to 15 °C
15 to 25 °C
25 to 35 °C
35 to 45 °C
> 45 °C
Ambient temperature
> 95 %
85 to 95 %
75 to 85 %
65 to 75 %
55 to 65 %
45 to 55 %
35 to 45 %
25 to 35 %
15 to 25 %
RH < 15 %

Figure(s) 15

Click here to download high resolution image



Figure(s) 16


Darwin
3.0
2.5
2.0
1.5
1.0
$p_{el,p}/p_{coal}$ [€/MWh / €/t]
1 M€
0
- 1
- 2
2.0
2.5
3.0
$p_{el,p}/p_{el,op}$ [-]
Dubai
2 M€
1
0
- 1
- 2
Ferrara
0
- 1
- 2 M€
Johannesburg
0 M€