Potential of Renewable Energies to Power a Natural Gas Driven Trigeneration System

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Thesis to obtain the Master of Science Degree in

Energy Engineering and Management

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May 2018

‘If you do not know what to do, do not do anything unless it is a master's thesis.’

(Author’s statement)

‘If you do not like how the table is set, turn over the table.’

(Frank Underwood)

ACKNOWLEDGEMENT

I would like to thank my supervisors Dr. Raquel Inês Segurado Correia Lopes da Silva and Dr. Sandrina Batista Pereira for all the help and effort made during the whole process of writing this dissertation. Especially for the patience, advices and kindness.

I am grateful for all the data provided by the Climaespaço management without which it would not be possible to finish this work. I would like to personally mention here and thank the CEO of Climaespaço Engie group Mr. João Castanheira.

It would not be possible to write this work without the support of my family. I want to thank my parents for the opportunity which they created for me and the conditions enabling me to take this studies and finish them. I want to thank my grandmother for the patience which she showed my during the process of writing the thesis. I also keep in mind all friends supporting me through that time.

Finally I feel obligated to thank the person mostly personally involved in this dissertation. This person is my fiancé and. I am grateful for all the time she gave me and that she has listened to all of my complaints, doubts as well as she has cheered me up to reduce my weakness. For all the love that she shares with me - thank You darling very much!

RESUMO

Nesta dissertação é analisado o potencial de incorporação de Fontes de Energia Renováveis (FER) em sistemas de trigeração. O caso de estudo considerado é a central da Climaespaço localizada em Lisboa. A conclusão da revisão da literatura é que há falta de regulamentação adequada sobre o apoio de centrais de trigeração na União Europeia combinada com a imaturidade da tecnologia. A avaliação de soluções FER adequadas para a central é feita e o potencial de FER na região é verificado. O cenário base é modelado e diferentes cenários são propostos e avaliados técnica e economicamente. O software EnergyPLAN é utilizado para simular cada cenário e obter resultados. Indicadores financeiros como o valor atual líquido, a taxa interna de retorno e o payback são também calculados. Os resultados são verificados e comparados com o cenário base para determinar se são técnica e economicamente viáveis. Dois dos cenários considerados são selecionados e recomendados para implementar, mostrando o potencial de biomassa para alimentar os sistemas de trigeração. Outras investigações precisam ser feitas no tópico com dados mais precisos e outras ferramentas selecionadas durante o processo para garantir uma melhor confiabilidade da análise e dos resultados obtidos.

Palavras-chave:

Substituição de combustíveis fósseis, Fontes de Energia Renováveis, Trigeração, EnergyPLAN

ABSTRACT

In this dissertation, the potential of incorporation of Renewable Energy Sources (RES) in trigeneration systems is analysed. The case study considered is the Climaespaço plant located in Lisbon. Conclusion from literature review is that there is a lack of appropriate regulations regarding support of trigeneration plants in European Union combined with immaturity of technology. Assessment of suitable RES solutions for this plant is carried out and the RES potential in the region is estimated. The baseline scenario is modelled, different scenarios are proposed with corresponding technical analysis and economic assessment. The software tool EnergyPLAN is used to simulate each scenario and obtain the technical results. The net present value, the internal rate of return and the simple payback time are calculated. The results are checked and compared with baseline scenario to decide if they are both technically and economically feasible. Two of the considered scenarios are selected and recommended to implement, showing biomass potential to power the trigeneration systems. Further investigation needs to be done in the topic with more accurate data and other tools selected through the process to ensure better reliability of the analysis and obtained results.

Keywords:

Fossil fuel replacement, Renewable energy sources, Trigeneration, EnergyPLAN

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NOMENCLATURE

Symbols

a	Discount rate/effective interest rate; Eq. 11	[-]
A	Total solar panel area; Eq. 8	[m^2]
Aux	Auxiliary boiler consumption; Eq. 7	[GWh]
$C_{abs\ chillers}$	Cooling produced by absorption chillers; Eq. 4,5	[GWh]
C_d	Discounted cost; Eq. 10	[€]
C_{el}	Cooling produced by electricity; Eq. 3,4	[€]
C_o	Total initial investment costs; Eq. 9	[€]
$C_{O\&M}$	Annual fixed cost; Eq. 10,13	[€]
C_t	Net cash inflow during the period t; Eq. 9	[€]
C_{total}	Total cooling produced; Eq. 4	[€]
COP_{dist}	Coefficient of performance for district heating for cooling; Eq. 5	[-]
COP_{el}	Coefficient of performance for electricity for cooling; Eq. 3	[-]
E	Energy produced; Eq. 8	[kWh]
E_a	Energy produced; Eq. 10	[GWh]
$E_{chillers\ total}$	Total electricity consumption of chillers; Eq.3	[GWh]
$E_{compression}$	Electricity consumption of compression chillers; Eq.1	[GWh]
$E_{cooling}$	Electricity demand for cooling purposes; Eq. 1	[GWh]
$E_{domestic}$	Domestic electricity consumption; Eq. 2	[GWh]
$E_{invisible}$	'Invisible' electricity consumption of chillers; Eq. 1,2	[GWh]
E_{total}	Total electricity produced; Eq. 6	[GWh]
$E_{without}$	Electricity consumption without chillers; Eq. 2	[GWh]
GT	Gas turbine consumption; Eq. 6	[GWh]
H	Annual average solar radiation on tilted panels; Eq. 8	[kWh/m^2]
$H_{abs\ chillers}$	Consumption of heat by absorption chillers; Eq. 5	[GWh]
H_{boiler}	Production of heat by auxiliary boiler; Eq. 7	[GWh]
H_{total}	Total heat produced; Eq. 7	[GWh]
I	Amount of financial outlays incurred; Eq. 14	[€]
I_t	Total investment cost; Eq. 10,12	[€]
IRR	Internal Rate of Return; Eq. 12	[%]
j	Year of analysis; Eq. 11	[-]
k_a	Discount factor; Eq. 10,11	[-]
n	Whole period in years; Eq. 11	[-]
η_{el}	Electric efficiency; Eq. 6	[-]
η_{R}	Solar panel yield or efficiency, Eq. 8	[-]
η_{th}	Thermal efficiency; Eq. 7	[-]
NPV	Net Present Value; Eq. 9,10	[€]

P_V	Price of the energy sold to the grid; Eq. 10	[€/kWh]
PR	Performance ratio, coefficient for losses; Eq. 8	[-]
r	Discount rate; Eq. 9	[%]
R	Revenues; Eq. 13	[€]
R_d	Discounted revenues; Eq. 10	[€]
R_N	Balance between revenues and operational and maintenance cost; Eq. 12,13	[€]
$SPBT$	Simple Payback Time; Eq. 14,15	[years]
t	Number of time periods; Eq. 9	[-]
Z_i	Annual gross benefits; Eq. 14	[€]
ΔZ	Reduced costs of energy use; Eq. 14	[€]

Acronyms

BAT - Best Available Technologies
CCHP - Combined Cooling Heating and Power
CHP - Combined Heat and Power
CO_2 - Carbon Dioxide
COP - Coefficient of Performance
DC - District Cooling
DH - District Heating
DHC - District Heating and Cooling
EE - Energy Efficiency
EU - European Union
FIT - Feed in Tariffs
GHG - Greenhouse Gases
LCOE - Levelized Cost of Electricity
LHV - Lower Heating Value
O&M - Operation and Maintenance
OECD - Organisation for Economic Co-Operation and Development
PV - Photovoltaics
RES - Renewable Energy Sources
WtE - Waste to Energy

1. INTRODUCTION

1.1 Framing and motivation

Climate change, security of energy supply and fossil fuels depletion are well-known issues that determine the need of finding pathways for sustainable energy production. These pathways include energy efficiency and renewable energy production. However, the worldwide current energy infrastructure was designed for conventional technologies, based on fossil fuels that have provided large and cheap energy storage. This flexibility of fossil fuels enables the production of energy whenever it is required. On the other hand, fluctuating Renewable Energy Sources (RES) as wind and solar are not flexible. Their intermittent nature introduces barriers to their high penetration into the electricity supply system, like the struggle to match the demand with the supply. In addition, the current energy systems consist of very segregated energy divisions, where the supply chains for mobility, electricity, heating and cooling have very little interaction with each other, disabling the use of possible synergies, what decreases efficiency.

The European Union (EU) is committed to increase the energy efficiency and the use of RES and reduce the emission of Greenhouse Gases (GHG), having performed different actions in this sense, namely the launch of the European 2020 strategy, where the members of the Union are obligated to meet national targets [1]. When it comes to the sector of climate change and energy [2], the goals, for 2020, are to increase by 20% the energy efficiency (EE) to reach the level of 20% of RES and to reduce GHG about 20% in comparison to the year 1990.

Furthermore, 2030 Climate and Energy Policy Framework from October 2014 [3] extend the 2020 goals and sets more ambitious target for the year 2030. Regarding the EE reduction 27% is the target and it is planned to be reviewed by the European Commission to reach even 30%. The participation of RES will reach 27% accompanied with the reduction of GHG of about 40% in 2030, in comparison to the year 1990 [2]. Only introducing RES to the overall energy balance worldwide and doing it in a sustainable way would enable to meet the future regulations. Even today’s Best Available Techniques (BAT), solutions most efficient and economically beneficial but based only in fossil fuels, would not be able to cope with the future expectations and decreasing resources.

It is expected that increasing EE would lead to a decrease in the GHG emissions, a reduction of energy demand and dependency, at the same time creating more jobs as well as improving the economic competitiveness [4]. According to the Final Report from European Commission [5], just changes in five sectors out of eight mentioned in the report, create the chance to save about 5,000 – 9,000 PJ of energy at the step of increasing the resource efficiency. This stands for 32-58% of the EE goal for the year 2020, so absolute reduction of 15,407 PJ in EU. Of course, there are many limitations to these findings, they are based on the case studies and approximations but potential for saving the energy only at this stage is impressive. The environmental aspect is strictly combined with the EE and the whole human mankind is the beneficent of decreasing the pollution, especially the air pollution which is related to energy conversion and consumption [6].

For the reasons mentioned above, there is a need to use more efficient energy systems. So far, the most known and already being used solutions are the polygeneration systems producing, from one feedstock, different energy forms (electricity, heat, cooling, fuels, etc.). Through this procedure the amount of wasted energy, during the energy conversion process, is minimized - leftover energy from one process, which is no longer needed, is used in another one. That is the reason why the overall efficiency is higher than in single production cycles, delivering just one product. Polygeneration systems popularity is growing among the years because of the increased focus about sustainable energy development and environmental policies. These systems are able to meet the restricted regulations inside EU and reduce the amount of feedstock used, which is also economically interesting. Polygeneration is one of the answers to the concept of smart energy systems. A smart energy system is defined as an approach where smart electricity, thermal and gas grids are integrated to achieve an optimal solution for each individual sector as well as for the overall energy system. These systems enable the identification of the least cost solutions used for integration of intermittent RES into current and future energy mix [7].

That is why it is crucial to combine RES with smart systems, like performed in polygeneration systems, to produce so-called “clean” energy in an efficient and economically feasible way. In the present dissertation the technical and financial viability of integrating RES in a trigeneration system, that is currently driven by natural gas, will be modelled and assessed. When it comes to the feedstock, in some of the scenarios there is one feedstock to produce different products while in other there is more than one (to check different configurations of the system). Of course, in the scenarios with more than one feedstock, higher cost of the investment is expected although it should also lead to diversification of the energy production. The trigeneration plant is located in Parque das Nações, district of Lisbon, capital city of Portugal. This plant supplies, heating and cooling, to the buildings located in the surrounding area. Power is also produced, but it is only used in the plant and the excess is sold to the national grid.

1.2 Problem statement

One of the problems faced nowadays by the polygeneration plants is the lack of appropriate regulations, specifying the amount of money earned by selling different types of energy at the same time [8]. Apart from the regulations missing at EU level, there is a strong need for clear national regulation, namely regarding financial support. Currently, the dominant tools of trade at energy market, used both in EU and the rest of the world, are the Feed-in-Tariffs (FIT). FIT are defined as the energy supply policy which aim is to support the growth of RES, in the way of long-term contracts for buying the produced electricity. The typical time of the contract is in the range of 10-25 years and the economic terms of the contract are individually connected with the investment, depending from many factors such as project size, location, type of technology used and the quality of resources. The reason of doing so, is to match the real needs in term of installation’s costs. What is extremely important, the policy designers are able to adapt the levels of support for already existing installations or even stop the support. This method is used to motivate the plants to keep their technologies up-to-date and improve technical parameters to meet new regulations. An alternative way is to set the payment levels above the nominal market prize [9]. Figure 1.1 shows the evolution of the main policy support schemes in EU-15 member states [10]. As showed, in Portugal FIT are the main source of the support for renewable or clean technologies.

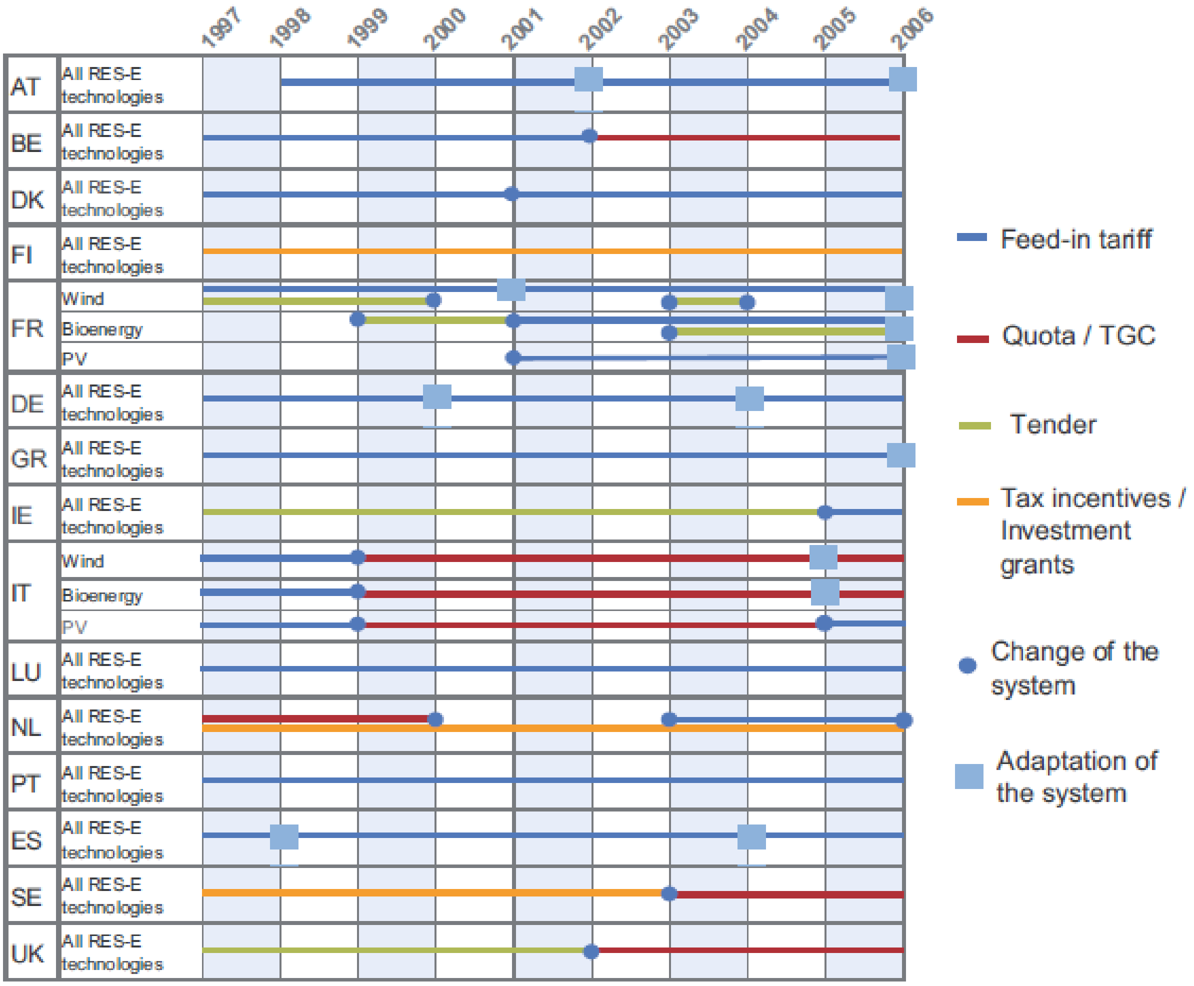


Figure 1.1 Evolution of the main policy support schemes in EU-15 member states [10]

The plant Climaespaço, which is the case study considered in this work, is strictly dependent from FIT, as it sells all of the surplus generated electricity under a FIT mechanism [11]. The plant its powered by natural gas, a fossil fuel, but since it produces electricity, heat and cooling, it presents higher efficiencies, hence is responsible for less GHG emissions than other non-renewable resources. At present, natural gas is the best and most common source of energy for such plants. For now, Climaespaço's FIT mechanism is still valid, but only until 2023, after this year, new levels of payments will be introduced. The problem is also connected with the fact that, recently, the support of high efficiency cogeneration/trigeneration plants in Portugal was strongly reduced. For sure new FIT would not be so beneficial for the plant which can result in reduced profitability of Climaespaço [11] [12].

In this way, it is crucial for this installation, as many others that benefit from the FIT mechanism, to seek for solutions that can maintain the financial sustainability, namely include RES into the energy balance. RES are free of charge or at relatively low price and the support is much bigger than for the systems operating on fossil fuels. Of course, appropriate investments need to be done to switch to different configuration, so this dissertation is trying to answer the question: how can the plant be environmental and financially sustainable.

1.3 Objectives

The main objective of this work is to assess the technical and financial feasibility of using RES in a trigeneration plant which input is, currently, natural gas. Different scenarios are assessed and compared with the baseline scenario. To reach this global objective, several specific objectives need to be accomplished:

- Analysis of the operation of the trigeneration plant;
- Assessment of suitable RES technologies for the trigeneration plant;
- Assessment of RES potential in the region of the trigeneration plant;
- Modelling of the baseline scenario and of the proposed scenarios;
- Technical and economic assessment of the different scenarios.

1.4 Present contribution

In this thesis, a technical and financial analysis of the potential of introduction of RES in the natural gas trigeneration system of Climaespaço, located in Lisbon, is carried out. Several scenarios are assessed using the EnergyPLAN tool, which provides hourly production data for each scenario. Each scenario is then checked with economic indicators to have a wide spectrum of comparison. By the results analysis the author suggests which scenarios are feasible to implement.

1.5 Thesis outline

The thesis is divided in six chapters:

- Chapter 1: Introduction - framework of the dissertation is presented, the main problem occurring in thesis is defined, objectives, motivation and present contribution are explained;

- Chapter 2: Literature review - the key facts about the topic discussed are mentioned and compared in the different literature sources, the main issues and challenges are highlighted;
- Chapter 3: Case study - description of Climaespaço plant is made with the presentation of the current system, the profiles of the typical operation days are shown;
- Chapter 4: Methodology - definition of the idea how the analysis is carried out is presented and described with detail, technical and economic analysis indicators are shown, software used for simulation is discussed;
- Chapter 5: Results and discussion - the values achieved with the simulation are presented in both technical and economic section with the corresponding discussion;
- Chapter 6: Conclusions - summing up the whole dissertation and issuing recommendations regarding the scenarios analysed;

2. LITERATURE REVIEW

2.1 Trigeneration systems

To describe what is trigeneration system, one has to bear in mind the concept of cogeneration, so-called Combined Heat and Power (CHP). The working principle of CHP is based on a heat engine which is used to simultaneously produce electricity and useful heat, using a single fuel source. The heat generated can be used to power the electricity generating system, for district heating and hot water production, making the system more efficient [13] [14]. Figure 2.1 compares the efficiency of a CHP system with the efficiency of separated heating and electricity production systems [15].

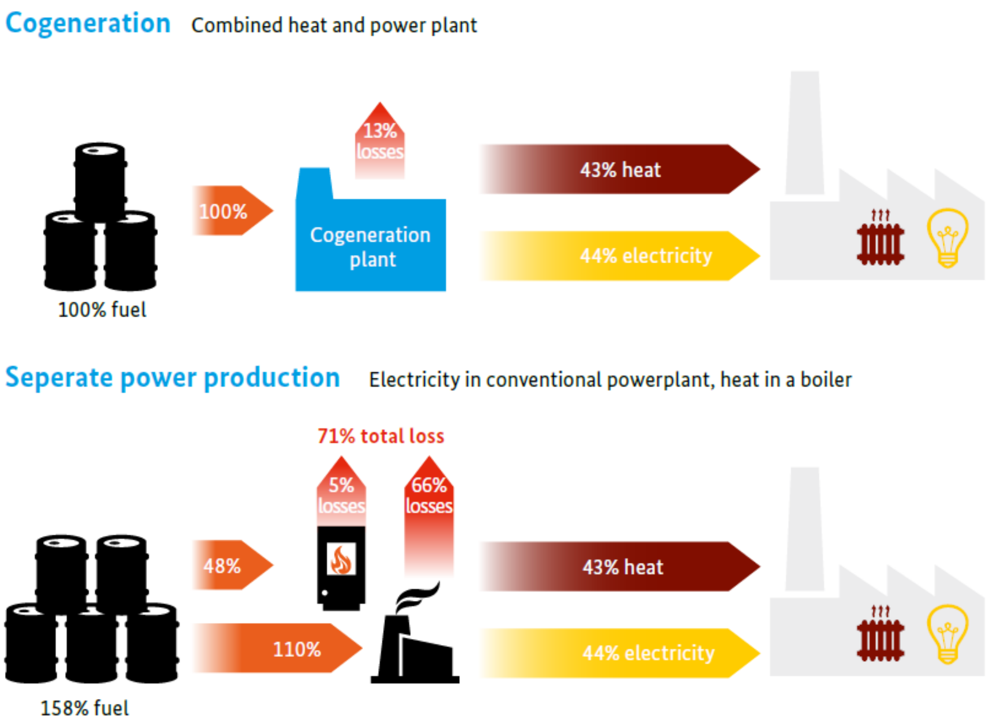


Figure 2.1 Efficiency of separate heat and power production versus cogeneration [15]

Typical efficiencies and losses are presented in both configurations as well as the amount of fuel needed. Depending on the source [6] [13] and on the system used the overall efficiency of a CHP system may vary between 80-90%. Figure 2.2 shows the technological options and types of fuel suitable to be used in cogeneration systems.

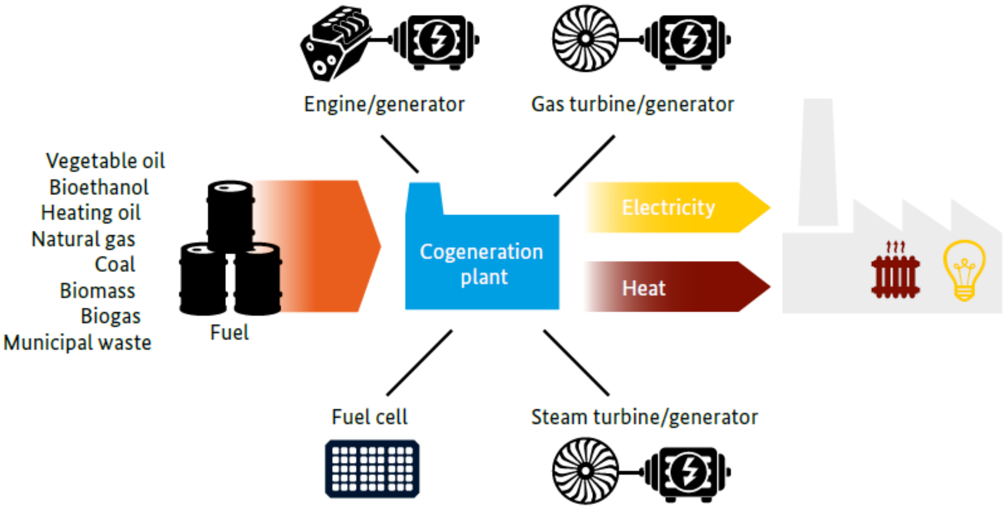


Figure 2.2 Types of fuel, technology and energy conversion process for cogeneration [15]

There are many different configurations to run a cogeneration system which enables to use this technology according to the needs and the available resources. However, cogeneration is just the first step in the polygeneration technology approach. The more advanced system, which is the natural successor of previous solution, is trigeneration technology. This system combines not only the electricity and heat generation but also provides another useful product, namely cooling, likewise from one fuel source. Trigeneration systems are also called in the literature Combined Cooling, Heating and Power (CCHP) systems. When it comes to the technology used, the main idea is to combine a cogeneration unit with an absorption/adsorption or a compression chiller. The chillers convert the leftover steam (after cogeneration system) to chilled water by the process of absorption/adsorption or by compression using electricity. As the heating yield is higher than the electric one, electricity is more expensive source of energy than heat, the major effort is made to use the absorption/adsorption chillers (instead of compression ones) as the main technology to generate cooling. The chillers using the ‘waste heat’ after cogeneration unit do not need the compressor as part of the system. These chillers use desiccant liquid and the circulating pump which delivers the drying agent to their internal heat exchangers. Consumption of electricity by absorption chillers is only about 8.5×10^{-3} $kW/kW_{refrigeration}$, in the case of the adsorption chillers using solid desiccant, the consumption is smaller, reaching about 1.1×10^{-3} $kW/kW_{refrigeration}$ [15].

Figure 2.3 illustrates the configuration of a trigeneration system using absorption technology. As shown there are several connections and interactions in the energy chain between different processes. The configuration can be adapted to the needs of a particular system. As already mentioned, absorption and adsorption technologies are playing an important role in trigeneration systems.

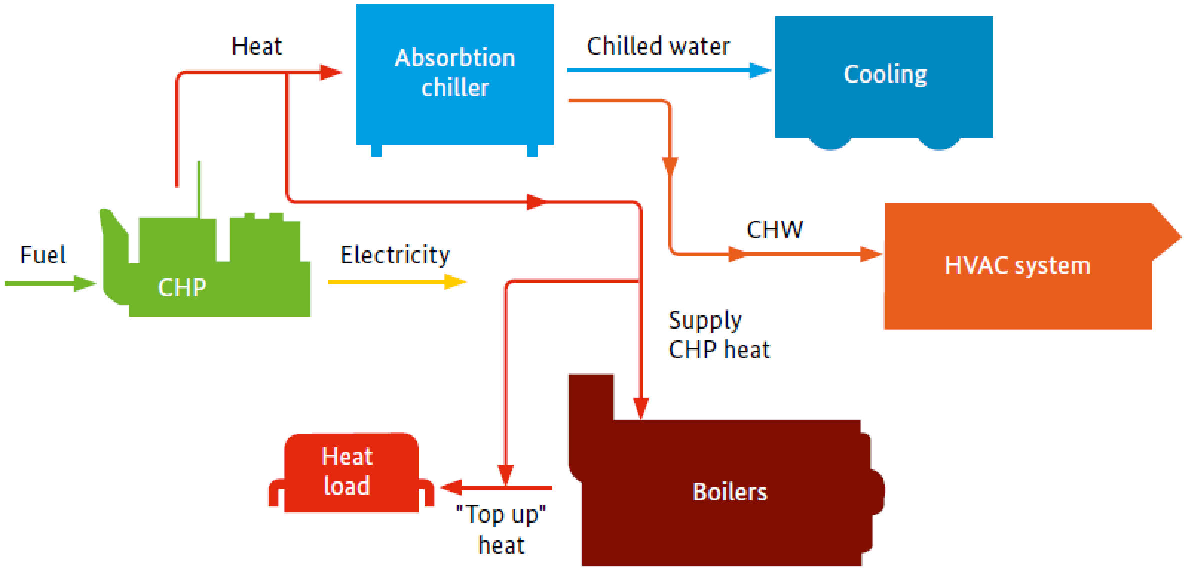
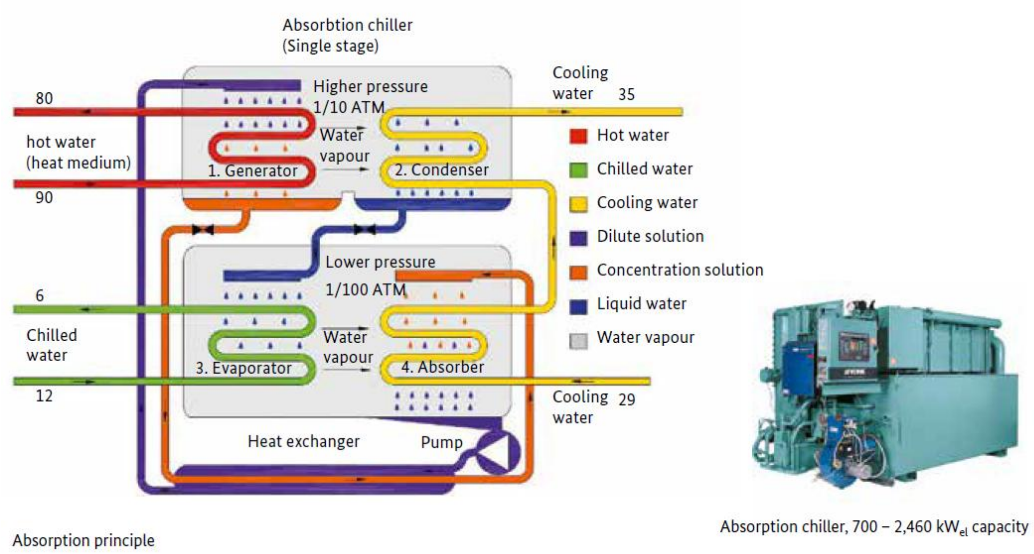


Figure 2.3 Elements of a trigeneration system (using absorption technology) [15]

Absorption technology is more widespread and it is based on the absorption refrigeration cycle. This cycle is alike vapour compression one, but instead of external equipment powered by electricity to change the refrigerant phase, it relies on the method using only heat and refrigerant itself. The absorption system is composed by a generator, a condenser, an evaporator and an absorber (Figure 2.4).



Absorption principle

Absorption chiller, 700 – 2,460 kW$_{el}$ capacity

Figure 2.4 Absorption process [15]

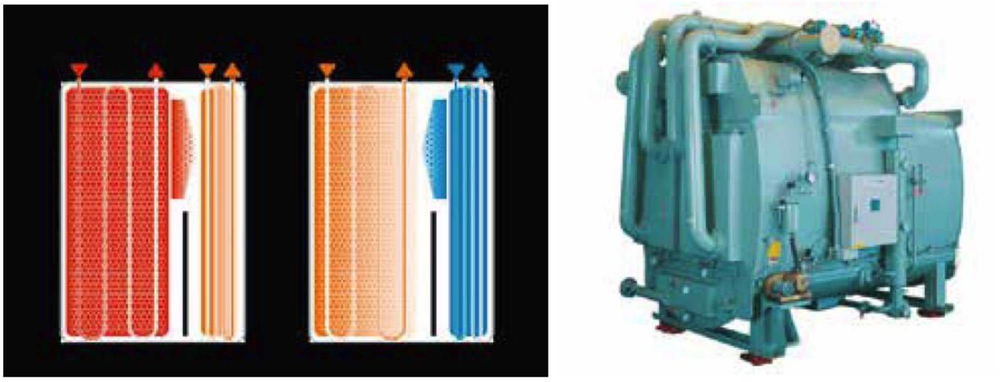
1. Generator - hot water is introduced, refrigerant and absorbent are separated using a boiling process, later the refrigerant is regenerated. The concentration solution leaving the generator is cooled down in absorber.

2. Condenser - the refrigerant vapour comes to the condenser at high temperature and pressure. Here, the refrigerant changes its phase to liquid, the heat is released. Mainly the water-cooled condensers are used.

3. Evaporator - in this component the liquid water vaporizes in conditions of low temperature and pressure, extracting the heat from chilled water.
4. Absorber - the refrigerant vapour at low pressure is condensed and then absorbed by the concentration solution. The chemical affinity between the refrigerant particles and absorber enables appropriate mixing - absorption process occurs. Closing cycle, the heat of condensation and absorption are together removed outside the absorber by the cooling water. Finally, dilute solution is achieved and pumped back into the generator [6].

The most popular refrigerant in the absorption systems is water while the most popular absorbent is lithium bromide (LiBr). In fact, LiBr is a salt with corrosive impact on the system - that is the reason of high maintenance cost (to prevent the corrosion).

The adsorption technology (Figure 2.5), is relatively new and not as widely used for trigeneration systems as absorption. Despite the fact that absorption and adsorption have many similarities, the driving force of the second process is different - it relies on the interaction between the solids and gases. In this kind of chillers there are adhesive forces between molecules and the surface of an adsorbent, instead of molecules being dissolved. In the chillers the adsorption chamber is equipped with appropriate solid substance, mainly: zeolite, alumina, silica gel, active carbon or some types of metal salts which adsorb the refrigerant in its neutral state. During the process of heating up, desorption of the solid is taking place and refrigerant vapour is released, which later on is cooled and liquefied. The liquid refrigerant is the cooling agent for the evaporator and it absorbs external heat, after this it turns back into a form of vapour. Finally, the refrigerant vapour is reabsorbed into the form of solid. Adding the heat, while the material is saturated, will enable the process of regeneration to happen and it results in discontinuous cooling.



Adsorption principle

Adsorption chiller, 50 kW_{el} capacity

Figure 2.5 Adsorption process [15]

Comparing to the absorption ones, adsorption chillers do not use any hazardous substances such as LiBr or NH_3, so there is no corrosion, the range of operating temperatures starts from 50°C and ends at 90°C. The stable operation is provided by the adsorption process and chilled water output is in the range of 3°C up to 9°C, even in the case of fluctuating hot water temperatures as well as flow rates, which is common situation for waste heat recovery applications [6] [15].

Summing up, trigeneration is an energy cascade method, reducing operation costs and emitted GHG, improving the reliability of energy supply. The important factor for further development of this technology is the implementation of RES into these systems, to boost RES application, decrease the fossil fuel consumption as well as to mitigate undesirable impact at environment. The effective trigeneration system should have the ability to convert the heat, at lowest as possible temperature, into cooling, which enables from thermodynamic point of view, high efficiency of cogeneration unit - the base for trigeneration system [16]. Typically, in CCHP systems, the flue gas with high temperature is used not only to generate power in the turbine and cooling in absorption chillers, but also for the production of heat in the heat exchangers, with appropriate sequence of utilizing the remaining thermal energy inside the flue gas. Through this process, the performance of the system is at high-efficiency and there is big potential for different configurations to reach the economic feasibility and environmental requirements.

2.2 RES technologies in context of trigeneration

Renewable Energy Sources is the term describing energy carriers which can be found within the surrounding ecosystem with the supply of resources at level considered as the infinite one. RES used in power generation can be divided into three basic categories:

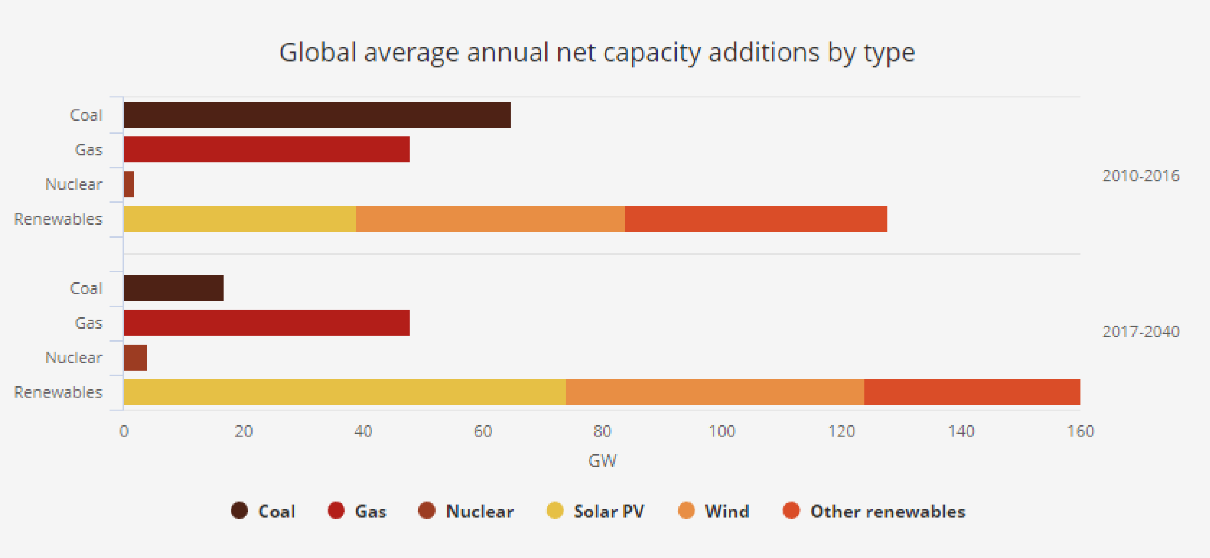
- The first one utilizes renewable resources as the main fuel source for the combustion process, for example installations using methane from landfills or gasifiers supplied by wood;
- The second category uses RES to increase the adequate thermal energy, needed to run conventional prime movers. The use of RES like biomass or geothermal energy, to produce the steam to generate power by steam turbine, is included in this category. The same case is with advanced solar thermal technologies, increasing the pressure of steam in the system or generating thermal energy through heat transfer in fluid, driving the gas turbine or reciprocating engine;
- The last category takes advantage of the natural forces of nature to produce power directly. By this description photovoltaics (PV) technology as well as water and wind turbines can be set as example [6].

RES are essential from sustainable development point of view and to achieve zero-carbon energy sector. Nowadays, there is a discussion if the production of energy by RES in the processes such as combustion is actually sustainable. However, as the issue is not yet legally formulated and burning biomass is still treated in many countries as zero-emission process (biomass is just releasing the amount of CO_2 previously absorbed) it will be used as zero-carbon technology in this dissertation. Zero-carbon energy sector would lead to maximizing both social and economic benefits, decreasing energy poverty, creating wealth and making simpler the access to energy. In the next years, the main role in the technology development will be reserved for innovation, although innovation in different fields would be equally important. Changes need to be done in policy, regulation, market design, business model as well as finance and infrastructure. Innovations in RES should include new ideas, to overcome current barriers and increase the use of renewable sources to energy production. Combining different policy instruments through all the lifecycle of technology is required, to implement new innovative solutions, in order to decarbonise the energy sector. That process includes starting from Research and Development installations and ending at market scale units, together with progress in the area of smart systems and information technology as well as incorporating new kinds of financial instruments [17].

According to International Renewable Energy Agency (IRENA), there are several trends connected with RES development in the nearest future. One of them is that the cost of generating power from renewable will continue to fall, so RES will be able to compete with other sources in order to meet requirements for new capacity installations. Over the last decade, many fluctuations of fossil fuels prices could be observed, proving the sensitivity of those fuels in regard to the local extraction and political influence. Despite this fact, RES deployment continued to progress, apart from higher or lower competitiveness in different years. Currently, in the in Organisation for Economic Co-operation and Development (OECD) countries, the cost of generating power from solar sources is lower than the nuclear power one. Levelized Cost of Energy (LCOE) from PV has fallen about 69% in the period 2010-2016 approaching the cost level of fossil fuels. It can also be found that worldwide, the competition helps in the process of spreading top available project development practices which leads to the reduction of both technology and project risks, as well as, makes RES the most cost-competitive in history. IRENA estimates that RES combined with energy efficiency is going to be responsible for 90% of required carbon reductions [17] [18].

The discussion concerning the future energy systems is highlighting three factors: fossil fuels replacement by RES; GHG reduction and increasing the efficiency of the installations. If one wants to combine the properties of these three factors the best solution is the implementation of RES into polygeneration systems. The polygeneration system addresses both issues, the cascade energy utilization decreases LCOE and increase the system efficiency, whereby economic and environmental issues are satisfied. For better understanding why such situation occurs, life cycle analysis can be studied. The assessment of this method by the researchers, studying the environmental impact of research object throughout its life, clearly shows, in the case of polygeneration systems, that it is better for the environment to generate power in this way than by stand-alone installations providing the same services [19]. The situation around the world is slowly changing, as the mankind is more aware that the way the energy industry operates now needs to be modified in the nearest future. In [20] it can be found that RES are responsible for 2/3 of the global investment worldwide in power plants, in time horizon of 2040. In the EU reality, the renewable sources stand for 80% of new capacity, using mainly wind power in ‘green’ production of electricity. However, it is also referred that because of Asia, mainly China and India, the PV electricity generation would be the greater than wind power until 2040. Intensified interest in RES is not only limited to the electricity, but there is also growing potential for heat and mobility generation.

Figure 2.6 shows the current trend in installing new capacities worldwide. As can be seen natural gas, due to the relatively low GHG emissions, is the last trending fossil fuel. For now, natural gas is also the major source of energy in trigeneration systems because of many reasons. Apart from low GHG emissions, it has also high LHV, easy way of storage and transportation.



World Energy Outlook 2017, IEA

Figure 2.6 Current trend in installing new capacities worldwide [20]

Figure 2.7 illustrates the energy flow in a gas-electricity integrated distribution system [21].

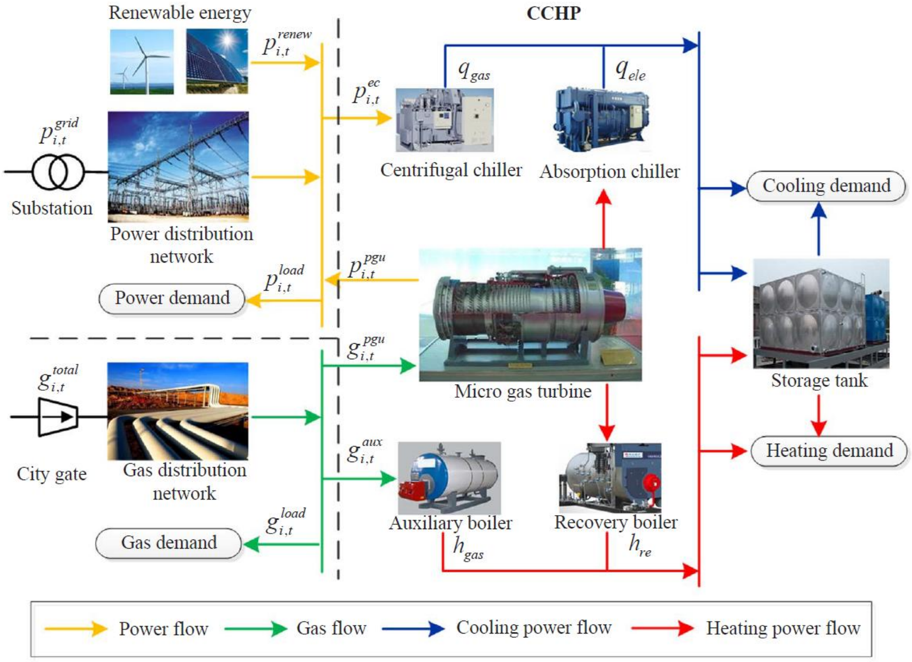


Figure 2.7 Energy flow in the gas-electricity integrated distribution system [21]

As presented in the scheme, in such systems, RES are responsible for producing electricity (PV and wind plants). However, electricity produced by RES is just additional power inserted to the system as the micro gas turbine is the main source for electricity and heat, the importance of RES is secondary in such system. Despite the current dependence on natural gas in trigeneration technology, there is a lot of effort made to figure out how in the future RES could replace the fossil fuels. The step further is already made and the proposals of the next generation systems are suggested - one of them is showed below (Figure 2.8).

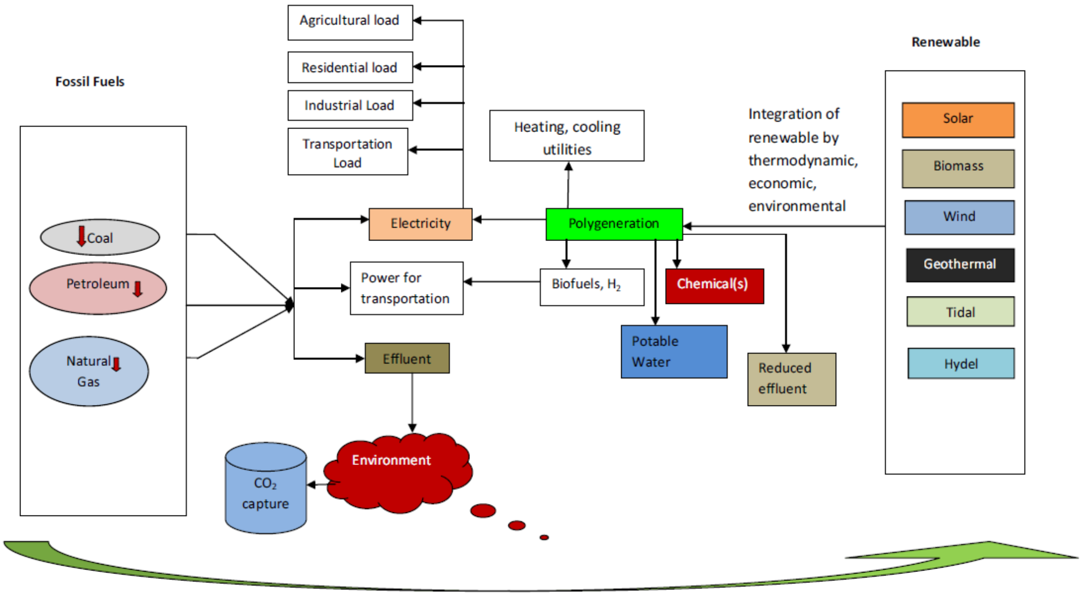


Figure 2.8 Transition from fossil fuel based energy systems to renewable based polygeneration [19]

In this scheme, it can be seen that RES are capable of giving much more products, apart from electricity and cooling mentioned in previous example. The wide range of outputs from polygeneration systems based on RES can be achieved and the energy sources to provide these outputs can be found in different fields of the nature. This mix of options, from solar to hydro system, enables the right combination with regards to the climate zone and its conditions, in the country that polygeneration operates. There is always at least one of RES at specified area to power such system, so the great advantage is the versatility, when it comes to the fuel supplying such installation.

2.3 RES in Portugal

In recent years, in Portugal, the electricity market underwent essential transformation. The reason of such changes is the process of unbundling of power transmission network, followed by liberalization in the context of generation and supply of energy. Nowadays, national electricity market is highly-deregulated with big emphasis on promotion of RES. In 2006 Portuguese customers were allowed to choose the electricity supplier and from January 2013 there are no longer regulated tariffs for final customers. That was the last step for the electricity market, when it comes to already mentioned liberalization process. Portugal is a world leader using RES, being currently, on the 3rd place, regarding the percentage of incorporation of RES inside the EU-28 group. Majority of this energy is from wind and hydro power. Looking ahead, Portugal has great potential for the use of RES, mainly solar and wind [22].

In 2013, the year of liberalization of electricity market, RES provided 23% of Portugal's electricity and in 2015, this amount increased to the level of 48%. The progress in this field ended up with astonishing the whole world, when Portugal has been entirely powered by RES, during four consecutive days in 2016. For approximately 107 hours all of the electricity production was covered by solar, wind and hydro power. In that year, wind energy was responsible for 22% of the overall electricity production and all RES provided 48% of the electricity production [23] [24].

The trend of incorporating RES to the national energy system in Portugal is clear. Looking at the timeframe 2000-2017, it can be observed that a rapid progress occurred in installed capacities of electricity generation.

As hydro power remained more or less at the same level (Figure 2.9), through all this period, solar, bioenergy and mainly wind capacities highly increased. From year 2015, RES capacities increased, with yearly average growth rate at level of 7%. At the same time, especially since 2011, working capacities of fossil fuels have begun to reduce.

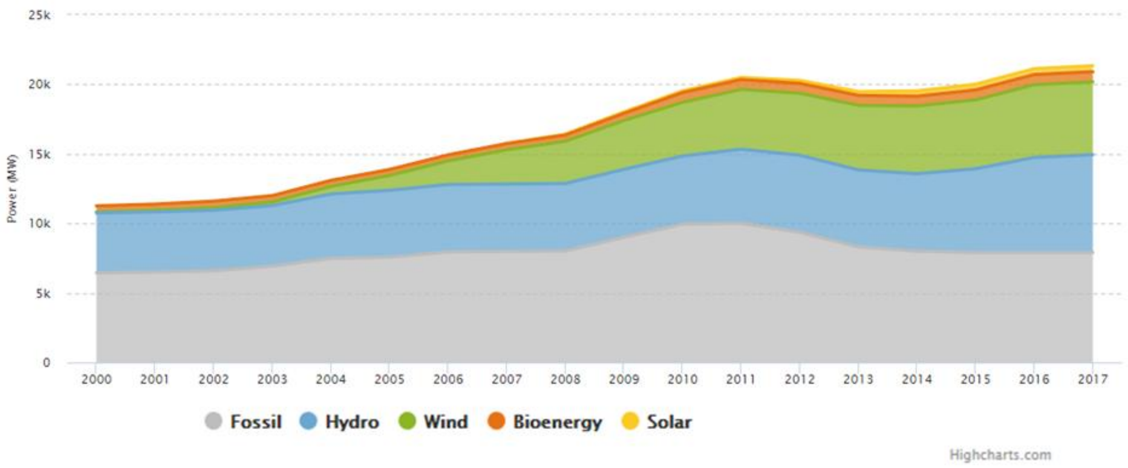


Figure 2.9 Evolution of the installed capacity of different sources of electricity generation in Portugal between 2000 and 2017 [24]

Figure 2.10 reveals the evolution of the electricity generation in mainland Portugal [24]. As can be seen in Portugal for long time was dependent from import. It can be caused by a gap in electricity generation or by the lower price of imported electricity compared to the one available in Portugal.

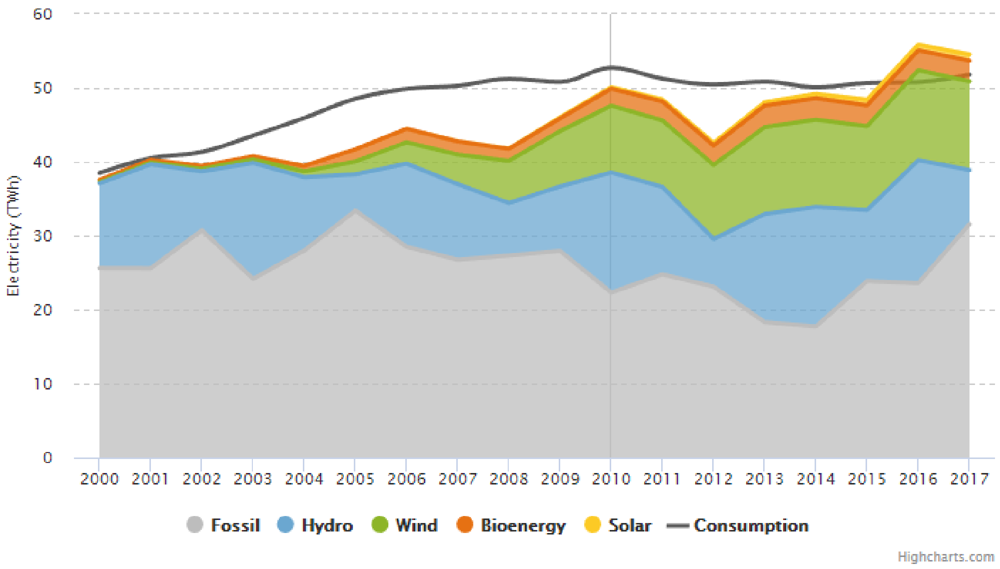


Figure 2.10 Evolution of the electricity generation in mainland Portugal between 2000 and 2017 [24]

Despite the huge increase of RES in the system, electricity generation from fossil fuels has also been progressing during the last four years. The more detailed analysis of last two years (Figure 2.11) explains this, as the result of the low rainfall and reduction of the hydro power potential. This can be caused by the periodical fluctuation in the amount of rainfall which was happening through the decades, one year rich with the amount of falling water from the sky, other one being quite dry. Unfortunately, it can be caused also by the climate change.

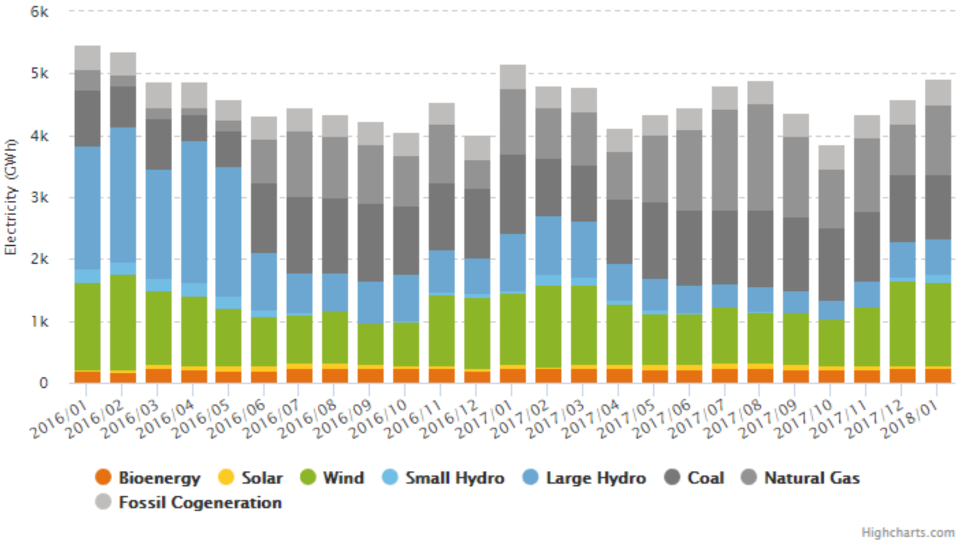


Figure 2.11 Distribution of the electricity generation by source for period 01/2016-01/2018 [24]

The overall current situation is well described in Figure 2.12. In January 2018, the RES-based electricity generation was responsible for 47.7% of the Portugal Mainland's total generation, which is equal to 2,341 GWh. During this month, natural gas-based power plants, the main fossil fuel source in Portugal, produced less electricity than wind parks. Despite the fact that in overall more electricity was produced from non-renewable sources than from RES, the main role in this distribution is played by wind farms.

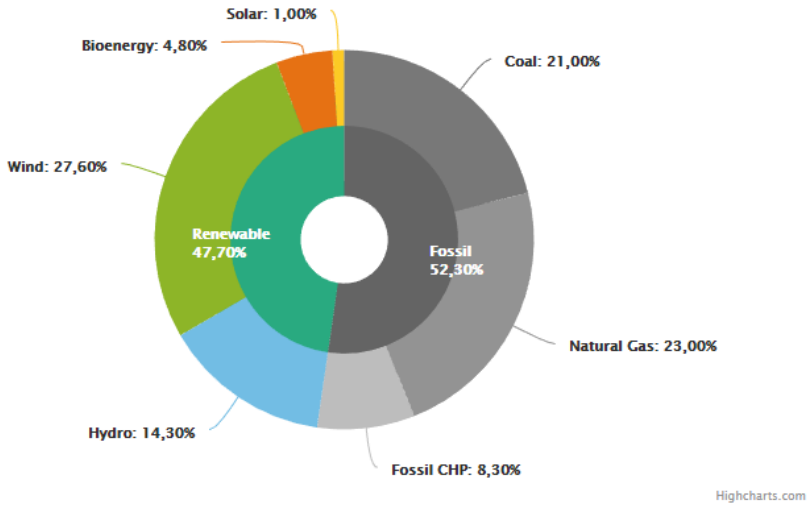


Figure 2.12 Electricity generation by energy sources in mainland Portugal for January 2018 [24]

The growth of the RES-based technologies also enables the reduction of specific GHG emissions from the electricity sector. The value of these emissions for 2017 was 360 kg/MWh. In the next years, the trend is expected to continue, allowing the process of Portuguese energy market decarbonisation. The evolution of specific GHG emissions is showed in Figure 2.13.

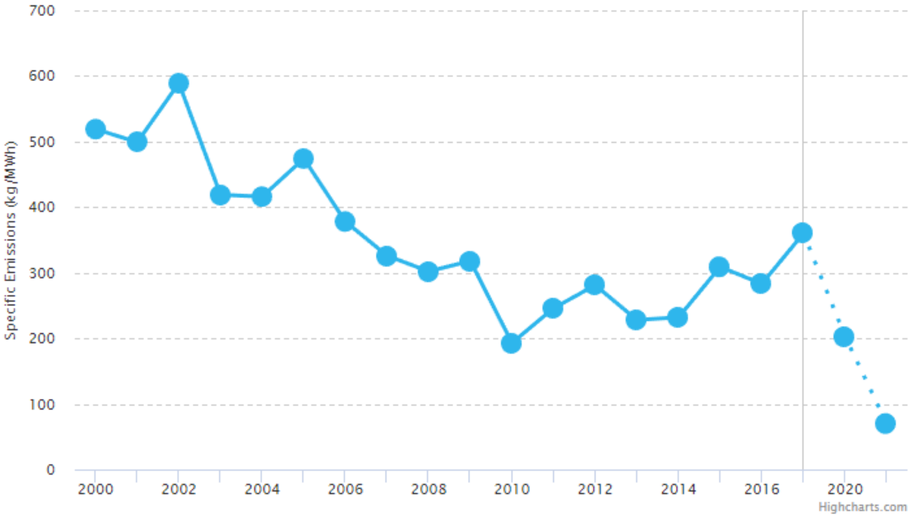


Figure 2.13 Evolution of the specific GHG emissions of the Portuguese electricity sector [24]

INEGI (Institute of Science and Innovation in Mechanical and Industrial Engineering) and APREN (Portuguese Association of Renewable Energies) worked on a project named e2p - Endogenous Energies of Portugal, where a database of the RES-based power plants installed in Portugal is gathered and presented on a map [25]. This map is presented in Figure 2.14.

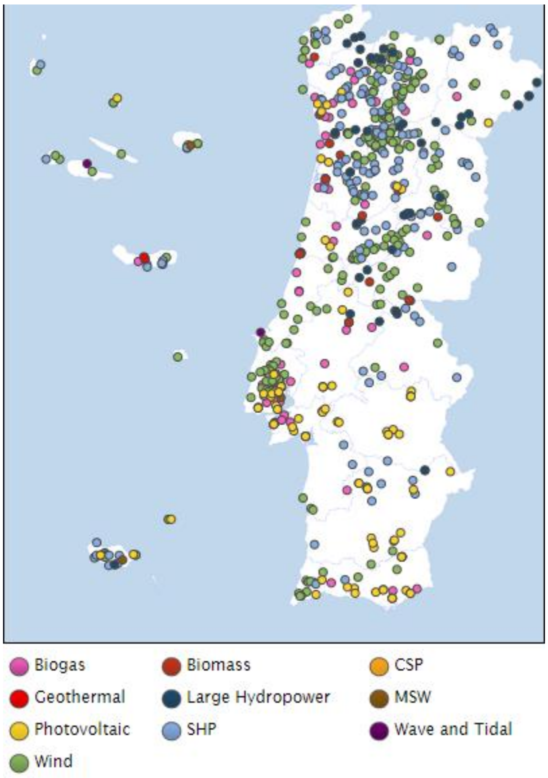


Figure 2.14 Map of all RES-based power plants in Portugal [25]

The bioenergy sector in Portugal, it is on development and has not an important role in the whole system, as other EU countries. However, as stated in [26], the potential of forestry sector is still untapped, and in the future, targets set for bioenergy, can be covered in large extent by this sector. Biomass conversion technologies, in Portugal, are mainly combustion systems. The utilization of the residues from agricultural, namely cereal straw, olive-stone and grapestone and agro-feeding industry is mainly limited to the heat production [27].

The main land types in use in Portugal are forests, bushes, pastureland and agricultural land. In the 2010 forest land was about 3.154 million hectares (mha), bushes and pastureland 2.853 mha and agriculture 2.114 mha. Forests used 37.6% of land places which put Portugal in the average of EU members. Figure 2.15 shows the distribution of land use in Portugal mainland [27].

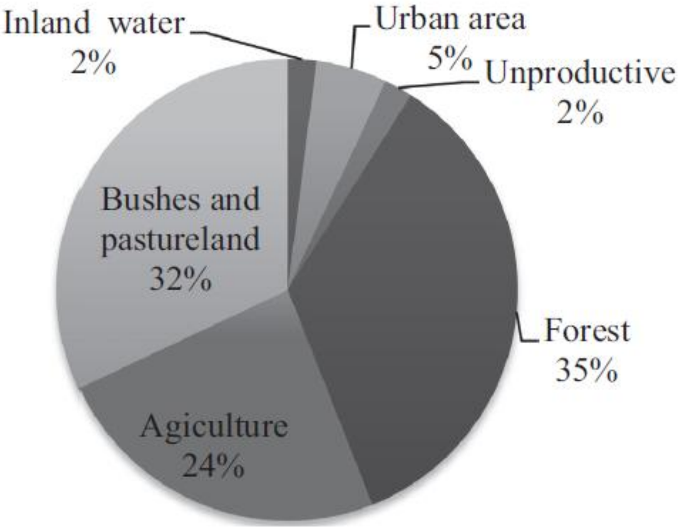


Figure 2.15 Distribution of land use in Portugal mainland [27]

As it can be seen, the urban area is only 5% of the whole land, with 2% of inland water and 2% of unproductive land. The rest of land, and its huge participation in the distribution, can be promising for bioenergy in this country, even assuming some restrictions.

The diversity and the distribution of RES in Portugal is quite wide, so there is a lot of RES potential to use in trigeneration systems. The main problem in Portugal is the not properly defined support for cogeneration/trigeneration plants, but with the green certificates from RES and almost infinite supply of the resources, the prospect of RES-based trigeneration systems is tempting. Another problem that occurs nowadays is the technology limitation. Not all RES are appropriate in case of this technology or easy to implement. However, there are many examples of research and proposed solutions in the area of trigeneration [28] [29], polygeneration [30] [31] or district heating and cooling [32] systems which can be adopted for the Portuguese needs.

3. CASE STUDY

The case study assessed in the present thesis is a trigeneration system (Climaespaço) located in Parque das Nações, Lisbon. It is the only DHC system in Portugal. An entire district was built from the scratch, so the solution used in this plant is relatively modern and efficient, using natural gas as a fuel source to power the trigeneration system. DHC supplies almost 3,500 customers, including 30 large consumers, 300 medium and more than 3,000 small ones. The length of the network of pre-insulated pipes, delivering cooling and heating medium across the estate, is equal almost to 85 km, taking into account four different pipes inserted into the ground, at distance of 21 km each. From many buildings supplied by the plant the greatest examples are: Lisbon Oceanarium, Vasco da Gama Shopping Mall, Altice Arena, Orient Railway Station, Hotel Myriad and Science Museum [11].

3.1 Climaespaço Plant

The plant is part of the Engie group. The installation cooling capacity is 35 MW, heating capacity is 29 MW and electrical capacity around 5 MW.

Trigeneration system enables to achieve high efficiencies, namely 30% for production of electricity and 55% of thermal energy production, which gives in sum the overall efficiency at level of 85% [33]. The operation scheme of the system is shown in Appendix.

The gas turbine converts natural gas (chemical energy) into mechanical energy. The turbine blades rotation spins a generator producing electricity. By these steps, normally there is a significant loss of energy. In this case, from power delivered by the fuel, so 16.2 MW, only about 31% is used by gas turbine in a way of mechanical energy, giving at the end through alternator 29% of electricity. Flue gases are used together with the new portion of natural gas, to feed the steam turbine. The 12 MW steam turbine, in the form of heat recovery boiler (Figure 3.1), is installed after the gas turbine, afterburning is used to increase thermal energy.

Figure 3.1 Heat recovery boiler of Climaespaço Plant [33]

This step prevents from wasting the heat energy, using it as a steam in heat exchangers or chillers. Another heat source is the auxiliary boiler with a capacity of 15 MW (also powered by natural gas) used to cover the peaks in heating and cooling demand. The division of heat steam between the heating and cooling purposes enables the flexibility of the entire system. The steam is distributed to machines according to the needs, providing quick reaction to the market needs and optimizing the process. Technical review of the gas turbine is possible without disruption of the system, as the auxiliary boiler is in place. The most important factor for Climaespaço and its clients is the heating and cooling production. Electricity is an additional product of the trigeneration system, being an extra income from FIT program. Heating needs are covered by three heat exchangers: two in form of shells/tubes and a plate one - each of them with capacity of 11 MW. Incoming water to the plant has the temperature of 65 ^{o}C and after heating up in the heat exchangers it leaves the system with 100 ^{o}C. In the reality, the difference of temperature is narrower to avoid losses. Inlet temperature is higher, reaching circa 70 ^{o}C and the outlet one is lower - nearly 90 ^{o}C. The water is delivered by the distribution pipes - Figure 3.2.

Figure 3.2 Distribution pumps of Climaespaço Plant [33]

Due to the hot climate and high temperatures, especially in summertime, the demand for cooling in Portugal is high. In Climaespaço, in order to produce the cooling from heat, two absorption chillers are used. Apart from them, to avoid full dependence from steam, two compression and two centrifugal chillers (Figure 3.3) are in stock to produce cooling from electricity.

Figure 3.3 Centrifugal chillers of Climaespaço Plant [33]

However, their role is secondary, as the production of cooling in this equipment is more expensive. The absorption chillers are the first ones to cool down the water and from them water is transported to the compression or centrifugal ones. Generally, two pairs of absorption-compression chillers are working constantly while the centrifugal chillers are kept in reserve. Despite the fact which chillers are operating in the particular moment, all of them: absorption, compression or centrifugal ones need different streams of water, especially the water from the Tagus river as a cooling agent. Interesting fact is that the water coming from the river is, according to the requirements of the process, cleaned and returns in better condition to the river than it has been in before the process. The difference in temperatures is just 8 ^{o}C and the amount of water in scale of the whole river is marginal, so the river is not heated up significantly, which is also important for environmental reasons. To meet the demand and easily react to market needs, the cooling system would not be complete without appropriate storage of the cooling water in the tank. The chilled water tank contains 15,000 m^{3} of water in two zones. First zone is the water which is coming back from clients with 12 ^{o}C and is pumped in the top of the reservoir. The second zone is the chilled water in the plant, taking its place in the bottom of the reservoir. These two zones are almost not mixing with each other due to different temperatures and densities. The tank stores the cooling water produced, mainly at night by chillers, as the electricity is the cheapest at that time [33].

3.2 Data treatment and analysis

To carry out the analysis of the trigeneration system used in Climaespaço, answering questions regarding production of the plant was necessary. Through the good offices of headquarters of the company in charge of Climaespaço, part of the requested data was provided, namely typical daily profiles [33]. Figure 3.4 and 3.5 show a typical daily profile of the heating and cooling distributed for a summer day and for a winter day, respectively.

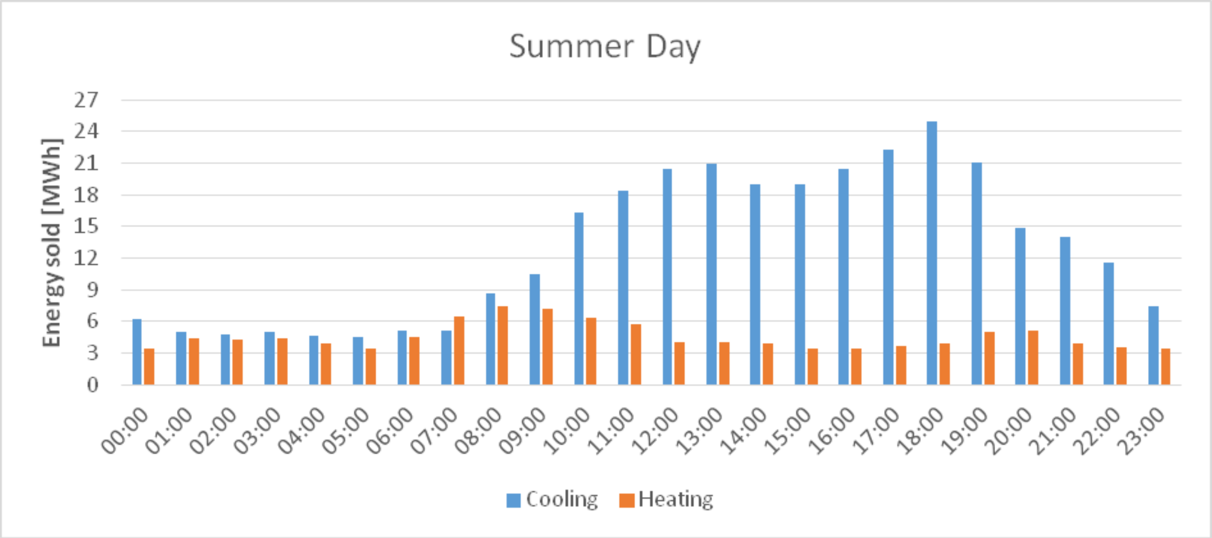


Figure 3.4 Typical daily profile of the heating and cooling distributed for a summer day in Climaespaço plant [33]

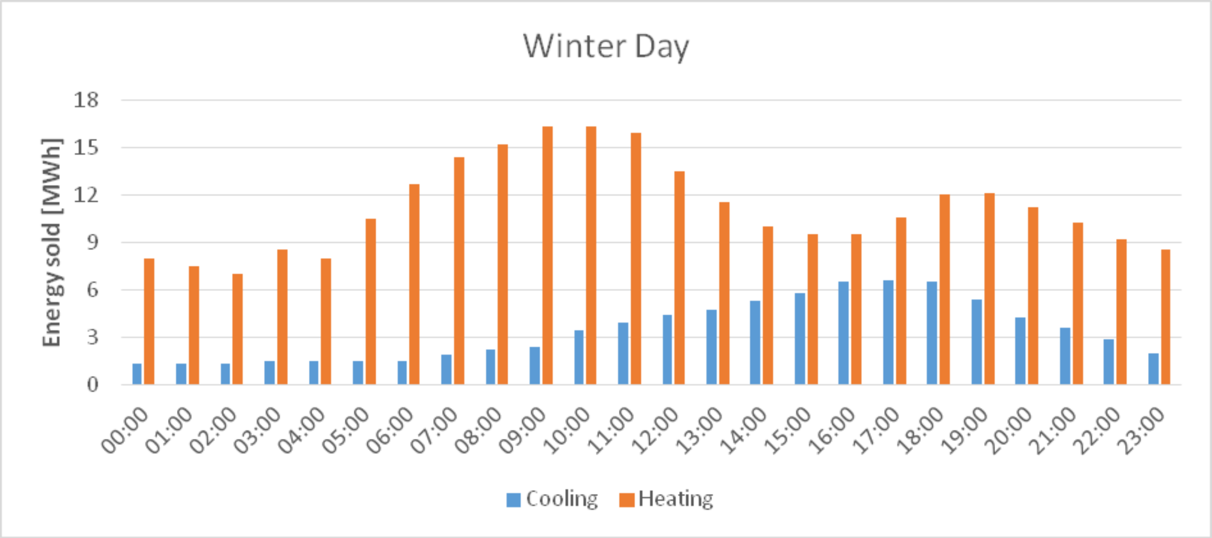


Figure 3.5 Typical daily profile of the heating and cooling distributed for a winter day in Climaespaço plant [33]

Naturally, there is a clear seasonal dependence of demand for both heating and cooling - heating demand is dominant during winter time while cooling demand is dominant during summer.

The next step was to understand how the whole process of the heating and cooling production in the plant occurs. As it was mentioned before, the chilled water tank plays the role of the storage tank. The chilled water is not produced as the daily profile shows but is just distributed in this way. The main production occurs during the night and early morning from 10 pm to 8 am due to the cheaper price of the electricity. This issue must be taken into account to convert energy distributed to actual energy produced. The following method, taken from another study where the same case study is assessed [34] was used: 10 highest values of cooling have been chosen and the average value of them was calculated. This value was assumed as the relative one but only for the time between 10 pm to 8 am. For period between 8 am to 10 pm calculation was slightly different. Average for the whole day was calculated and each value (from the leftover group) was divided by it. In the heating production case, only average value for the whole day was computed, and each indicator was divided by it, without looking on the highest values. The relative value for the production was achieved and is presented below in Figures 3.6 and 3.7, for both summer and winter day.

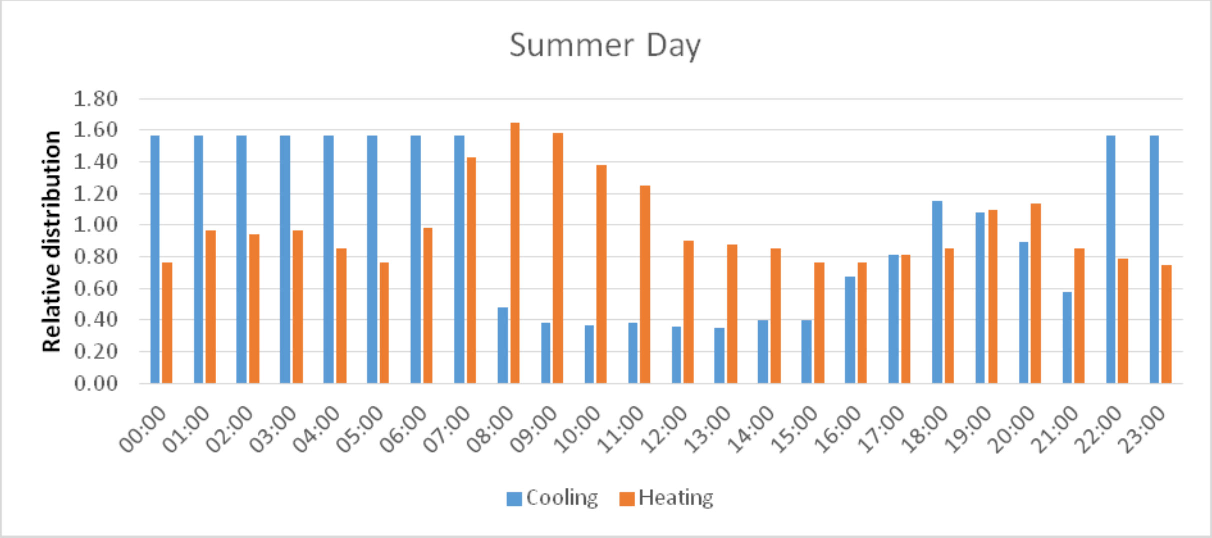


Figure 3.6 Relative distribution of the typical daily profile of heating and cooling production for a summer day in Climaespaço plant

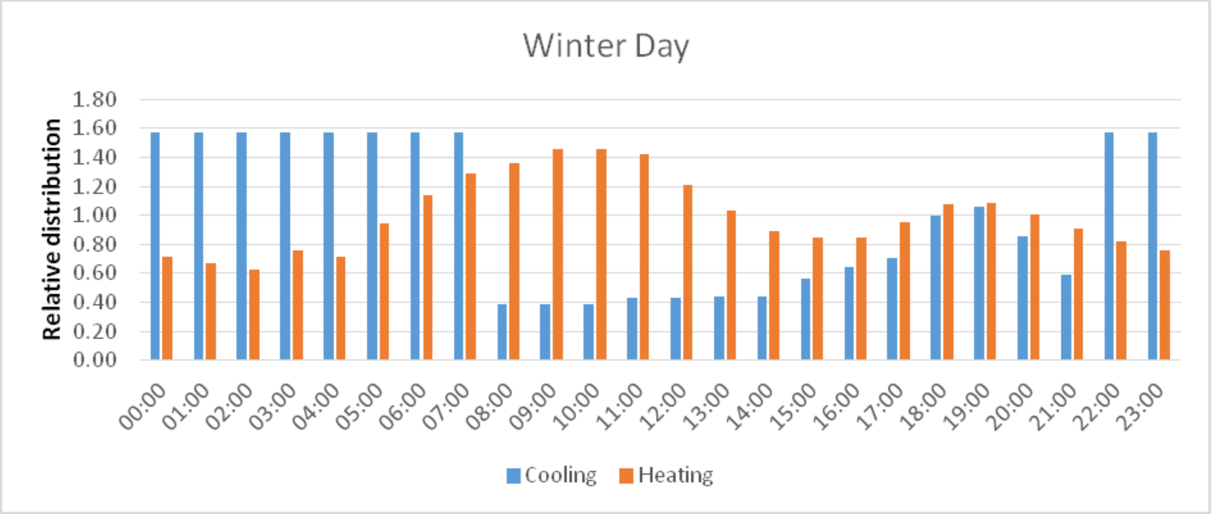


Figure 3.7 Relative distribution of the typical daily profile of heating and cooling production for a winter day in Climaespaço plant

The last step was to multiply both numbers: the achieved relative distribution and the original data provided from the company. The result of this operation is shown below (Figures: 3.8 and 3.9).

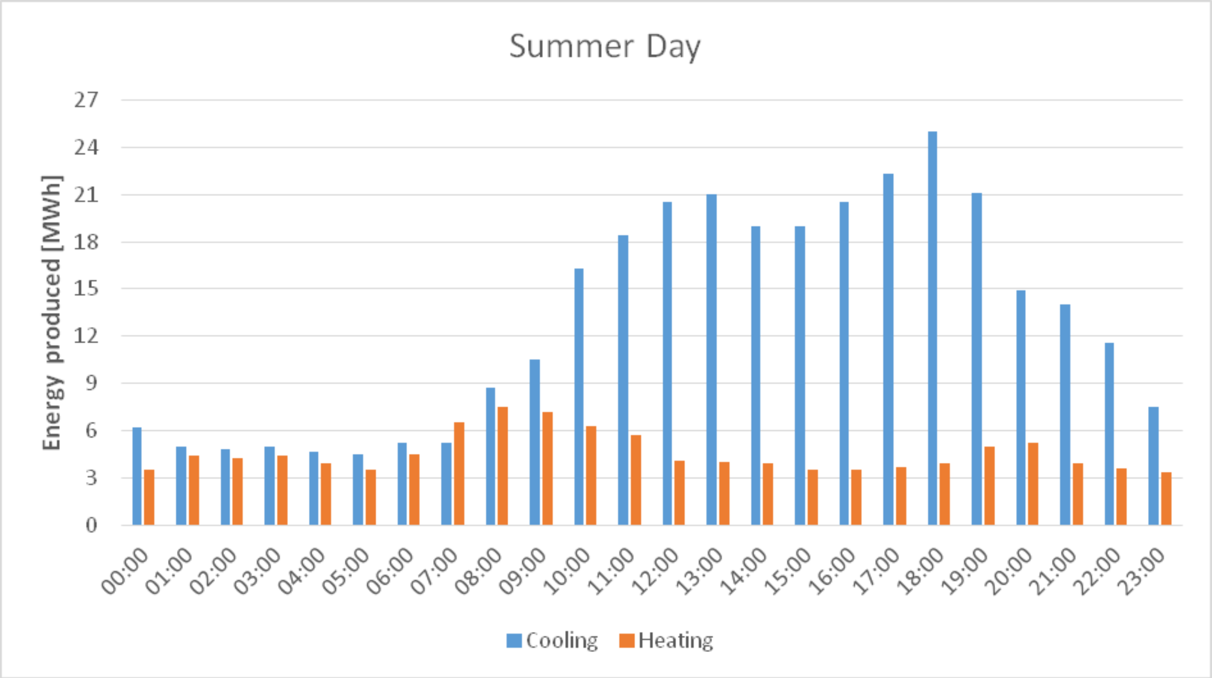


Figure 3.8 Estimated typical daily profile of heating and cooling production for a summer day in Climapespaço plant

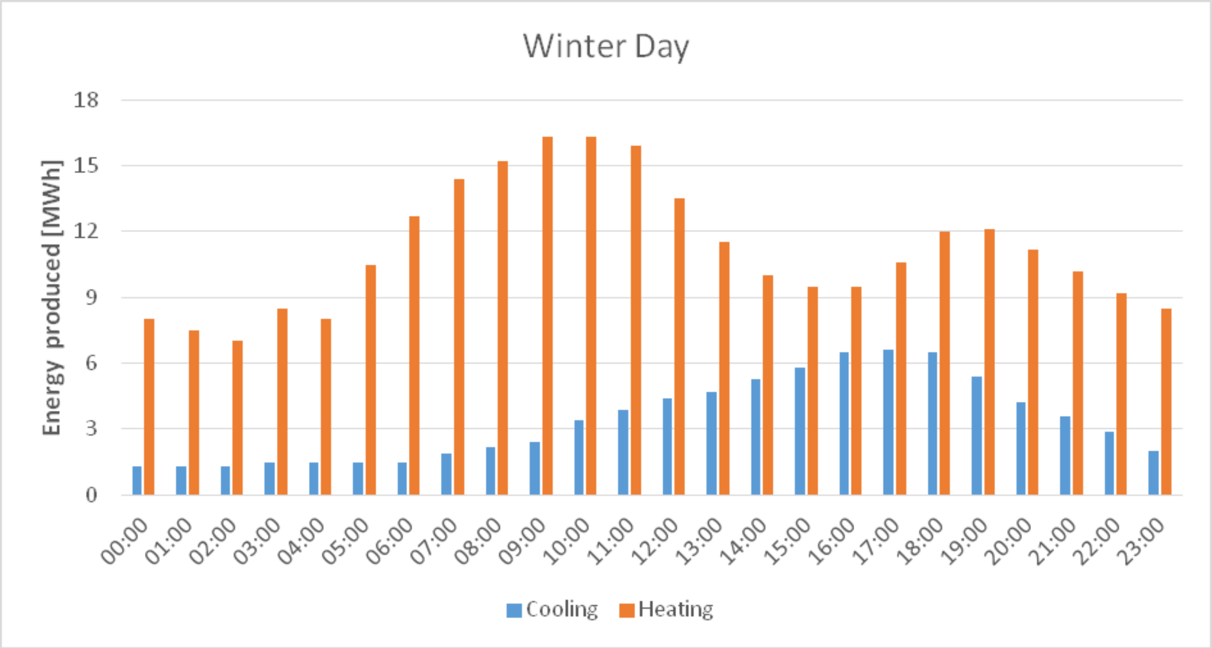


Figure 3.9 Estimated typical daily profile of heating and cooling production for a winter day in Climapespaço plant

The rest of the necessary data and the methodology for calculating energy production and demand of the plant was also taken from another study [34]. This data concerns the daily indicators in the plant, originated from the year 2012. In order to achieve the hourly data, it was necessary to combine daily indicators with relative distributions. Each daily parameter was divided by 24 and multiplied by its relative distribution equivalent. For heating and cooling approximation, it was important to use appropriate profile (of summer or winter day) and exact hour. (Figure 3.10).

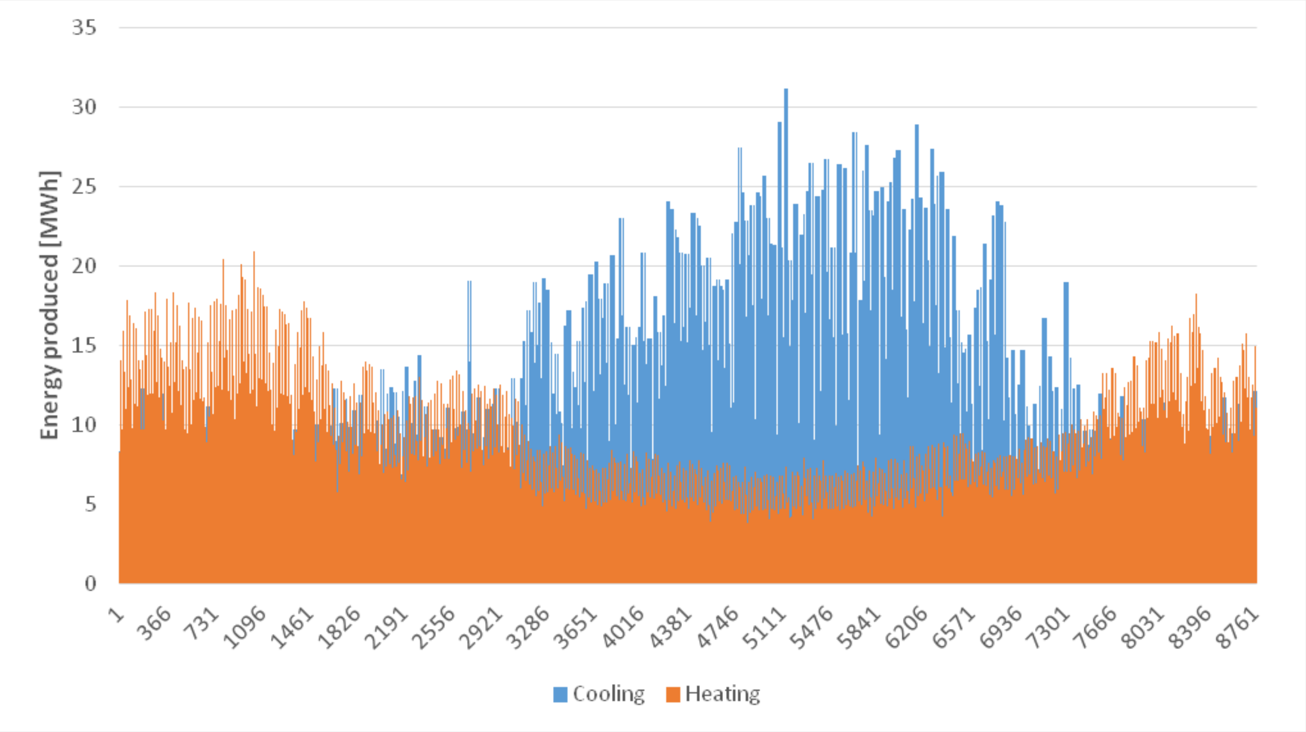


Figure 3.10 Heating and cooling hourly production estimated distribution for the year 2012

Due to the lack of data, showing the hourly profiles of electricity production inside the plant, the daily values were divided by 24, in order to have an hourly profile - Figure 3.11.

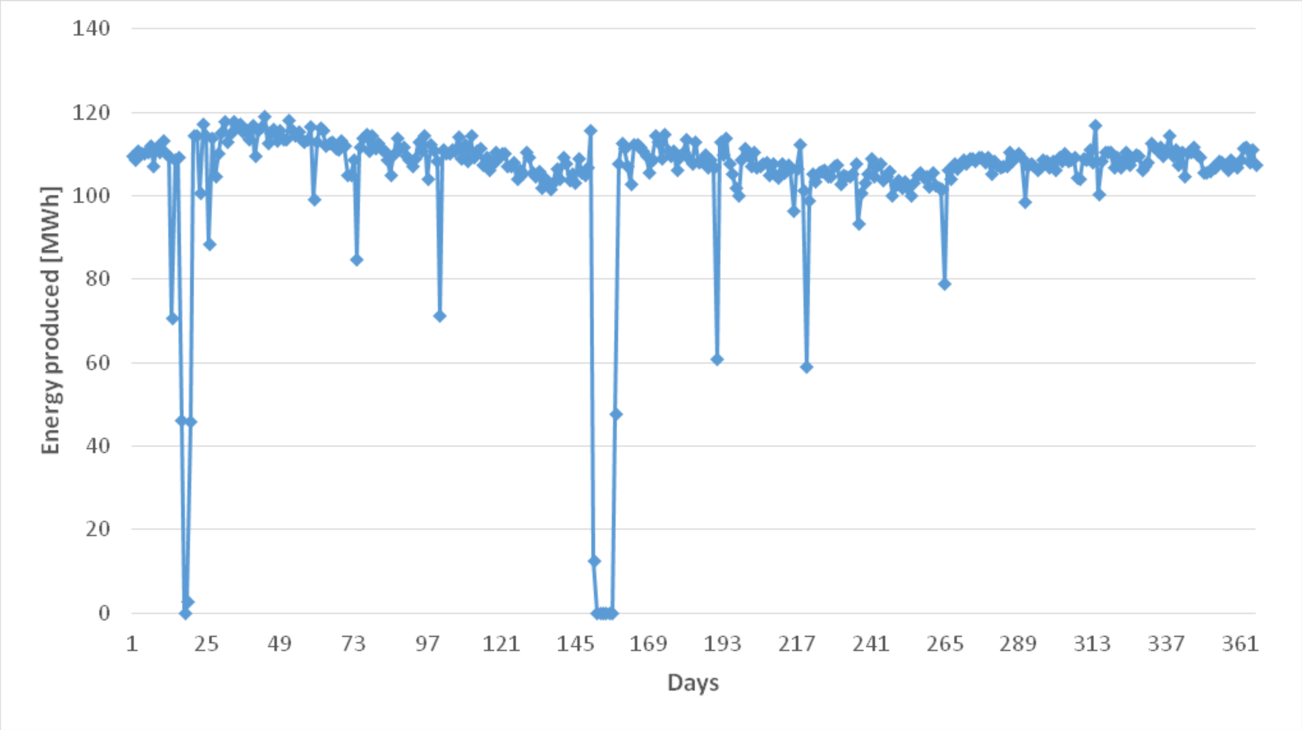


Figure 3.11 Estimated daily electricity production for the year 2012

To provide reliable results double verification was made before starting the simulations. The daily data of electricity, cooling and heating production was summed and compared with the sum of the hourly values, created by multiplying distributions. The results were commensurable, proving correctly made process of preparing the distributions. Seasonal dependence of the heating and cooling production can be clearly seen at Figure 3.10. The main problem for the provider of those products, Climaespaço plant, is the difference in levels of heating and cooling demand. While cooling is needed almost all year, having its peaks in summer, heating demand, even in the winter time, is not that big. The greatest emphasis is placed on cooling sector in Portugal because of the climate and weather. When it comes to the electricity production, it can be found at Figure 3.11 that the production was reduced or even stopped in some periods. As the assumption of maximizing the usage of gas turbine to gain benefits in plant is set, the reason of such points could be either the optimization to meet the market needs, not using the nominal turbine power, or the requested yearly maintenance of the device.

3.3 Scenarios considered

The main purpose of this thesis is to analyse Climaespaço plant and suggest future solutions which could be used to replace or improve the current system. In order to evaluate different configurations, the following scenarios were considered:

- **Baseline scenario**

This scenario represents the system as it is now. The system was modelled and validated based on the data provided, giving data that will be used also in the next scenarios.

- **Scenario 1**

In this scenario, the assumption regarding Climaespaço plant cooperation with Valorsul Project installations is made [35]. The main idea of this cooperation is to import the leftover steam from Waste to Energy (WtE) plant of Valorsul, which is currently wasted energy. In this scenario, the delivery of steam and the construction of a new 5.5 km pipeline are considered (as this is the distance between the plants). Nevertheless, the demand of Climaespaço plant to be covered is relatively small, comparing to the entire amount of the steam produced by the WtE plant. Because of that, the price of this steam which would enable the system to be profitable and the cost of construction the pipeline must be considered in the economic analysis. This scenario is divided into two parts due to the different approaches in the utilization and the amount of steam imported from WtE plant.

  - Scenario 1a

This scenario is the combination of the baseline scenario with an assumption that part of the heat, in the form of steam, is taken from WtE plant. The idea is to optimize the usage of the gas turbine, which will still be producing the electricity and heat, but in a way to reduce the natural gas consumption by covering the rest of heat demand from WtE plant. The natural gas driven auxiliary boiler is also in operation.

  - Scenario 1b

In this scenario, the majority of heat demand is covered by the wasted energy from Valorsul WtE installation and the electricity for internal purposes is bought from the grid. The gas turbine is removed from the plant, but the back-up 15 MW boiler remains. This auxiliary boiler is powered by natural gas and covers part of the demand during the peaks and is the emergency source for the plant, in case there is a problem in delivery of the steam from WtE plant.

- **Scenario 2**

In this scenario, the system based on the gas turbine is completely removed and replaced by a biomass boiler system. Back-up boiler remains in the system but it is also supplied by biomass. This scenario is the first one with the assumption of 100% RES energy production. Scenario 2 is divided in two parts also.

  - Scenario 2a

In this scenario, it is assumed that the biomass boiler covers all heat demand, production of electricity is also included in this solution. Biomass boiler works as CHP unit, a base for trigeneration, producing the electricity, which excess is sold to the grid and heat, later on used for heating and cooling purposes. The appropriate type of biomass was suggested and its price assumed in the economic analysis.

  - Scenario 2b

This scenario is different from the previous since it includes PV and wind power installations in the plant to produce electricity. The distributions for the software are made from calculating the parameters out of the weather data, provided for the geographical area of plant. The appropriate efficiency of the PV panels and type of wind turbine was chosen.

- **Scenario 3**

The last scenario is the combination of the scenario 1b with scenario 2b. The solution proposed is a highly diversified RES system accompanied with relatively high electricity production. It is based on the use of steam from WtE plant, the installation of an auxiliary 15 MW boiler based on biomass and of PV and wind power systems in the plant.

4. METHODOLOGY

4.1 Technical analysis

4.1.1 EnergyPLAN tool

The software used in this work is called EnergyPLAN. The program itself is a deterministic tool, using hourly data such as electricity, cooling, heating distributions and much more, to simulate a one year operation of a given energy system. The range of inputs is wide, from energy demand and power capacities with separate RES section, to detailed costs. From outputs energy balance, RES participation, CO_2 emissions and fuel consumption are the fundamental ones. The model existing in the EnergyPLAN software is the example of applying manual heuristics to find optimal configurations of energy systems. Different regulation strategies can be chosen, depending on user's needs: technical analysis with balancing heat or/and electricity demands as well as separate market economic simulation. The software is able to model high-RES systems and helps to find optimal utilization, for example of otherwise limited RES-based power production, in different energy sectors [36] [37] [38]. Due to the reasons mentioned above and the fact that EnergyPLAN provides detailed results (crucial to obtain in this dissertation) as well as it is widely used by other researchers, this tool has been chosen for technical analysis. Regarding the version of software used during simulations it was EnergyPLAN 12.5 from 23rd of September 2016. The starting page of the program is attached below in Figure 4.1.

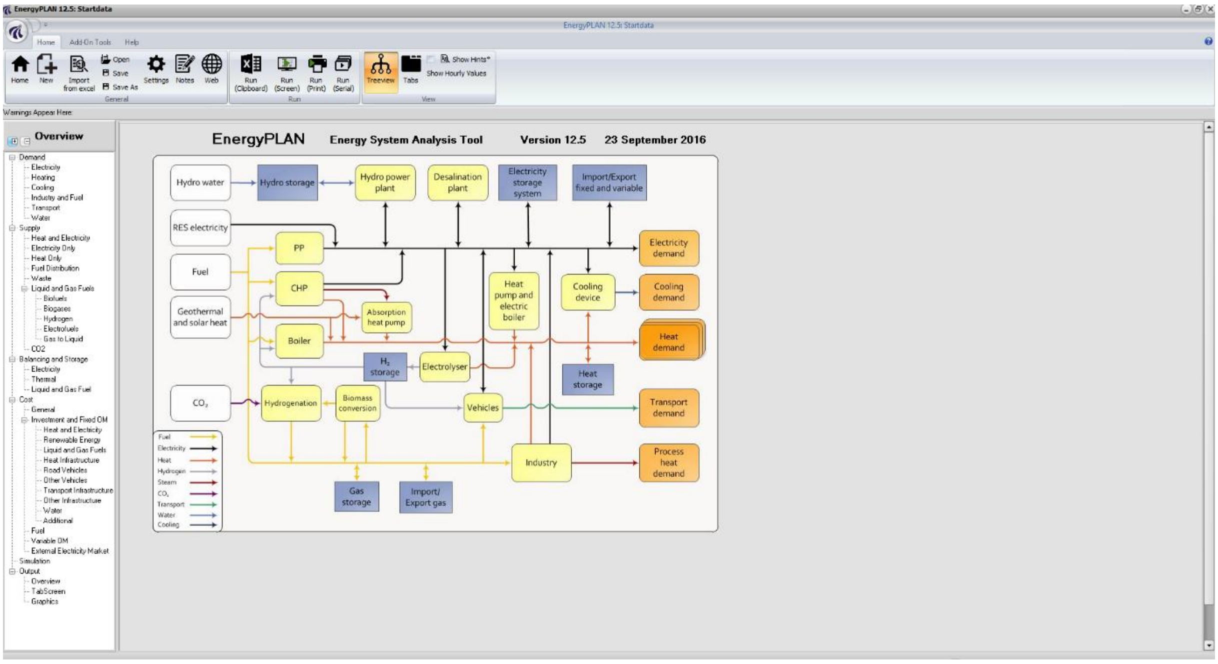


Figure 4.1 Interface of EnergyPLAN [36]

At the top, there are three sections: Home, Add-On Tools and Help. Home section gathers the most important buttons, from technical point of view. Add-On Tools are mainly to convert units, compare versions used or to edit distributions. Help section enables to obtain more information about the software and find the solution according to the problem. At the left side, there is an overview tab with each spreadsheet used in the program. Main ones are: Demand, Supply, Balancing and Storage, Cost, Simulation and Output, which include sub-sections. At the centre, during start-up of the software, diagram, showing interconnection between different branches of the network, always appears. It shows the available synergies between the energy sectors (Figure 4.2). According to this scheme, EnergyPLAN gives the user the opportunity to construct the energy system. Diagram is detailed with energy currents, forms, products and by-products.

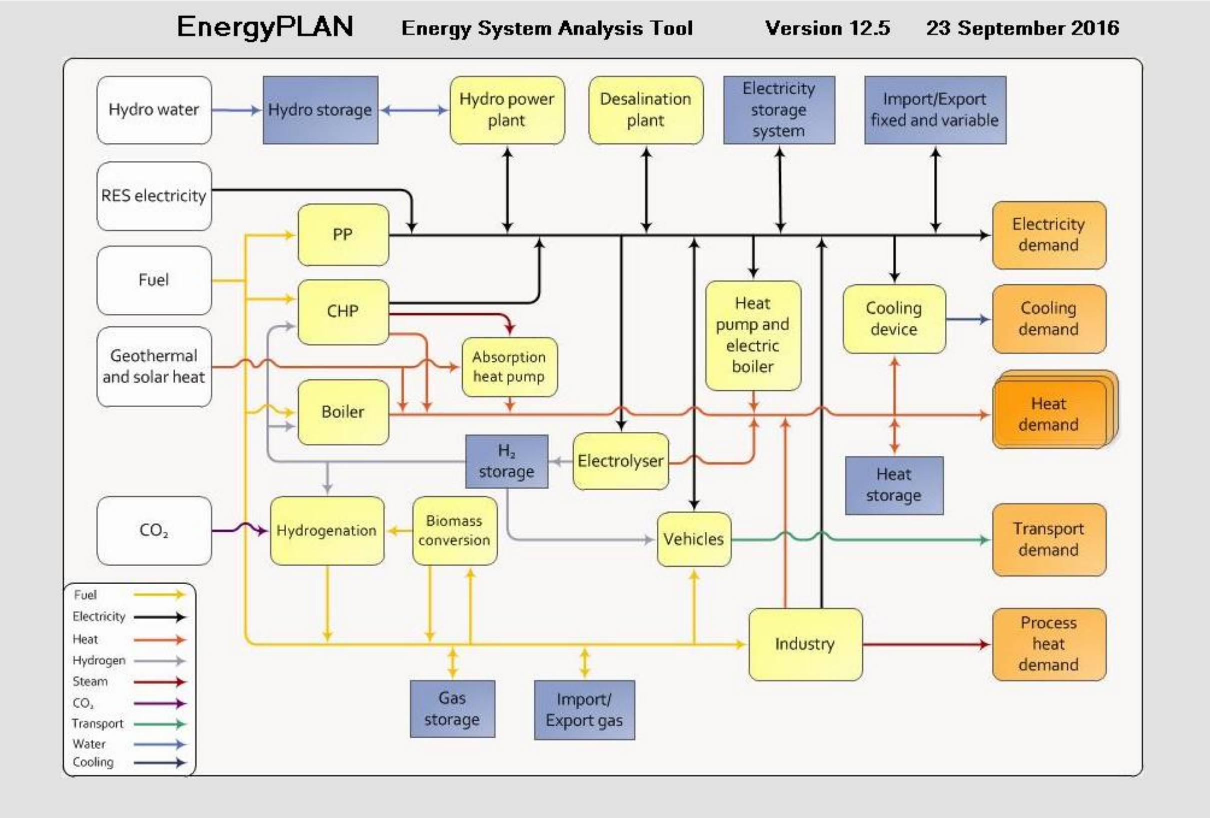


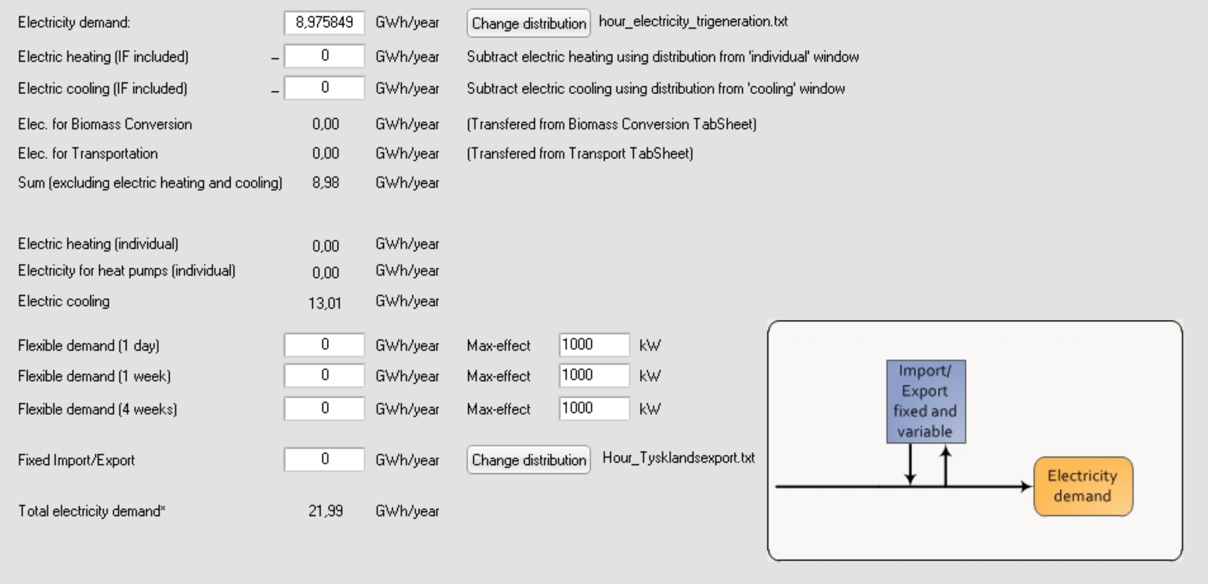
Figure 4.2 Synergies scheme [36]

4.1.2 Simulating scenarios

The process of simulating scenarios in EnergyPLAN will be shown in this section, following the example of some spreadsheets used in baseline case.

The first parameter which one has to bear in mind is the electricity demand of the system, so in this case electricity consumption of the plant. The software, at this stage, gives the opportunity to include electrical heating or cooling in the total electricity demand balance.

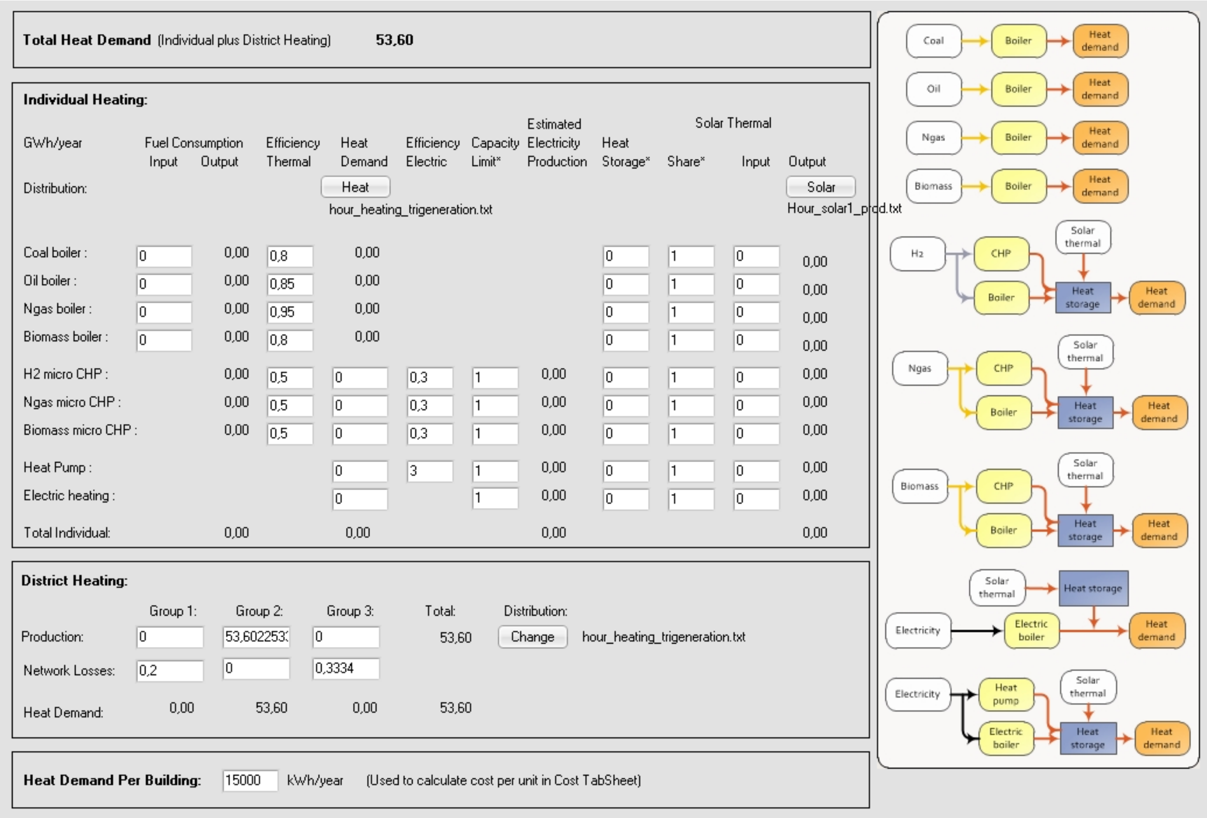
The input parameter presented on the screen (Figure 4.3) is simply calculated as the sum of the daily values of electricity consumption for internal purposes in the plant [34]. Created previously hourly distributions are selected. The electrical cooling demand is computed by the program automatically, from data provided in different section, which would be mentioned later. As it can be seen, the total electricity consumption is the sum of the electricity for internal purposes and the electrical cooling one.



Electricity demand:	8,975849	GWh/year	Change distribution	hour_electricity_trigeneration.txt
Electric heating (IF included)	– 0	GWh/year	Subtract electric heating using distribution from 'individual' window	
Electric cooling (IF included)	– 0	GWh/year	Subtract electric cooling using distribution from 'cooling' window	
Elec. for Biomass Conversion	0,00	GWh/year	(Transfered from Biomass Conversion TabSheet)	
Elec. for Transportation	0,00	GWh/year	(Transfered from Transport TabSheet)	
Sum (excluding electric heating and cooling)	8,98	GWh/year		
Electric heating (individual)	0,00	GWh/year		
Electricity for heat pumps (individual)	0,00	GWh/year		
Electric cooling	13,01	GWh/year		
Flexible demand (1 day)	0	GWh/year	Max-effect	1000 kW
Flexible demand (1 week)	0	GWh/year	Max-effect	1000 kW
Flexible demand (4 weeks)	0	GWh/year	Max-effect	1000 kW
Fixed Import/Export	0	GWh/year	Change distribution	Hour_Tysklandsexport.txt
Total electricity demand*	21,99	GWh/year		

Figure 4.3 Electricity demand spreadsheet [36]

Secondly, the amount of heat needed in the entire cycle has been calculated. The process was similar as previously, so the sum of the daily values of the heat consumption, was computed [34]. Achieved value was put in the district heating section, in second group as the Climaespaço plant can be defined as a CHP small scale unit. This group contain installations where heat and electricity production is coupled. Heat distribution is selected from the data created with the same principle as in electricity demand example (Figure 4.4) [39] [40].



Total Heat Demand (Individual plus District Heating) **53,60**

Individual Heating:

GWh/year	Fuel Consumption Input	Output	Efficiency Thermal	Heat Demand	Efficiency Electric	Capacity Limit*	Estimated Electricity Production	Heat Storage*	Solar Thermal Share*	Input	Output
Distribution:				Heat hour_heating_trigeneration.txt							Solar Hour_solar1_prod.txt
Coal boiler :	0	0,00	0,8	0,00				0	1	0	0,00
Oil boiler :	0	0,00	0,85	0,00				0	1	0	0,00
Ngas boiler :	0	0,00	0,95	0,00				0	1	0	0,00
Biomass boiler :	0	0,00	0,8	0,00				0	1	0	0,00
H2 micro CHP :		0,00	0,5	0	0,3	1	0,00	0	1	0	0,00
Ngas micro CHP :		0,00	0,5	0	0,3	1	0,00	0	1	0	0,00
Biomass micro CHP :		0,00	0,5	0	0,3	1	0,00	0	1	0	0,00
Heat Pump :				0	3	1	0,00	0	1	0	0,00
Electric heating :				0		1	0,00	0	1	0	0,00
Total Individual:		0,00		0,00			0,00				0,00

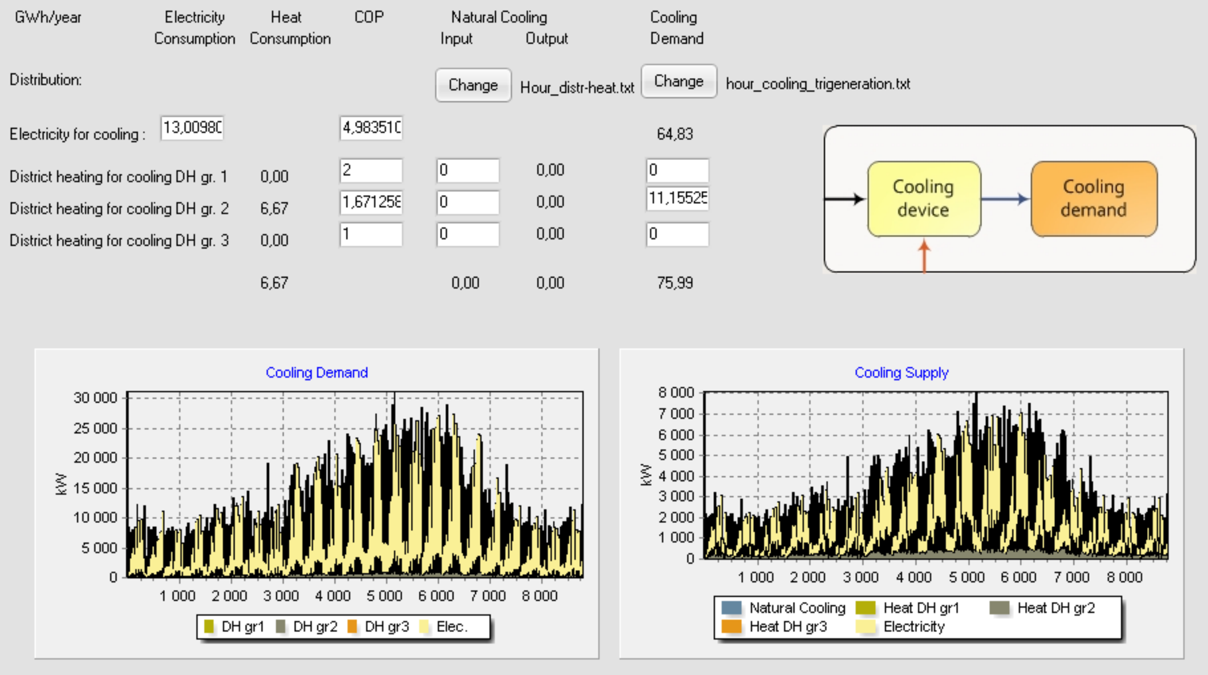
District Heating:

	Group 1:	Group 2:	Group 3:	Total:	Distribution:
Production:	0	53,602253	0	53,60	Change hour_heating_trigeneration.txt
Network Losses:	0,2	0	0,3334		
Heat Demand:	0,00	53,60	0,00	53,60	

Heat Demand Per Building: 15000 kWh/year (Used to calculate cost per unit in Cost TabSheet)

Figure 4.4 Heating demand spreadsheet [36]

The last step regarding demand section was to insert the data for the amount of cooling needed, together with the electricity demand for cooling itself. Here, the software asked for the parameters from which part of them could not be achieved directly (from the data provided). Thus, each parameter had to be calculated with individual approach - Figure 4.5.



GWh/year	Electricity Consumption	Heat Consumption	COP	Natural Cooling Input	Natural Cooling Output	Cooling Demand	
Distribution:				Change	Hour_distr-heat.txt	Change	hour_cooling_trigeneration.txt
Electricity for cooling :	13,0098		4,98351			64,83	
District heating for cooling DH gr. 1		0,00	2	0	0,00	0	
District heating for cooling DH gr. 2		6,67	1,67125	0	0,00	11,1552	
District heating for cooling DH gr. 3		0,00	1	0	0,00	0	
		6,67		0,00	0,00	75,99	

Figure 4.5 Cooling demand spreadsheet [36]

When it comes to the calculation of electricity for cooling, following formulas have been used:

$$E_{cooling} = E_{compression} + E_{invisible} \tag{1}$$

$$E_{invisible} = E_{domestic} + E_{without} \tag{2}$$

$$COP_{el} = \frac{C_{el}}{E_{chillers\ total}} \tag{3}$$

$$C_{el} = C_{total} - C_{abs\ chillers} \tag{4}$$

$$COP_{dist} = \frac{C_{abs\ chillers}}{H_{abs\ chillers}} \tag{5}$$

Such a process was necessary, to bring even the most complex expressions to the values available in the data, computed directly as the sum of daily values [34]. Again, appropriate distributions have been chosen.

In supply section the auxiliary boiler capacity of 15 MW with the efficiency of 95% were selected [33]. The problem occurred during thermal capacity approximation. The main idea was to achieve the indicators, giving the same outputs in the software, as the current system. The electric capacity was set 5 MW like the turbine one but the task was also to put the value of thermal capacity. It was possible by the optimization process, with empirical tests in the software. After couple of efforts the value of thermal capacity was set as 7.8 MW. In order to compute above capacity, program required also electric and thermal efficiencies. They were calculated one step before, using following formulas:

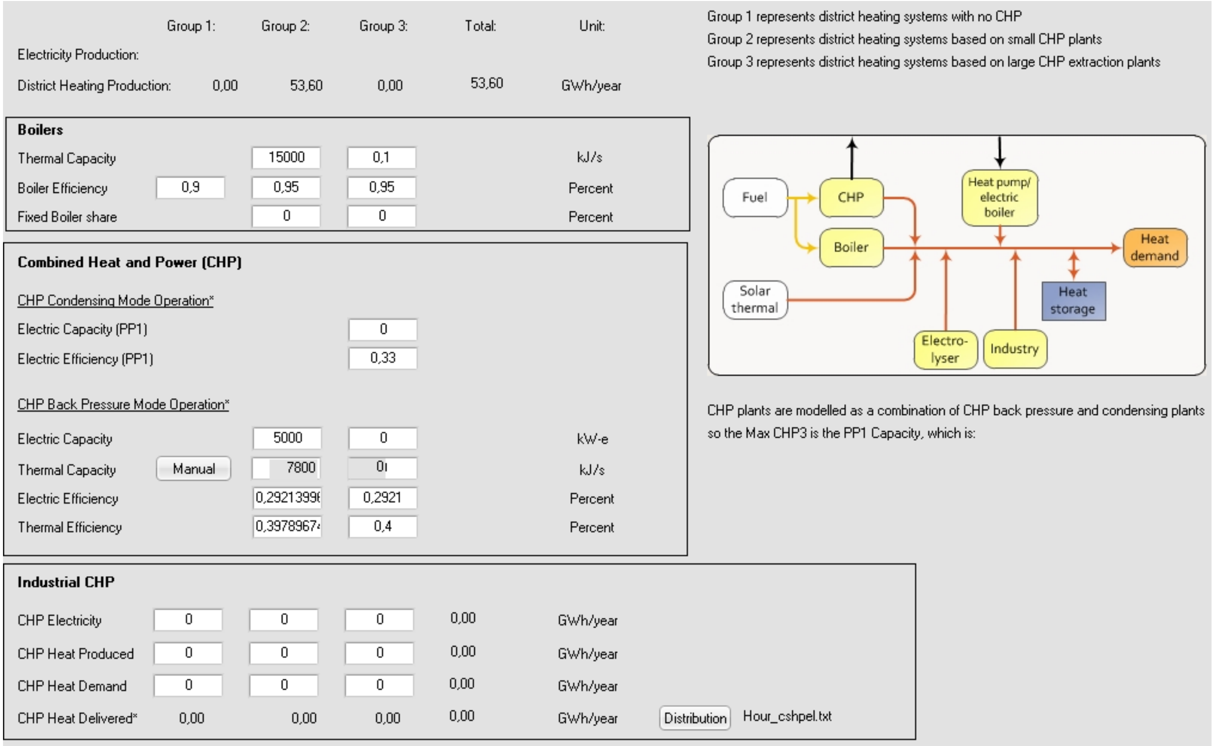
$$\eta_{el} = \frac{E_{total}}{GT} \tag{6}$$

Gas turbine consumption was converted from Nm^3 of natural gas to GWh.

$$\eta_{th} = \frac{H_{total} - H_{aux}}{GT + Aux} \tag{7}$$

Auxiliary boiler consumption was also converted from Nm^3 of natural gas to GWh.

The spreadsheet is presented in Figure 4.6.



	Group 1:	Group 2:	Group 3:	Total:	Unit:
Electricity Production:					
District Heating Production:	0,00	53,60	0,00	53,60	GWh/year

Group 1 represents district heating systems with no CHP
Group 2 represents district heating systems based on small CHP plants
Group 3 represents district heating systems based on large CHP extraction plants

Boilers

Thermal Capacity		15000	0,1	kJ/s
Boiler Efficiency	0,9	0,95	0,95	Percent
Fixed Boiler share		0	0	Percent

Combined Heat and Power (CHP)

CHP Condensing Mode Operation*

Electric Capacity (PP1)			0	
Electric Efficiency (PP1)			0,33	

CHP Back Pressure Mode Operation*

Electric Capacity		5000	0	kW-e
Thermal Capacity	Manual	7800	0	kJ/s
Electric Efficiency		0,2921399	0,2921	Percent
Thermal Efficiency		0,3978967	0,4	Percent

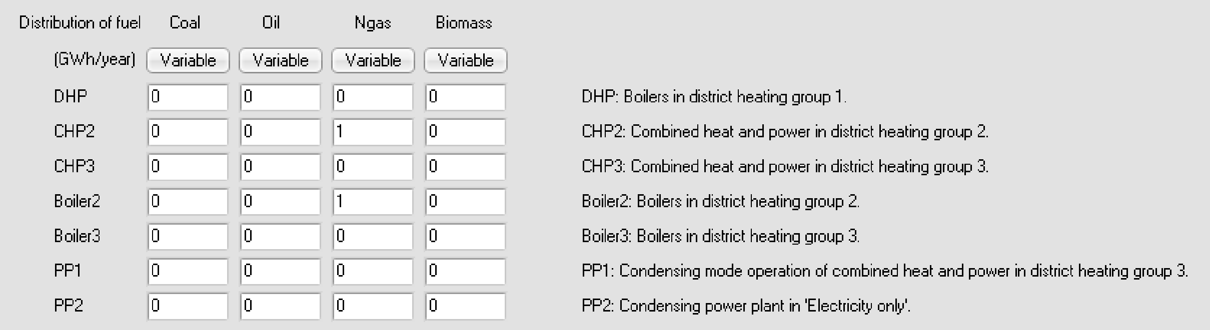
CHP plants are modelled as a combination of CHP back pressure and condensing plants so the Max CHP3 is the PP1 Capacity, which is:

Industrial CHP

CHP Electricity	0	0	0	0,00	GWh/year	
CHP Heat Produced	0	0	0	0,00	GWh/year	
CHP Heat Demand	0	0	0	0,00	GWh/year	
CHP Heat Delivered*	0,00	0,00	0,00	0,00	GWh/year	Distribution Hour_cshpel.txt

Figure 4.6 CHP supply section [36]

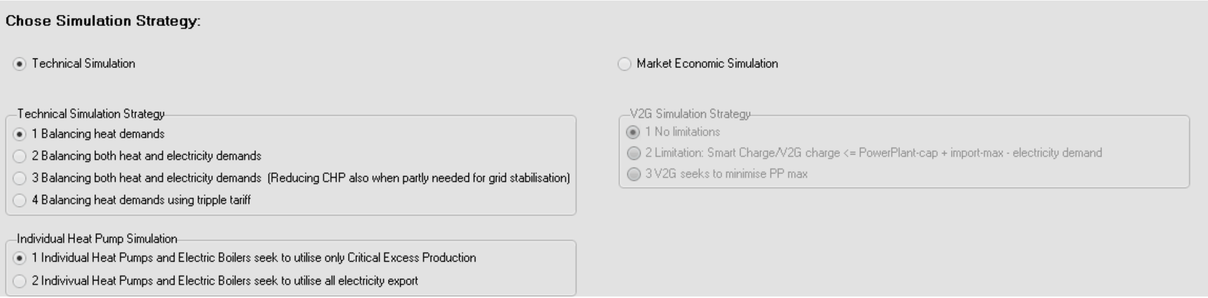
After filling the demand and supply section, EnergyPLAN requested the information about the fuel source and its proportions in case of the mixture. In described baseline scenario case the only fuel was the natural gas, so in section CHP 2 (group 2 of CHP) and Boiler 2 (group 2 of Boiler) value one was put (Figure 4.7).



Distribution of fuel	Coal	Oil	Ngas	Biomass	
(GWh/year)	Variable	Variable	Variable	Variable	
DHP	0	0	0	0	DHP: Boilers in district heating group 1.
CHP2	0	0	1	0	CHP2: Combined heat and power in district heating group 2.
CHP3	0	0	0	0	CHP3: Combined heat and power in district heating group 3.
Boiler2	0	0	1	0	Boiler2: Boilers in district heating group 2.
Boiler3	0	0	0	0	Boiler3: Boilers in district heating group 3.
PP1	0	0	0	0	PP1: Condensing mode operation of combined heat and power in district heating group 3.
PP2	0	0	0	0	PP2: Condensing power plant in 'Electricity only'.

Figure 4.7 Fuel distribution section [36]

At the end, as a last step to run a simulation, the decision about kind of simulation strategy occurred. For the purpose of the study technical simulation, with balancing the heat demands has been chosen (Figure 4.8), to let the CHP unit assumed in simulation run properly, with maximizing the production, as heat capacity is higher.



Chose Simulation Strategy:

● Technical Simulation

○ Market Economic Simulation

Technical Simulation Strategy

● 1 Balancing heat demands
○ 2 Balancing both heat and electricity demands
○ 3 Balancing both heat and electricity demands (Reducing CHP also when partly needed for grid stabilisation)
○ 4 Balancing heat demands using tripple tariff

V2G Simulation Strategy

● 1 No limitations
○ 2 Limitation: Smart Charge/V2G charge <= PowerPlant-cap + import-max - electricity demand
○ 3 V2G seeks to minimise PP max

Individual Heat Pump Simulation

● 1 Individual Heat Pumps and Electric Boilers seek to utilise only Critical Excess Production
○ 2 Indivivual Heat Pumps and Electric Boilers seek to utilise all electricity export

Figure 4.8 Simulation section [36]

Described procedure was based on the baseline scenario and depending on scenario the procedure is slightly different, with some other inputs to fill. However, the principle is the same - program asks for the detailed data about the energy system with demand and supply section mainly.

4.1.3 RES electricity production assumptions

To model the PV and wind power production it was necessary to gather appropriate meteorological data as well as to evaluate potential capacities. In order to do that, several steps combining many tools and techniques were made.

PV plant simulation

First step was to obtain solar irradiation data at the location of Climaespaço plant. It was possible thanks to the following website with its internal database [41]. The parameters were measured from 31.12.2005 to 31.12.2006. The most important parameter from the simulation point of view was irradiation [Wh/m^2]. After gathering the suitable data, formula for calculation of the energy produced out of this irradiation was needed. Using another website with its calculation tool [42] it was possible to compute this energy.

$$E = A \times \eta_R \times H \times PR \tag{8}$$

Shadings were not included and the losses in performance ratio are normally in the range between 0.5 and 0.9 [42], so the default value 0.75 was used. At this step, only the meteorological data was known, so further assumptions needed to be done about the area, efficiency and loses. Efficiency was set as default one in [42], so 15% as the standard value of PV panels worldwide. To evaluate area of the solar panels the rooftop area of Climaespaço main building was checked. The assumption, at this step, was made that almost all possible space at the rooftop is available for solar panels installation.

Because there was no data provided about the size of the plant, the measurements in Google maps tool were used, shown in Figure 4.9 [43].

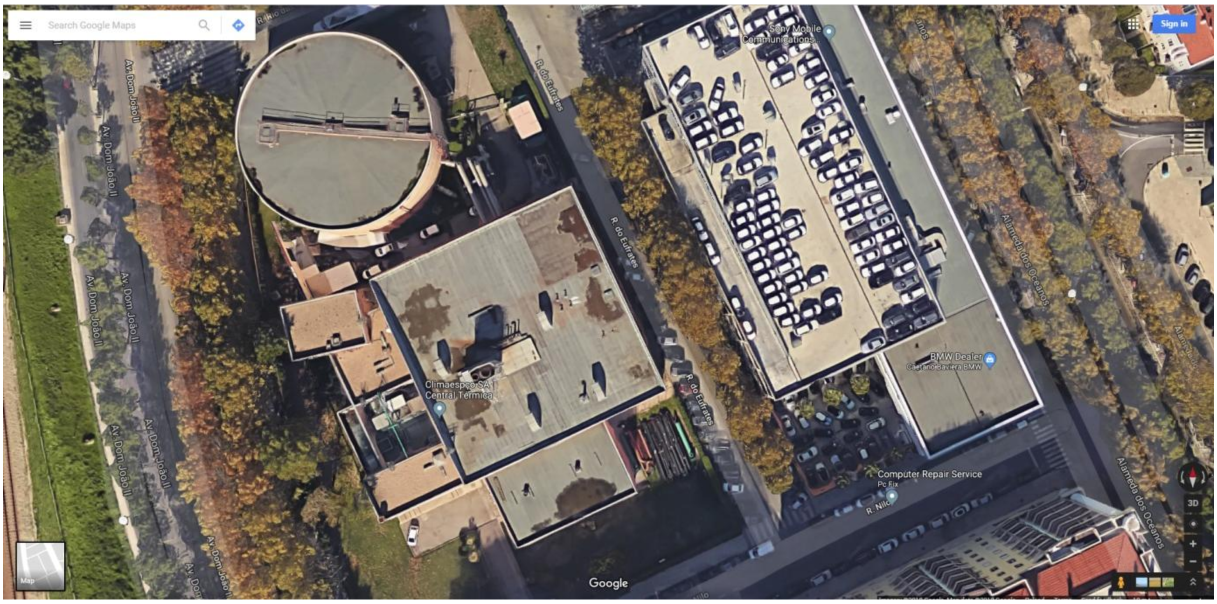


Figure 4.9 Climaespaço view in Google Maps tool [43]

Thanks to this procedure estimation of the area on the roof was made and is presented on the draft below (Figure 4.10). The dimensions are given in millimetres.

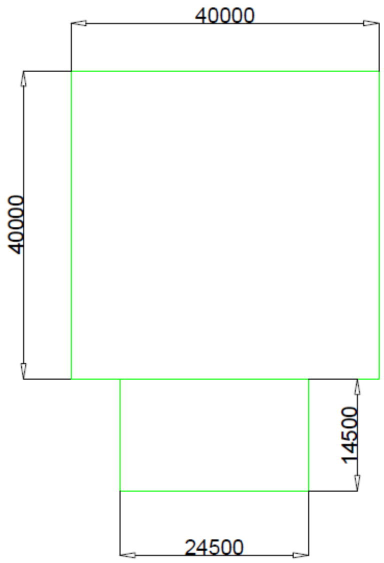


Figure 4.10 Dimensioned sketch of the Climaespaço's main building rooftop

The estimated area of the main building rooftop is around 1,955 m^2, but as it is presented on the picture from Google Maps, not all area is available for the PV panels because of the space occupied by the chimney and ventilation network. Uncertain is also the shadow, made by these installations, which could affect the work of the panels. Due to these unknown factors, the approximation of around 60% of whole rooftop area is set as an available area. That means area of around 1,173 m^2 is disposable. However, due to the fact that EnergyPLAN software asks for hourly data to create distributions, the main equation was adapted to meet the requirements of the software. In formula, instead of annual average value of solar radiation hourly values are used and energy produced for each hour is calculated. The maximum value achieved is set as the projected capacity and is used to divide other results to obtain distribution.

Wind plant simulation

The same dataset was used to obtain the distributions is in wind section [41]. The turbine EO10 from the company Eocycle with the nominal capacity of 10 kW was chosen from internal database of Homer software [44] [45]. To properly estimate the power of the turbine corresponding to the wind speed, wind turbine power curve was needed. In [45], the requested data was presented in the form of the table, but it was more convenient to present it in the form of the graph (Figure 4.11).

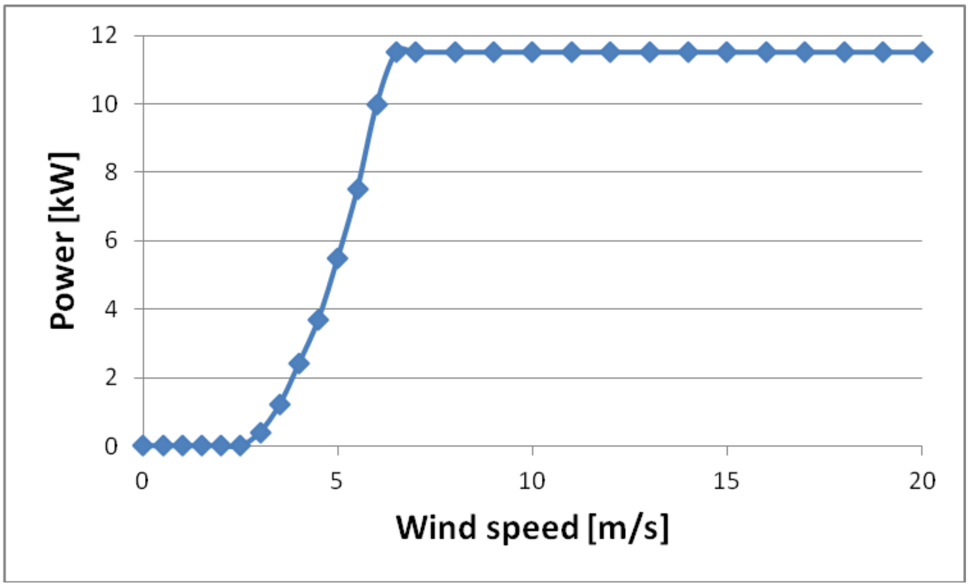


Figure 4.11 EO10 power curve

Cut-in and cut-out speeds of the wind turbine are respectively 2.75 and 20 m/s. The maximum power is 11.5 kW. The wind turbine power curve clearly shows that between the minimum and maximum power there is a zone in which the power value is not constant. Further step was necessary to link the value of the speed with appropriate power in this zone. For this purpose, polynomial trend line with 4th degree was used in Excel. The formula and coefficient of determination are presented on the following graph (Figure 4.12).

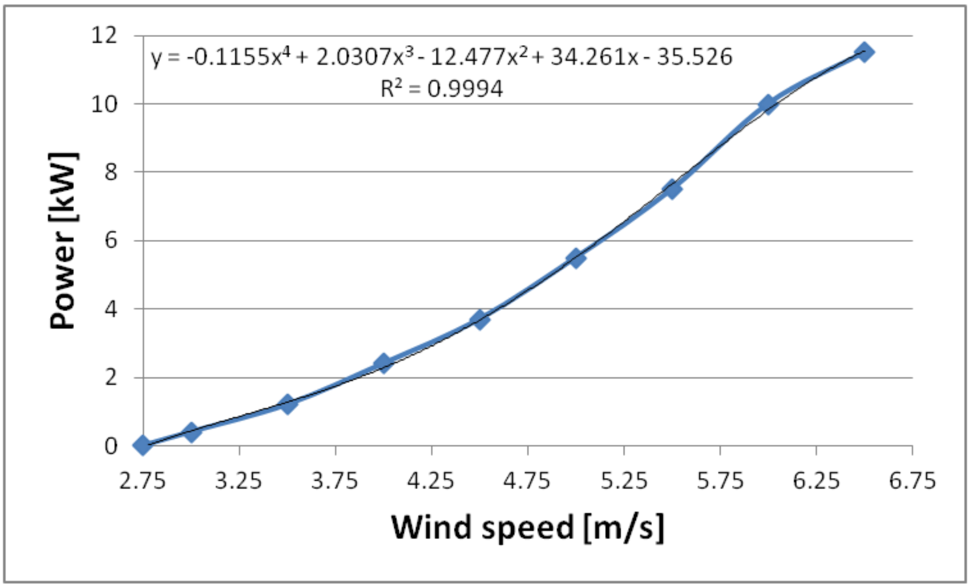


Figure 4.12 Fraction of EO10 power curve with polynomial trend line

After this, it was possible to obtain the distribution by dividing the hourly values by the maximum one. In the EnergyPLAN tool power capacity of the wind turbine was set as 11.5 kW due to the fact that was the biggest power achieved and all the results where compared to it, during the process of creating the distribution. The final assumption was made that in the area of Climaespaço plant, there will be four such turbines (due to the small amount of space available, surroundings, noise policy, etc.).

4.2 Economic assessment

In order to analyse the economic viability of the scenarios proposed, several indicators were calculated.

4.2.1 EnergyPLAN results

Apart from calculating economic indicators externally, there is also a way to use internal cost database of the EnergyPLAN [36]. By using the software and putting the prices in cost section, it is possible to achieve some results regarding economic analysis: such as CO_2 emission cost, fuel cost, fixed O&M cost or RES participation in energy production. The appropriate results from tool will be also used in the economic assessment process.

4.2.2 NPV

Net Present Value is a parameter describing the balance between current value of cash inflows and outflows for examined period of time. In capital budgeting NPV is used to find out profitability of projected projects or investments [46]. There are several formulas and their derivatives to calculate NPV, the most important ones are presented below:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o \qquad (9)$$

$$NPV = R_d - C_d = P_V \times E_a \times k_a - (I_t + C_{O\&M} \times k_a) \tag{10}$$

$$k_a = \sum_{j=1}^{n} \frac{1}{(1+a)^j} = \frac{(1+a)^n - 1}{a \times (1+a)^n} \tag{11}$$

4.2.3 IRR

Internal Rate of Return is a parameter used in capital budgeting in order to estimate the profitability of potential investments. IRR is such discount rate that makes NPV equal to zero (can be treated as r from eq. 8 giving the value of NPV=0) [47]. There is no direct formula to calculate IRR, it can be calculated from already mentioned NPV equation or computing different parameters:

$$R_N \times \frac{(1+IRR)^n - 1}{IRR \times (1+IRR)^n} = I_t \tag{12}$$

$$R_N = R - C_{O\&M} \tag{13}$$

Thus, IRR sometimes could not be calculated using analytical methods, Excel is used in order to achieve results.

4.2.4 SPBT

The most common static criterion used for assessing economic efficiency is Simple Payback Time. It is defined as the time needed to recover investment outlays, incurred for the implementation of a given project. SPBT is calculated from the moment the investment is launched to the moment when the sum of gross profits obtained as a result of the implementation of the investment will balance the incurred outlays [48]. In case the annual gross benefits are fixed, the SPBT value can be calculated from the following expressions:

$$SPBT = \frac{I}{Z_i} \tag{14}$$

$$SBPT = \frac{I}{\Delta Z} \tag{15}$$

5. RESULTS AND DISCUSSION

5.1 Baseline scenario

Technical analysis

The procedure for calculating the basic technical parameters of Climaespaço plant has undergone double verification process. Table 1 reveals the needed inputs to run the simulation in EnergyPLAN for one year.

Table 1 Inputs requested to run simulation in EnergyPLAN

Input	Value
Electricity demand without cooling [GWh]	8.98
Electricity demand for cooling purposes [GWh]	13.01
Total electricity demand [GWh]	21.99
Consumption of heat by absorption chillers [GWh]	6.67
Consumption of heat to produce steam [GWh]	53.60
Total heat demand [GWh]	60.28
Coefficient of Performance for electricity for cooling [-]	4.98
Coefficient of Performance for district heating for cooling [-]	1.67
Electric efficiency [%]	29
Thermal efficiency [%]	40
Estimated CHP electric capacity [kW]	5,000
Estimated CHP thermal capacity [kW]	7,800

The system modelled in the tool was validated by the data provided and treated previously. Table 2 compares the results obtained in the simulation with the data provided.

Table 2 Comparison of the data gathered and the simulation results

	Data gathered	Simulation results
Electricity produced [GWh]	38.44	35.22
Heat production of CHP [GWh]	54.98	54.95
Heat production of auxiliary boiler [GWh]	5.27	5.33
Total heat produced [GWh]	60.25	60.28
Natural gas consumed [GWh]	143.71	143.71

As it can be seen in the table, while using EnergyPLAN regulation strategy of balancing heat demand, the heat production is equal to the demand, but the production of electricity is noticeably lower than in the real case. The reason why such situation occurs is that program does not consider the afterburn, so it cannot match the power production with the heat production. To meet heat demand, the software focuses mainly on the heat production parameter, neglecting the fact of lower electricity production at the same time. From the results of the simulation of heat production (Figure 5.1), it is clear that CHP works along all year while boiler is used only in some periods. Maximum heat production occurs in winter, and, during this period, sometimes the auxiliary boiler production is higher than the CHP production. Production of heat in summer has a lower level. Only time by time CHP provides maximum production. As EnergyPLAN does not distinguish between the heat used for heating or cooling purposes, it is hard to have clear view what are the proportions of these products. Generally, as CHP is optimized to meet heat demands, in summer it is not utilized at the highest range which easily affects the electricity production. The figures that show the heat demand in each scenario (Figures 5.1, 5.4, 5.7 and 5.9) have all the same axis' range to facilitate comparison.

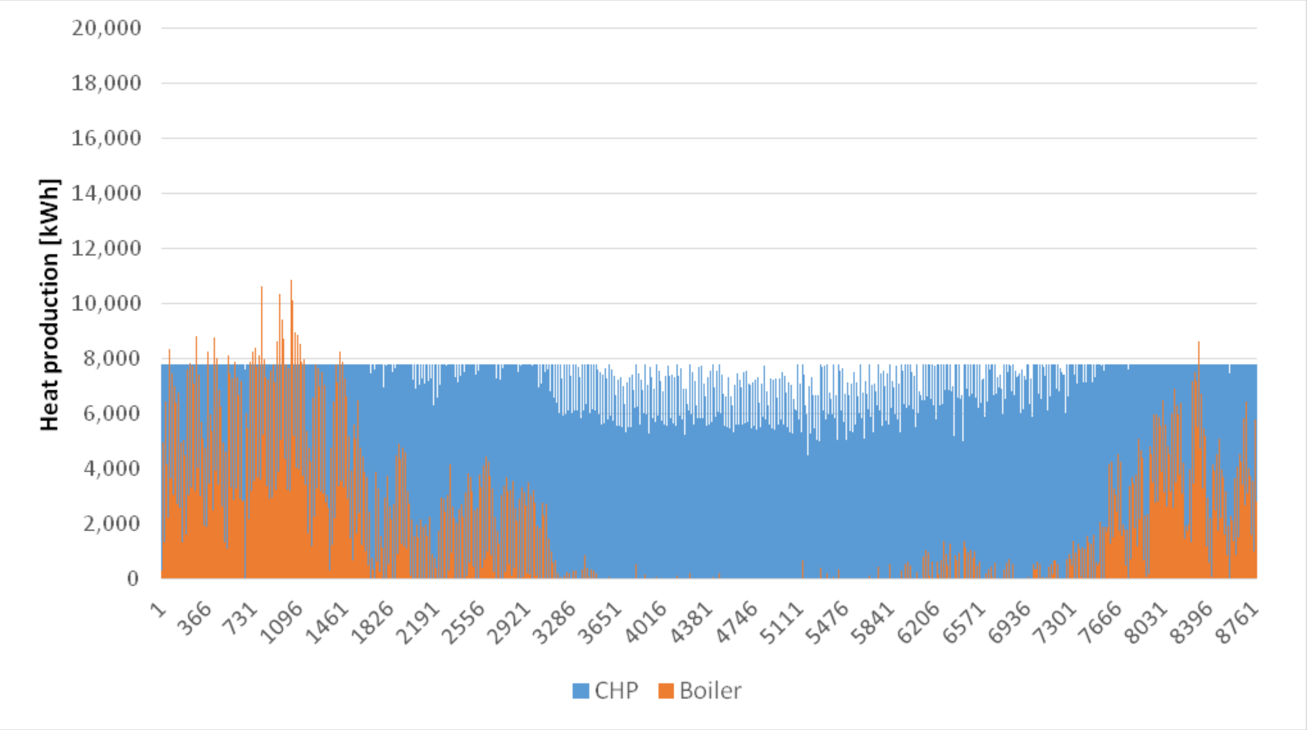


Figure 5.1 Hourly distribution of heat production by source in baseline scenario

Electricity production from CHP unit (Figure 5.2) is lower during summer due to the strategy of meeting heat demand. Only in the winter CHP unit works permanently at the maximum power. The figures that show the electricity production in each scenario (Figures 5.2, 5.5 and 5.10) have all the same axis' range to facilitate comparison.

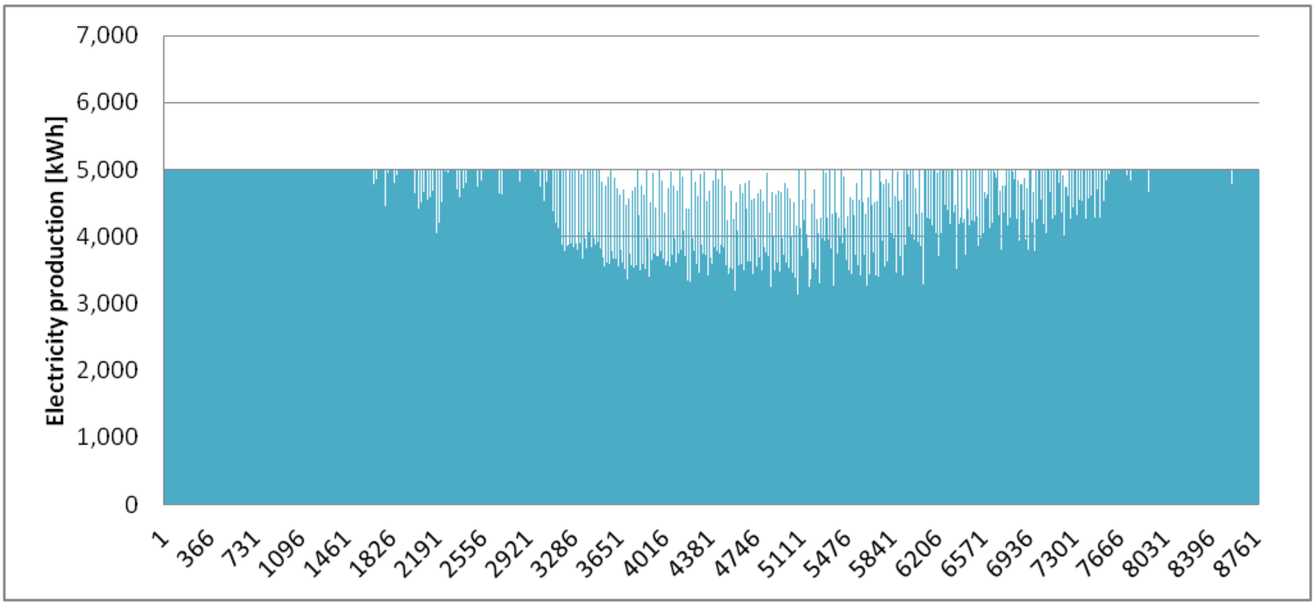


Figure 5.2 Hourly distribution of electricity production from CHP in baseline scenario

As the CHP utilization is biggest during the winter time, it is nothing surprising that the natural gas consumption is at its peak, during that time, as shown in Figure 5.3. In summer fuel consumption value is significantly smaller. The figures that show the natural gas consumption in each scenario (Figures 5.3, 5.6 and 5.8) have all the same axis' range to facilitate comparison.

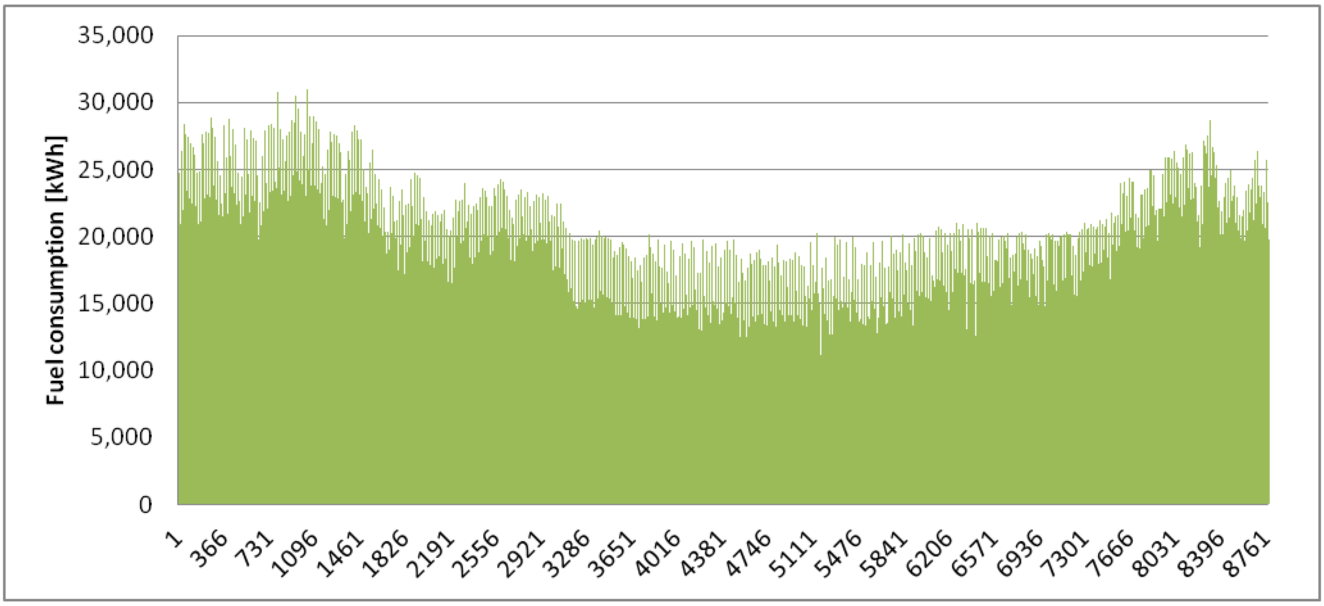


Figure 5.3 Hourly distribution of natural gas consumption in baseline scenario

Economic assessment

To simulate the income, currently available data was used and for calculation of the expenditures internal database of EnergyPLAN for horizon 2020 was used [36]. Such decision about the calculation of costs was dictated by the fact that year 2020 was the nearest data available in the software as well as this year is the most likely for potential investment. The revenues that result from the selling of electricity (88 €/MWh), cooling (50 €/MWh) and heating (41 €/MWh) were considered according to information provided [33]. As EnergyPLAN does not distinguish in the result section how much heating or cooling was produced out of heat and it is impossible to obtain distribution of cooling itself, different approaches regarding sales were made. In previous sections, demand was equal to production, which is generally true, but that is not answering the question about the real products sold on the market. Due to this fact (that not all of production is sold to the market), the amount of heating and cooling sold are assumed as following thanks to the information provided: 60 GWh/year of cooling and 40 GWh/year of heating [33]. When it comes to the price of the electricity imported from grid, it was assumed as the average of the seasonal and daily prices presented in [49], according to long time tariff: 99.0875 €/MWh. The export of the electricity to the grid is 15.82 GWh and import from the grid is 2.58 GWh. For the horizon of 2020, the interest rate is 3%, CO_2 emission price is 28.6 €/t and price of natural gas is 9.1 €/GJ [36]. The CO_2 emission factor and the percentage of RES generation of the electricity imported from the grid was not considered in this study. As there is no further investment in baseline scenario only cash flow for the year 2020 was calculated. The result obtained is - 162,512 €. Below each revenue and cost are presented in the Table 3.

Table 3 Cash flow simulation of baseline scenario

Parameter	Result
Cash flow [€]	- 162,512
Heating export income [€]	1,640,000
Cooling export income [€]	3,000,000
Electricity export income [€]	1,392,160
Electricity import cost [€]	255,646
Fuel cost [€]	4,707,940
O&M costs [€]	401,000
CO_2 emission costs [€]	830,086

From calculations it can be observed that the way Climaespaço plant operates now will not be profitable in year 2020 and changes in the system need to be done.

5.2 Scenario 1

The main assumption of this scenario is the cooperation between Climaespaço plant and Valorsul Project WtE [35]. As this scenario is divided into two parts, each of them has different inputs and system configurations.

5.2.1 Scenario 1a

Technical analysis

In this scenario the inputs were the similar to the ones of the Baseline scenario, with a difference regarding the steam delivered from WtE. The amount of steam in GWh units was set as fixed value, in a way to cover around half of the heat demand of Climaespaço. The distribution of heat delivered from WtE is considered uniform, the rest of heat is still being produced by the gas turbine and the recovery boiler, programmed as CHP unit with appropriate capacities. The results obtained are presented in Table 4.

Table 4 Results of simulation in EnergyPLAN scenario 1a

Parameter	Result
Electricity produced [GWh]	18.73
Heat production from CHP [GWh]	29.22
Heat production from auxiliary boiler [GWh]	1.07
Steam delivered from WtE [GWh]	30.00
Total heat produced [GWh]	60.29
Natural gas consumed [GWh]	74.56

Due to the fact that CHP is cooperating in heat production with the steam delivered from WtE plant, product structure is slightly different than in the baseline scenario. The amount of electricity produced is lower because CHP does not work as much as in the previous case. On the other hand, less fuel is consumed (decrease of 48%), due to the additional steam from WtE. The utilization of auxiliary boiler is marginal.

Looking at the Figure 5.4, different tendency than in baseline scenario can be seen. Heat produced by the CHP unit is always bigger than the one produced by the boiler. Maximum heat production of CHP is happening less frequently than in the baseline scenario and it occurs only in winter. Auxiliary boiler is also used only in winter time, to cover the demand peaks. Important issue to mention here is the fact that CHP works permanently, which is good but rarely on its maximum power - not satisfactory regarding efficiency.

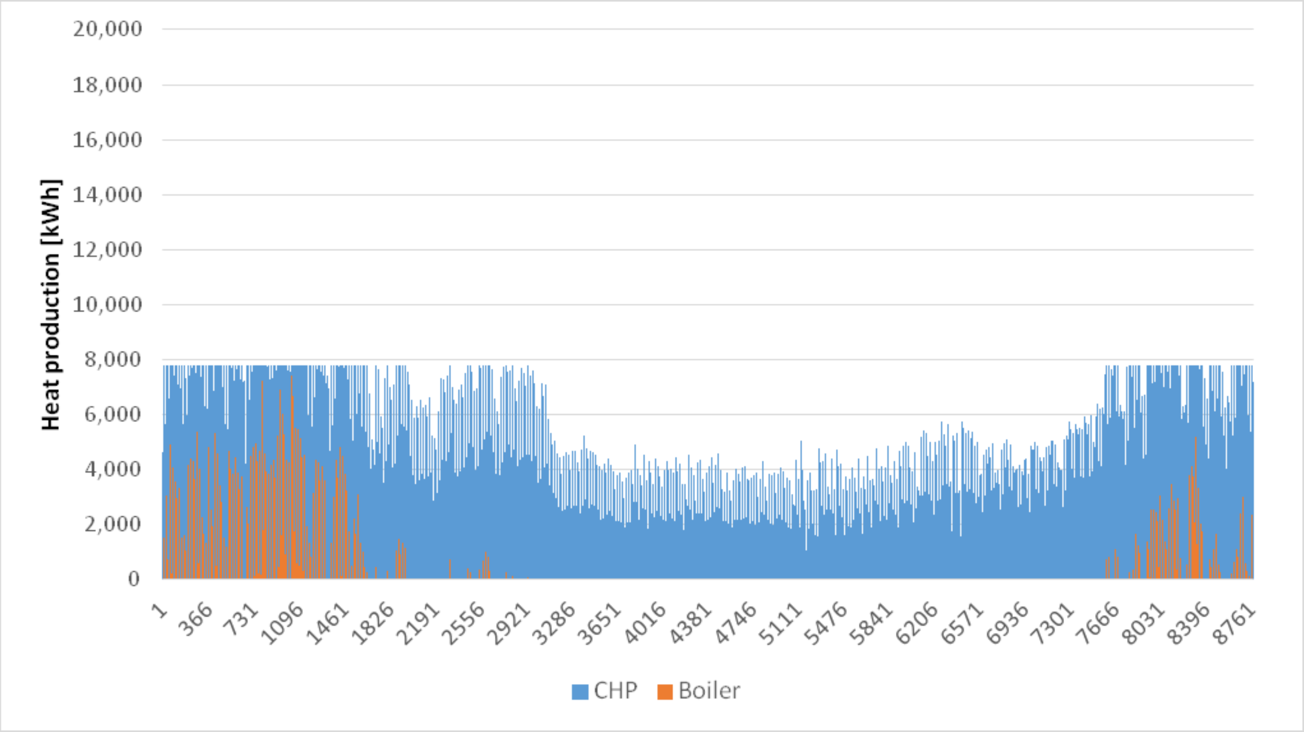


Figure 5.4 Hourly distribution of heat production by source in scenario 1a

Regarding the electricity production (Figure 5.5), trend is the same as in heat production as the simulation has been made with strategy to follow the heat demands. Maximum production occurs during winter but not so frequently as in the baseline scenario. In the summer the electricity production is significantly lower. The export of electricity is lower by almost 56% than in baseline scenario while import is higher by almost 298%.

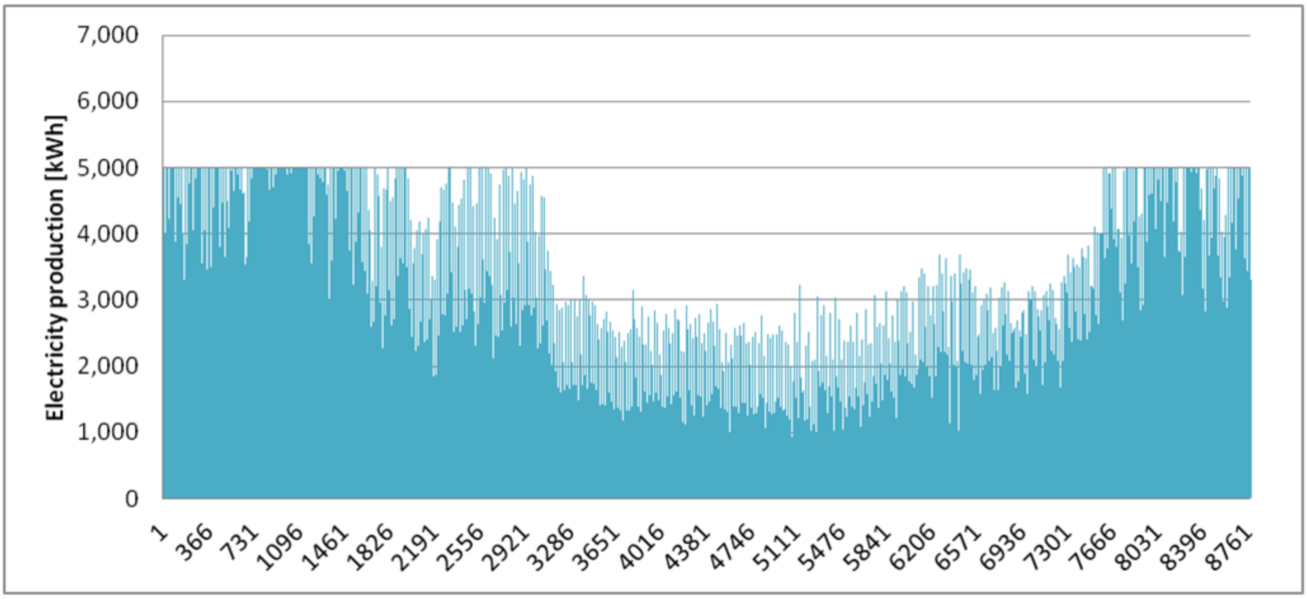


Figure 5.5 Hourly distribution of electricity production from CHP in scenario 1a

The main advantage of this scenario is the smaller consumption of natural gas (Figure 5.6). As expected, the gas natural consumption tendency is similar tendency of the utilization of CHP and auxiliary boiler.

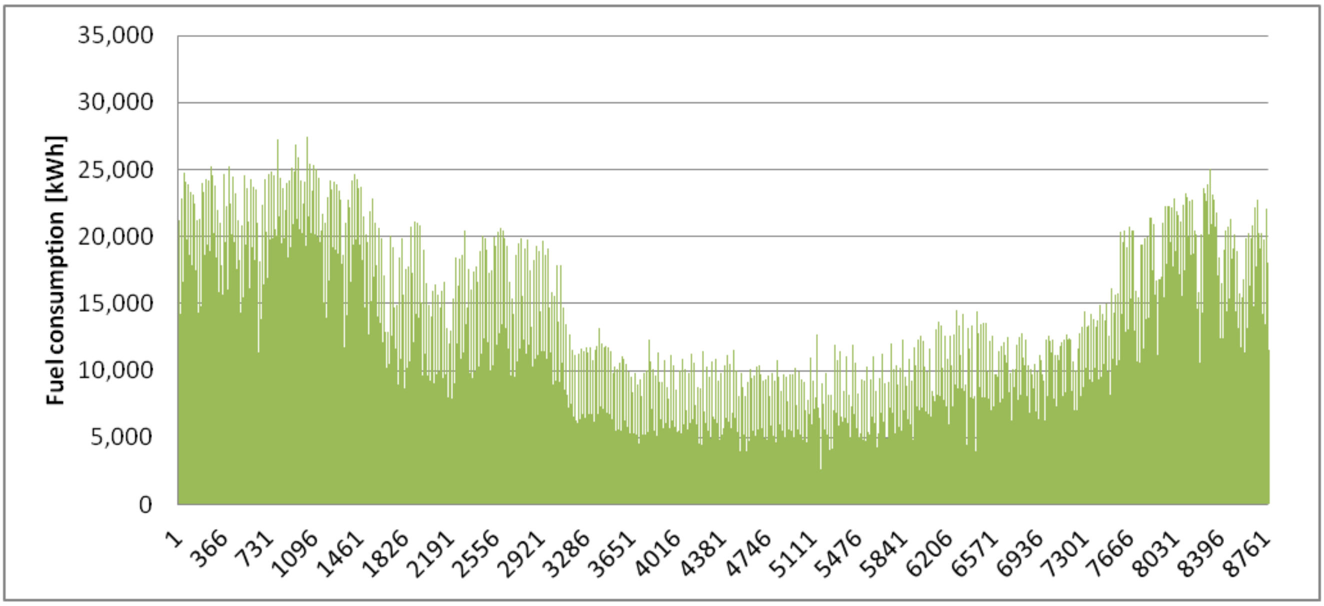


Figure 5.6 Hourly distribution of natural gas consumption in scenario 1a

Economic assessment

The majority of assumptions made in the baseline scenario were also used in scenario 1a. Again, cost database of EnergyPLAN for the year 2020 was used [36]. The timeframe for all analysis, apart from baseline scenario, is 25 years. Pipeline cost and energy loss along the pipeline were taken into consideration. When it comes to the cost of pipeline per one meter, it depends from which source data is gathered [50] [51]. Values between 600 – 1,200 USD/meter or 650 – 1,250 USD/meter are referred, for this study an average value was used: 925 USD and recalculated in euro [52], which gave around 751.5 €/meter. The energy loss in the pipeline was defined as 6.4% [53]. The cost of the steam is 40,000 €/GWh according to EnergyPLAN database [36]. The export of electricity is 7.00 GWh and import is 10.26 GWh. Fixed O&M cost and the investment cost have been taken into account. Table 5 reveals the results obtained.

Table 5 Economic assessment for scenario 1a

Parameter	Result
NPV [€]	-9,843,603
IRR [%]	-
SPBT [years]	-
Heating export income [€]	1,640,000
Cooling export income [€]	3,000,000
Electricity export income [€]	616,000
Electricity import cost [€]	1,016,638
Fuel cost [€]	2,442,586
Fixed O&M costs [€]	412,000
CO_2 emission costs [€]	430,659
Steam price [€]	1,282,051
Pipeline cost [€]	4,133,250

What is the most important from the achieved results shown in Table 5, is the fact that despite that NPV<0 and IRR as well as SPBT could not be determined. The biggest cost is related to the pipeline construction. Perhaps, if an appropriate agreement between Valorsul Project and Climaespaço installation will be made or an external sponsor will be found, the cost will decrease. The fuel and CO_2 emission costs are lower than in baseline, but the electricity import cost is significantly higher, compensating the difference. Summing up, it is not feasible scenario and the main problem is that import of the electricity is higher than export combined with huge investment cost.

5.2.2 Scenario 1b

Technical analysis

The technical analysis is done in the similar way as in scenario 1a, but the amount of steam delivered from WtE plan and the way this steam is distributed are different. The amount of steam in GWh unit was set after couple of iterations, to make a compromise between highest possible usage of the leftover steam and necessity to use back-up boiler during peaks. The distribution of heat delivered from WtE is variable and depends on the real heat demand. The results obtained are presented in Table 6.

Table 6 Results of simulation in EnergyPLAN scenario 1b

Parameter	Result
Electricity imported from the grid [GWh]	21.99
Heat production of auxiliary boiler [GWh]	6.28
Steam delivered from WtE [GWh]	54.00
Total heat produced [GWh]	60.28
Natural gas consumed [GWh]	6.61

What is important to describe at this point is the fact that electricity demand of Climaespaço is fully covered from the grid. As main products of the plant are heating and cooling, they were given priority with this solution. The lack of electricity produced and sold to the grid is compensated with the cheaper and cleaner way to produce the main products.

Figure 5.7 illustrates the hourly distribution of heat production by source for Scenario 1b. As expected, since steam is supplied to the system according to the needs of Climaespaço, its distribution is no longer constant. The auxiliary boiler is a permanent heat source, producing heat all year without significant peaks. Another interesting tendency is that the highest supply from WtE is during winter while production of the boiler is during summer. The amount of steam was estimated through an iteration approach, making a compromise between the steam from WtE plant and the auxiliary boiler. While maximizing the steam from WtE, the boiler was still producing heat (in EnergyPLAN simulation) generating unnecessary heat. That is why the amount of steam is not responsible for meeting the whole heat demand of the plant.

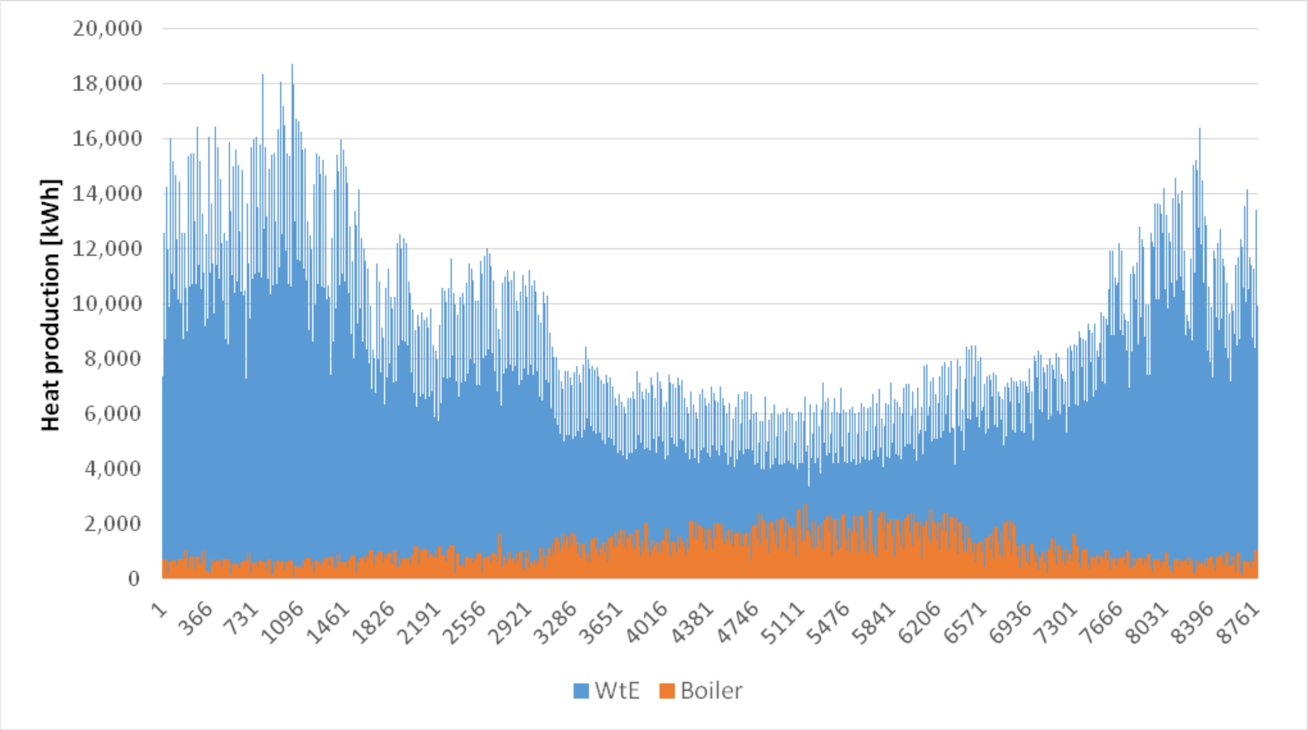


Figure 5.7 Hourly distribution of heat production by source in scenario 1b

Because the CHP system is no longer used, the consumption of natural gas is much different than in the previous cases (Figure 5.8). The only facility supplied by natural gas is the auxiliary boiler and it is producing heat all year, mainly in the summer, thus the consumption of fuel is also higher during that time.

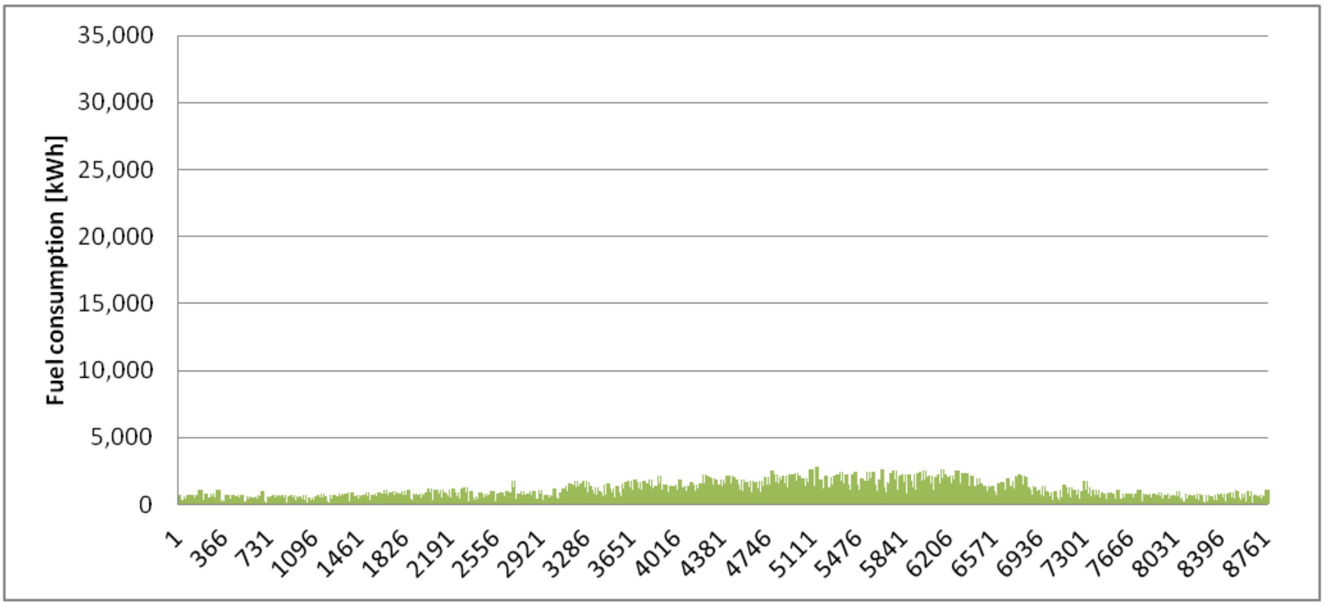


Figure 5.8 Hourly distribution of natural gas consumption in scenario 1b

Economic assessment

The same methodology was used as in Scenario 1a. This time, the export of electricity was none and the whole electricity was imported from the grid, about 21.99 GWh. The results are presented in Table 7.

Table 7 Economic assessment for scenario 1b

Parameter	Result
NPV [€]	- 9,328,481
IRR [%]	-
SPBT [years]	-
Heating export income [€]	1,640,000
Cooling export income [€]	3,000,000
Electricity export income [€]	0
Electricity import cost [€]	2,178,934
Fuel cost [€]	216,544
Fixed O&M costs [€]	197,000
CO_2 emission costs [€]	38,181
Steam price [€]	2,307,692
Pipeline cost [€]	4,133,250

As can be observed, like the previous scenario this one is not economically feasible since NPV<0 and no IRR or SPBT are reached. Lower cost of the fuel or CO_2 emission do not have significant effect in the overall case due to no income from electricity selling, price to pay for the energy demand and even higher cost of the steam. This scenario is slightly better but still not feasible.

5.3 Scenario 2

This scenario is also divided into two parts. The replacement of the current system with a biomass-based solution is simulated. Depending on the scenario, the usage of other RES in Climaespaço plant for power production is either taken into account (scenario 2a) or not (scenario 2b). These are 100% RES-based scenarios.

5.3.1 Scenario 2a

Technical analysis

For this scenario, completely new parameters of the system had to be assumed. The solution chosen to replace current installation is based on a biomass boiler working as CHP. The technology simulated in the EnergyPLAN was based on an existing plant located in Latvia [54]. Forest residues are assumed as biomass fuel. It is an interesting energy source and biomass type, as in Portugal forests occupy large part of the whole country and wood is widely accessible. Both capacities, electric and thermal are from dataset of Latvia plant. Due to the lack of data regarding efficiency (there was only information obtained from [55] regarding the overall planned efficiency - 75%, at the project stage), the same overall efficiency as in baseline scenario was set - 69%. The electric and thermal efficiencies due to this fact are also the same. Inputs and the most important parameters obtained during the simulation are presented below in Tables 8 and 9.

Table 8 Inputs for the simulation of scenario 2a

Input	Value
Electric efficiency [%]	29
Thermal efficiency [%]	40
CHP electric capacity [kW]	6,400
CHP thermal capacity [kW]	15,000

Table 9 Results of scenario 2a

Parameter	Result
Electricity produced [GWh]	25.69
Heat production of CHP [GWh]	60.21
Heat production of auxiliary boiler [GWh]	0.07
Total heat produced [GWh]	60.28
Biomass consumed [GWh]	151.39

As it can be seen, almost all the heat demand was covered by biomass boiler, only for small period of time back-up boiler was used. LHV of biomass was assumed at level of 12.6 MJ/kg (with 30% of moisture) [56]. It corresponds to around 44,310 tonnes of biomass annually. To determine if the amount of biomass consumed during the process is in an acceptable range local biomass resource should be checked and further detailed analysis needs to be done [57]. The amount of electricity produced is not as significant as in baseline scenario, but it still plays an important role in the system.

CHP system based on biomass is almost twice bigger when it comes to maximum heat production than the one in baseline scenario (Figure 5.9). Due to this fact, the auxiliary boiler is almost never used - only in some winter days. The drawback of this solution is utilizing half of CHP during summer which reduces the efficiency and the electricity production.

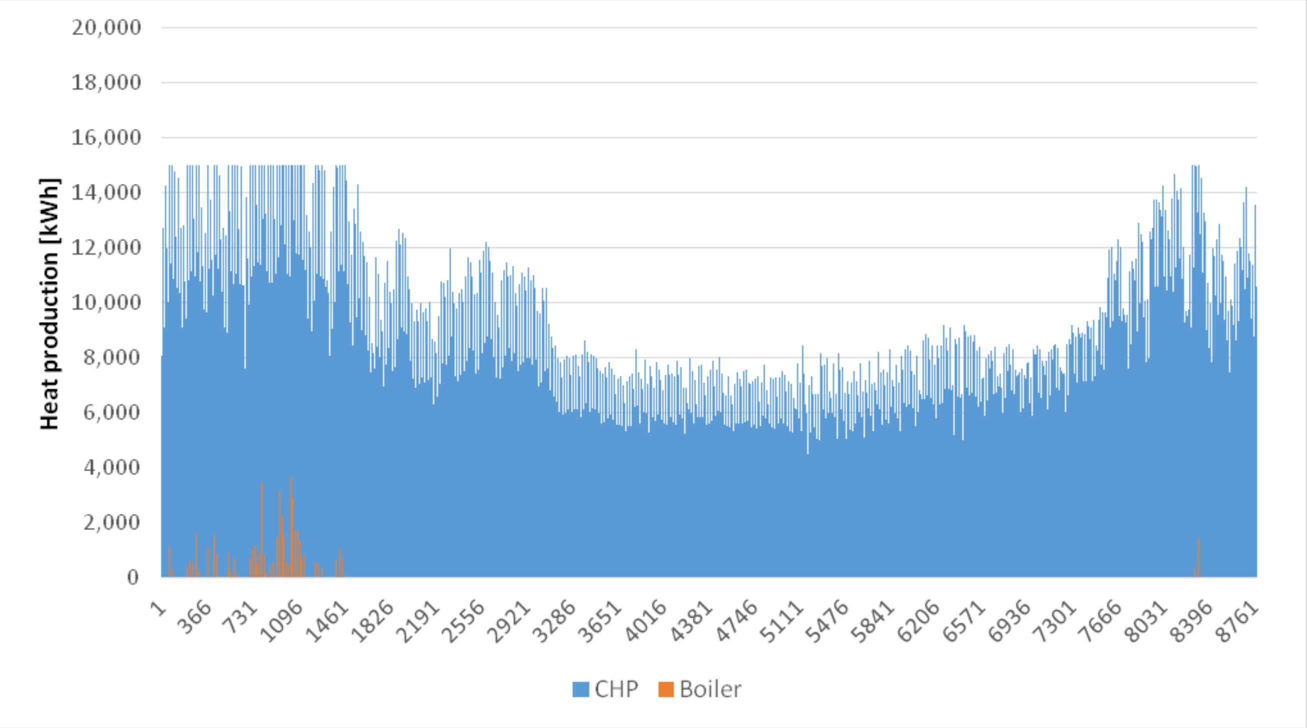


Figure 5.9 Hourly distribution of heat production by source in scenario 2a

Different configuration of the system and proportions of heat to electricity produced, have effect on the electricity production (Figure 5.10). Comparing to baseline scenario the produced electricity is much less, even the maximum power is higher. The distribution is similar to the one from scenario 1a.

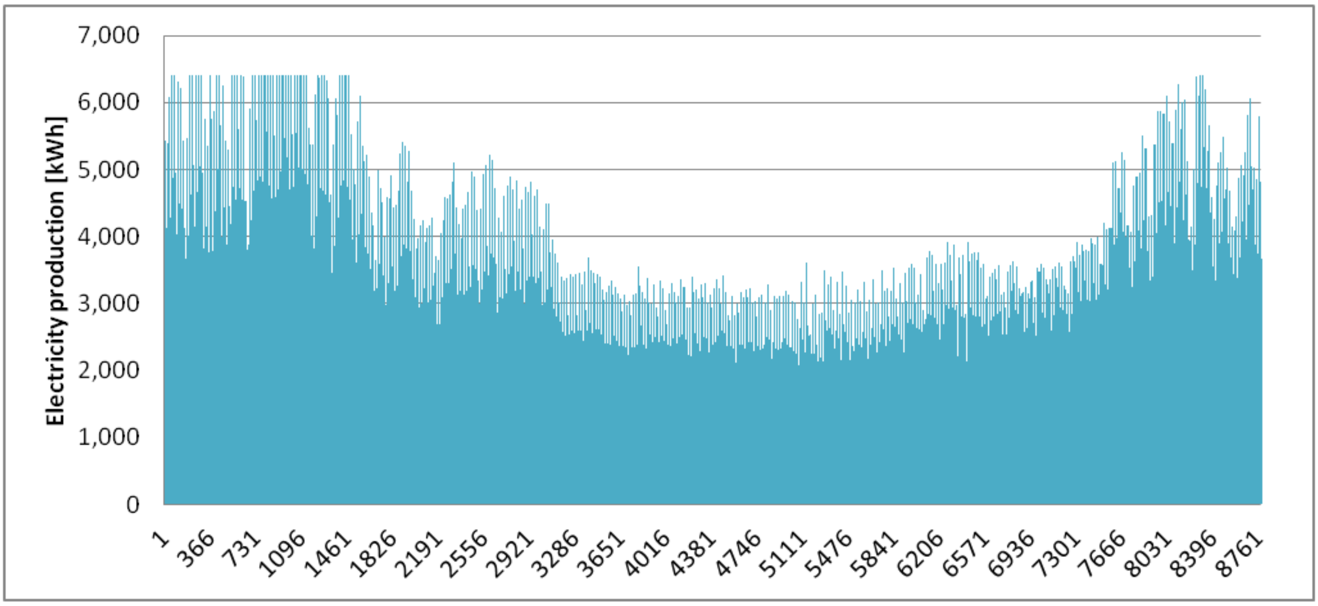


Figure 5.10 Hourly distribution of electricity production from CHP in scenario 2a

Economic assessment

The same methods were used as in Scenario 1a or 1b. Forest residues and wood chips cost was defined as 4.5 €/GJ [58]. As there is no clear decision about feed in tariffs for renewable trigeneration system in Portugal, the baseline scenario tariffs were used. Electricity export was 9.39 GWh and import was 5.69 GWh (Table 10).

Table 10 Economic assessment for Scenario 2a

Parameter	Result
NPV [€]	26,902,409
IRR [%]	25.78
SPBT [years]	3.87
Heating export income [€]	1,640,000
Cooling export income [€]	3,000,000
Electricity export income [€]	826,320
Electricity import cost [€]	563,807.9
Biomass fuel cost [€]	2,452,518
Fixed O&M costs [€]	464,000
CO_2 emission costs [€]	0
Biomass CHP cost [€]	7,680,000

In scenario 2a, both NPV and IRR are greatly above the requirements (NPV>0 and IRR>Interest rate). Even the SPBT is around four years which is quite a promising result. Fuel cost is similar to the one in scenario 1a but accompanied with no cost of CO_2 emissions. The important point to mention at this stage, is the fact that, there is more exportation of electricity (so gaining money) than importation. The cost of the boiler is divided into 25 years, taking into account a discount rate of 3% [36]. This is the first scenario which can replace the baseline scenario with satisfactory results of economic analysis.

5.3.2 Scenario 2b

Technical analysis

In this scenario PV and wind plants were considered to produce electricity, apart from the electricity generated by CHP. The summary of general parameters describing the PV and wind plants and the results of the simulation are shown below, in Tables 11 and 12.

Table 11 Input for the simulation of scenario 2b

Input	Value
Electric efficiency of PV [%]	15
Solar panels surface [m^2]	1,173
Performance ratio of PV [-]	0.75
Wind turbine maximum power [kW]	11.5
Estimated PV plant capacity [kW]	131.35
Estimated wind plant capacity [kW]	46

Table 12 Results of scenario 2b

Parameter	Result
Electricity produced from PV [GWh]	0.22
Electricity produced from wind [GWh]	0.18
Electricity produced from CHP [GWh]	25.69
Total electricity produced [GWh]	26.09
Heat production of CHP [GWh]	60.21
Heat production of auxiliary boiler [GWh]	0.07
Total heat produced [GWh]	60.28
Biomass consumed [GWh]	151.39

PV and wind power systems are playing a negligible role in the entire electricity production. CHP remains the main electricity source. Heat production is equal to scenario 1a.

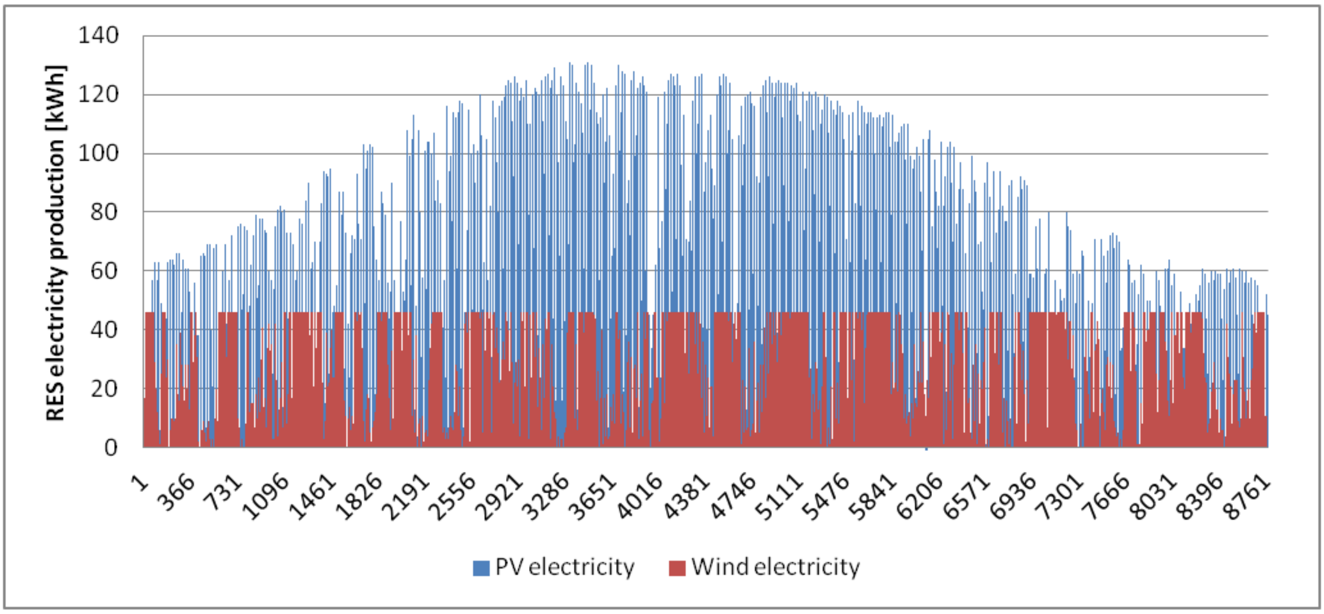


Figure 5.11 Hourly distribution of electricity production from PV and wind power in scenario 2b

The graphs showing the heat and electricity production from CHP are exactly the same as in the Scenario 2a, in Figure 5.9 and 5.10, respectively, so they are not shown here. Figure 5.11 presents the electricity production from RES (PV and wind).

The electricity produced from wind is more or less stable during whole year and the distribution is almost uniform, but the electricity production from PV is strictly connected with the season. As it can be seen, summer production peaks are around twice bigger than those in the winter. Nevertheless, the amount of electricity produced by PV and wind in this system is relatively small, mainly because restrictions area around the plant to build such installations.

Economic assessment

The same assumptions were made as in Scenario 2a, being added the price of the electricity sold from PV and wind. Based on [59]**,** the majority of FIT from RES are in the range of 80 to 120 €/MWh, and keeping in mind that Portuguese government in 2015 set the tariff at 95 €/MWh for small scale units [60], the FIT considered in the analysis for the electricity remains the same as from the biomass system or baseline scenario, so 88 MWh/year. Electricity export is 9.65 GWh and import is 5.54 GWh (Table 13).

Table 13 Economic assessment of scenario 2b

Parameter	Result
NPV [€]	27,339,809
IRR [%]	25.62
SPBT [years]	3.89
Heating export income [€]	1,640,000
Cooling export income [€]	3,000,000
Electricity export income [€]	849,200
Electricity import cost [€]	548,945
Biomass fuel cost [€]	2,452,518
Fixed O&M costs [€]	466,000
CO_2 emission costs [€]	0
Biomass CHP cost [€]	7,680,000
Wind plant cost [€]	51,000
PV plant cost [€]	134,000

Comparing to scenario 2a, in this scenario NPV is slightly higher, so IRR is slightly lower and SPBT is longer. The difference between scenario 2a and 2b is relatively small, so it is actually up to investor choice which one would be better. Scenario 2b could also replace the baseline scenario as it gives promising economic results.

5.4 Scenario 3

Technical analysis

This scenario is an example of wide diversification of RES sources to power the system but relatively high import of the electricity occurs. Data used in order to simulate this scenario required combining inputs from scenarios 1b and 2b. The results are presented, below, in Table 14.

Table 14 Results of scenario 3

Parameter	Result
Electricity produced from PV [GWh]	0.22
Electricity produced from wind [GWh]	0.18
Total electricity produced [GWh]	0.40
Electricity imported from the grid [GWh]	21.59
Steam delivered from WtE [GWh]	54
Heat production of auxiliary boiler [GWh]	6.28
Total heat produced [GWh]	60.28
Biomass consumed [GWh]	6.61

The mix of power sources gives interesting values. This option incorporates the advantages of already mentioned scenarios like usage of RES electricity sources, utilizing the leftover steam from WtE (otherwise wasted). Unfortunately, it also has disadvantages of both scenarios like importing almost whole electricity from the grid.

The graph showing heat production is exactly the same as in scenario 1b (Figure 5.7) and the graph of electricity production is exactly the same as in scenario 2b (Figure 5.11).

Economic assessment

The combination of assumptions from scenario 1b and 2b were used. There is no export of electricity, but the import is 21.59 GWh (Table 15).

Table 15 Economic assessment of Scenario 3

Parameter	Result
NPV [€]	- 6,287,373
IRR [%]	-
SPBT [years]	-
Heating export income [€]	1,640,000
Cooling export income [€]	3,000,000
Electricity export income [€]	0
Electricity import cost [€]	2,138,308
Biomass fuel cost [€]	107,082
Fixed O&M costs [€]	200,000
CO_2 emission costs [€]	0
Steam cost [€]	2,307,692
Pipeline [€]	4,133,250
Wind plant cost [€]	51,000
PV plant cost [€]	134,000

As in scenario 1a or 1b, this scenario is not satisfactory from the economic point of view. There is no way to build this system with NPV highly under 0, even after 25 years and no IRR to fit into the equation. Again, no export of electricity and no income from selling, accompanied with high cost of pipeline, steam and additional of RES brought the scenario to negative economic effect.

5.5 Comparison of scenarios

Table 16 provides a summary of the results of all scenarios. In the line, ‘RES share of PES’, where ‘PES’ means primary energy source, for the case of the scenarios where steam is from WtE it is assumed that PES of the whole process is waste incinerated in the WtE plant. RES electricity generation in this case is the sum of production of electricity from CHP based on biomass, PV and wind. It is important to mention that EnergyPLAN does not take into account the imported electricity to RES share of PES.

Table 16 Comparison of the results of all scenarios

	Baseline scenario	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 3
NPV [€]		-9,843,603	- 9,328,481	26,902,409	27,339,809	- 6,287,373
IRR [%]				25.78	25.62	
SPBT [years]				3.87	3.89	
RES share of PES [%]	0	30.1	83.2	100	100	100
Ratio of RES electricity production to overall electricity demand [%]	0	0	0	116.8	118.6	1.8
RES electricity production [GWh]	0	0	0	25.69	26.09	0.4

Figure 5.12 shows the comparison of NPVs for the different scenarios.

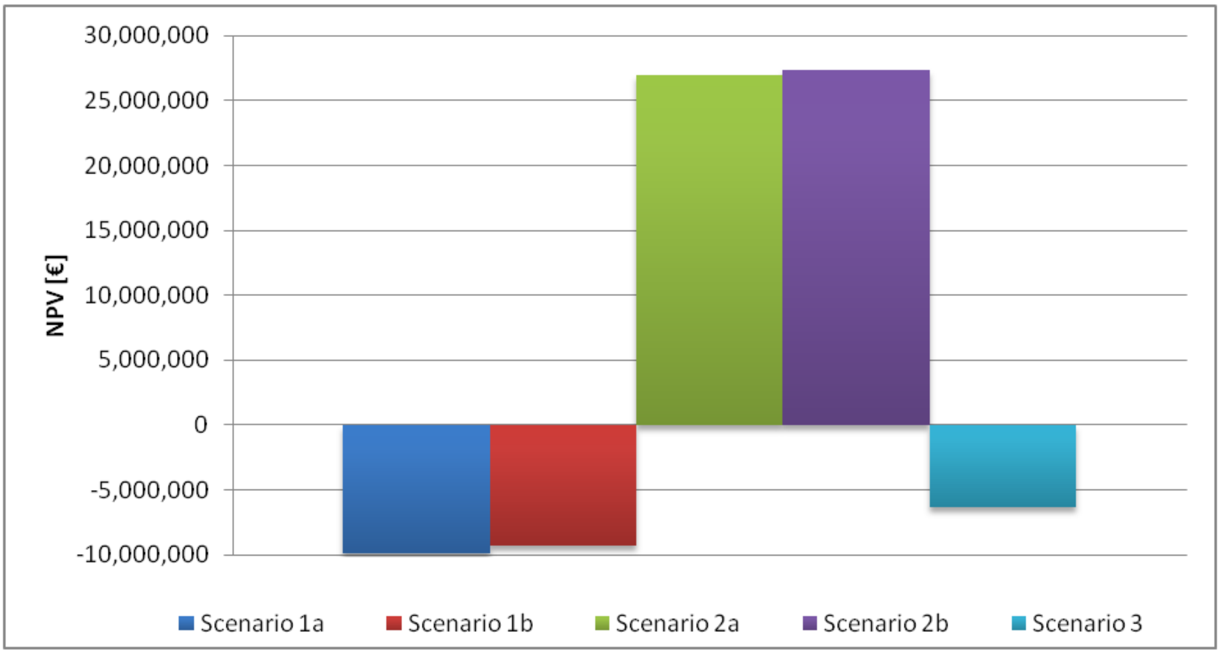


Figure 5.12 Comparison of NPVs of each scenario calculated for 25 years perspective

As it can be seen, only two out of five mentioned scenarios present a positive NPV in the 25 years perspective. Scenario 1a, scenario 1b and scenario 3 have a negative NPV, which results in unfeasibility of them. The satisfactory values of NPV are those of Scenario 2a and Scenario 2b. The difference between them is not significant, so other parameters should be compared to find out which one is better. Apart from NPV it is important to assess the IRR. Figure 5.13 presents a comparison of IRR for the different scenarios.

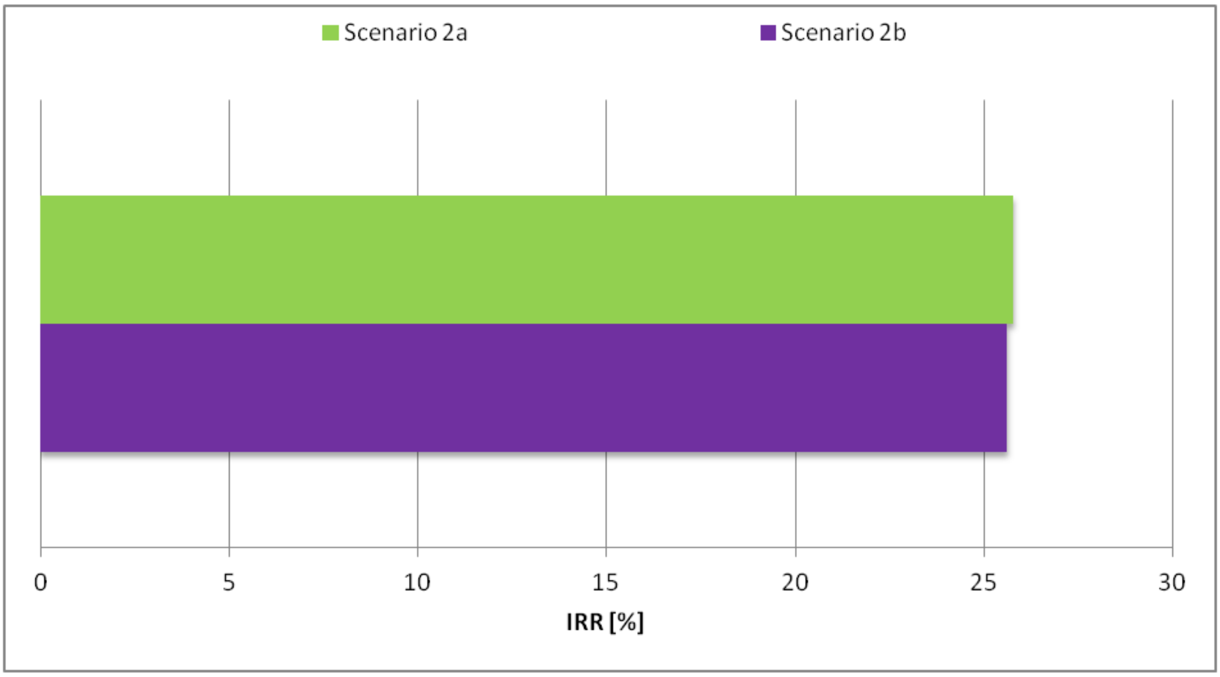


Figure 5.13 Comparison of IRRs from selected scenarios

As only the scenarios with positive and calculated for the defined timeframe NPV can be used for IRR calculation, there just two of them on the Figure 5.13. Both of them have IRR higher than the interest rate assumed (IRR>3%). Scenario 2a and scenario 2b (with biomass boiler solution) have quite high IRRs, similar to each other. Figure 5.14 shows the SPBT for the two scenarios mentioned above. SPBT is actually the static criterion of economic effectiveness assessment.

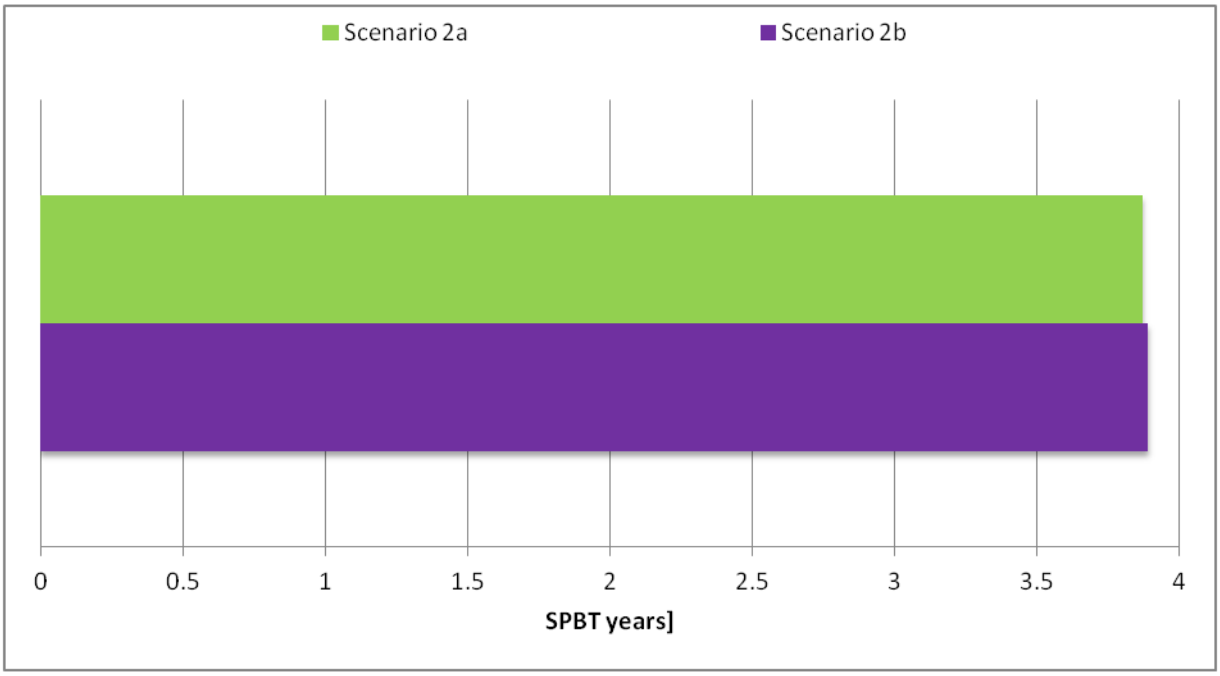


Figure 5.14 Comparison of SPBTs of selected scenarios

SPBT describes the time after which theoretically investment will pay off. The hierarchy of scenarios is the same as in IRR case: scenario 2a is slightly better than scenario 2b (both paying off in less than four years). The last issue considered in the analysis was the feature of EnergyPLAN, so RES participation in each energy segment (Figure 5.15) and RES electricity production (Figure 5.16).

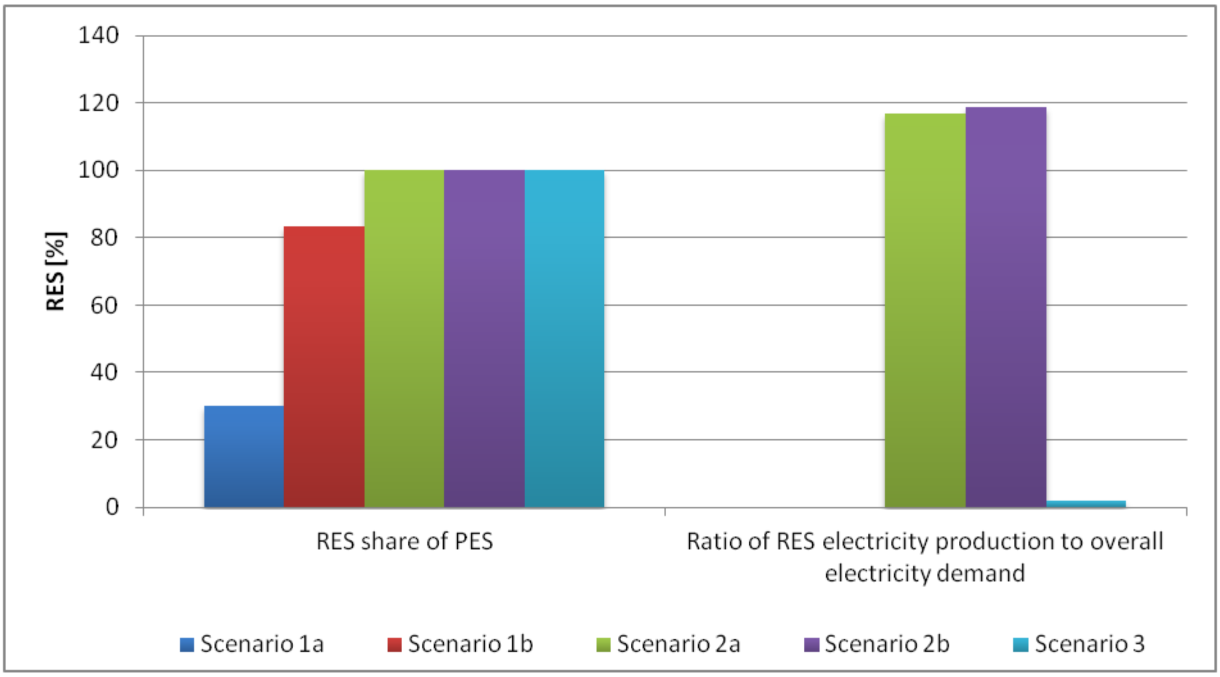


Figure 5.15 Comparison of RES participation in each energy source

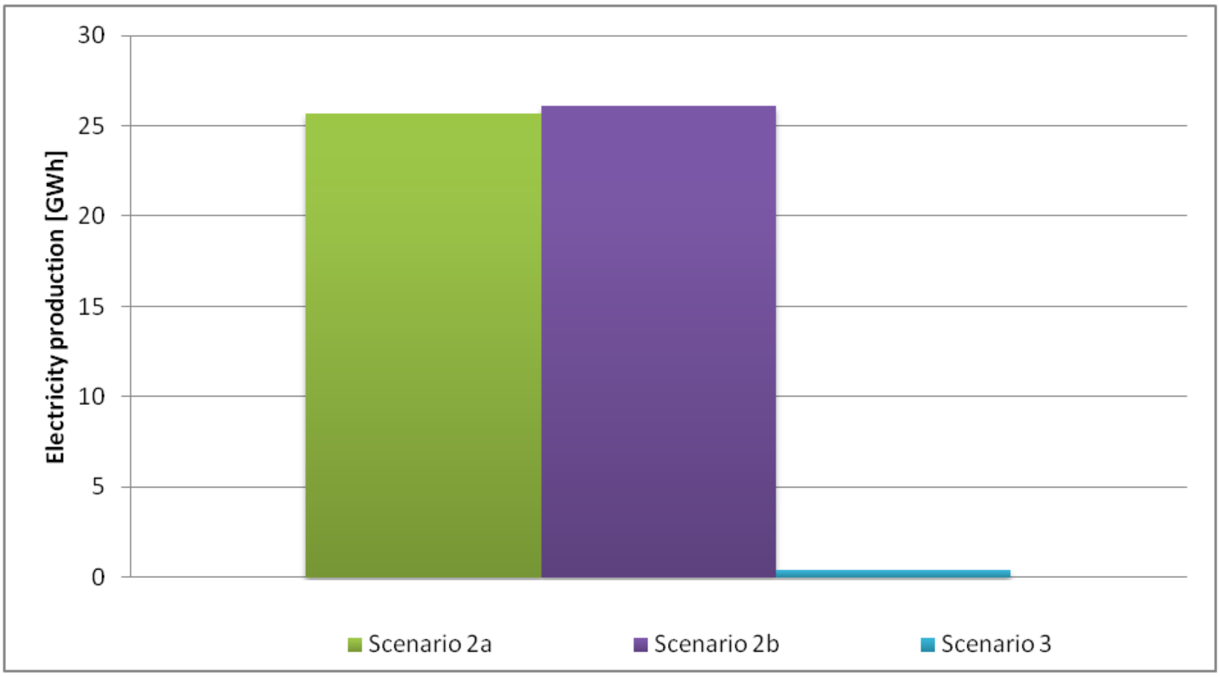


Figure 5.16 Production of electricity from RES

At Figure 5.15 two indicators were checked. When it comes to the first part of the graph: RES share of PES reaches 100% only in scenarios: 2a, 2b and 3. In second part of the graph the ratio is computed only for already mentioned scenarios. Electricity production is greater than overall electricity demand so the ratio is above 100% in case of scenarios: 2a and 2b. It shows that only the production of electricity from RES is enough to supply the whole system.

Regarding the Figure 5.16, it shows how much electricity was produced from RES in each scenario. More than 25 GWh is produced in scenarios with CHP biomass boiler (with addition of PV, wind or without) and only 0.4 GWh for the last scenario with huge diversification of energy sources.

Taking into account all of data above, from economic assessment only two scenarios can be indicated as satisfactory to implement them in the future and replace the baseline scenario. They give promising results with small difference between them (installation of additional RES for electricity generation), with NPV, IRR, SPBT, and RES participation at similar level. Actually, it is up to potential investor which one to choose as it was once mentioned, if the investor wants to have bigger NPV and RES participation scenario 2b should be chosen but if the investor prefers the scenario with better IRR and SPBT scenario 2a should be chosen.

6. CONCLUSIONS

In this dissertation, the main effort has been done to check if trigeneration systems could operate with the utilization of RES, using Climaespaço plant in Portugal as a case study. Technical analysis and economic assessment have been done to compare the suggested scenarios.

It was verified in the literature review that trigeneration technology is not clearly supported in Portugal. With the future perspective ahead, regulations are going to change but there is no certainty. Portugal is the country with high RES potential especially wind, hydro and solar and with one of the highest indicators regarding RES participation in EU. Natural from this point of view is the approach to exchange already existing installations with renewable sources. However, the idea might seem simple but the realization still faces some boundaries such as not well defined FIT or other forms of supporting RES sector combined with immaturity of technology. Energy sector has not found yet fuel able to compete with natural gas in trigeneration system, mainly because of the easiness of maintenance of this fuel. Nevertheless, analysis carried out in this work shows that, even now RES gives satisfactory results.

Both technical and economic analysis enabled to have a deep insight in the topic discussed. Technical part gave the author opportunity to clearly realize how such systems work and what are expected demands and products needed. EnergyPLAN was the main tool used for creating the simulations. As the same demand values were used, basing on the current plant, the main challenge was to project solutions with appropriate initial parameters. At the technical stage every scenario described is equal to each other with no sure leader as all of them are able to supply the system. The key point was to implement RES and present an economically feasible scenario. Due to that, actually all scenarios are somehow replacing the current system, only scenario 1a partly-using gas turbine is considered. As there was no need to remove the auxiliary boiler due to its back-up function it remained in the system during simulation stage (in scenarios 1a and 1b powered by natural gas, in scenarios 2a, 2b and 3 by biomass). There were issues not covered in this thesis regarding technical analysis. In the scenarios with the steam delivered from the WtE plant, as it is not clear how the cooperation of Climaespaço and Valorsul Project would look like and who would pay the cost of the interconnection, only hypothesis were considered. The assumptions made in scenario 2a and 3 regarding wind and PV plants in Climaespaço area are also questionable, as it is hard to forecast such plants. The big issue, occurred during simulation of baseline scenario and the demand section, crucial for further analysis. As EnergyPLAN is a tool which needs hourly data for the calculation process, it was crucial to find out if there are such to run the simulation. In this dissertation, creating the baseline was possible because of the combination of existing data followed by the approximations, which resulted in some degree of uncertainty (as the data are not always direct or from the same time). The software despite its advantages such as the simulation of whole year production in plant with hourly time step, forced the user to support with different external data. EnergyPLAN is mainly the software for national energy systems and is suited for this scale simulation but not for so specified installation. Technical analysis, in overall, enabled to analyse how the scenarios should work but it was the economic assessment that verified the actual feasibility of those scenarios. From the economic part it can be seen that only two scenarios out of assumed five, were actually feasible and significantly satisfactory at the same time. The scenarios which can be recommended are Scenario 2a and 2b, so the scenarios with the CHP biomass-based unit. Values of these scenarios are interesting, although it is important to mention that the cost of delivery and storage of the biomass was not included in the analysis. All scenarios were analysed with the timeframe of 25 years, with the help of EnergyPLAN cost database and its functions to simulate the fixed O&M and investment costs. The investment cost in scenarios was planned as the initial cost to be paid at the process of building the projected installation. The data regarding the cost and profit sections is also assumed with the degree of uncertainty, as only average data were available.

Summing up the whole analysis section in the dissertation, RES-based trigeneration systems are feasible ones but more accurate data is needed regarding such plants, with some pilot installations which will lower the uncertainty degree. PV and wind plants are not appropriate RES to power the trigeneration systems, as they are producing only electricity, while type of source producing heat is necessary. Such RES technologies are appropriate as the addition but not as the main component of the system. The main renewable source to power the trigeneration should be a fuel from which both electricity and heat could be generated and natural candidate from this position is biomass such as in scenario 2a and 2b.

An issue that should be considered in the future is incorporating the decision-making techniques combined with sensitivity analysis. Consultation with the person from the management of Climaespaço is needed in more advance way. It is important to set the appropriate criteria in order to evaluate the performances in different aspects of operation of the plant. Not only economic impact is important but there are environmental and society ones to examine.

REFERENCES

[1] EUROPEAN COMMISSION, “EUROPE 2020 A European strategy for smart, sustainable and inclusive growth,” 2010. [Online]. Available: http://ec.europa.eu/eu2020/pdf/COMPLET%20EN%20BARROSO%20%20%20007%20-%20Europe%202020%20-%20EN%20version.pdf (last attempt 23.01.2018).

[2] EUROPEAN COMISSION, [Online]. Available: https://ec.europa.eu/info/business-economy-euro/economic-and-fiscal-policy-coordination/eu-economic-governance-monitoring-prevention-correction/european-semester/framework/europe-2020-strategy_en (last attempt 23.01.2018).

[3] European Council, 2014 page 5. [Online]. Available: http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf (last attempt 23.01.2018).

[4] ICF International, "Study on Energy Efficiency and Energy Saving Potential in Industry from possible Policy," 2015 pages 185-186. [Online]. Available: https://ec.europa.eu/energy/sites/ener/files/documents/151201%20DG%20ENER%20Industrial%20EE%20study%20-%20final%20report_clean_stc.pdf (last attempt 23.01.2018).

[5] EUROPEAN COMMISSION, "Study on the Energy Saving Final Report," 2016 page 58. [Online]. Available: http://ec.europa.eu/environment/enveco/resource_efficiency/pdf/final_report.pdf (last attempt 23.01.2018).

[6] N. Petchers, Combined heating, cooling & power handbook : technologies and applications, pages 9-10, 275, 721-722, 2003.

[7] B. V. Mathiesen, H. Lund, D. Connolly, H. Wenzel, P. A. Østergaard, B. Möller, S. Nielsen, I. Ridjan, P. Karnøe, K. Sperling and F. K. Hvelplund, “Smart Energy Systems for Coherent 100% Renewable Energy and Transport Solutions,” *Applied Energy,* vol. 145, pp. 139-154, 2015.

[8] progRESsHEAT Report: Barriers and Drivers, pages 91-92 2016. [Online]. Available: http://www.irees.de/irees-wAssets/docs/publications/projektbericht-report/17-05_progressheat_d3.2__barriers_drivers_local_level.pdf (last attempt 23.01.2018).

[9] NREL, 2010 page 1. [Online]. Available: http://helapco.gr/pdf/FiT_vs_FiP_NREL.pdf (last attempt 23.01.2018).

[10] G. Resch, M. Ragwitz, A. Held, T. Faber and R. Haas, 2007 page 2. [Online]. Available: https://www.cesifo-group.de/DocDL/dicereport407-forum5.pdf (last attempt 24.01.2018).

[11] J. Castanheira, „District Heating and Cooling: A smart solution for smart cities: Climaespaço, the Lisbon DHC,” 2017, pages 26-28, 32.

[12] Climaespaço Engie, [Online]. Available: http://www.climaespaco.pt/duplo_clima.htm (last attempt 24.01.2018).

[13] M. Stojkov, E. Hnatko, M. Kljajin, M. Živić and K. Hornung, “CHP and CCHP Systems Today,” *International Journal of Electrical and Computer Engineering Systems,* vol. 2, no. 2, pp. 75-79, 2011.

[14] H. A. Moussawia, F. Fardouna and H. Louahlia, “Selection based on differences between cogeneration and trigeneration in various prime mover technologies,” *Renewable and Sustainable Energy Reviews,* vol. 74, pp. 491-511, 2017.

[15] DFIC - Dr. Fromme International Consulting, Cogeneration & Trigeneration – How to Produce Energy Efficiently, pages 18-26: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, 2016.

[16] M. Chorowski, “TRIGNERACJA - zalety i ograniczenia,” *Nowa Energia,* no. 4, pp. 1-9, 2014.

[17] Internation Renewable Energy Agency, sections: Innovation & Technology, Energy Transition, Power. [Online]. Available: http://www.irena.org (last attempt 07.02.2018).

[18] IRENA, [Online]. Available: http://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017 (last attempt 06.05.2018).

[19] K. Jana, A. Ray, M. M. Majoumerd, M. Assadi and S. De, “Polygeneration as a future sustainable energy solution – A comprehensive review,” *Applied Energy,* no. 202, pp. 88-111, 2017.

[20] International Energy Agency, [Online]. Available: https://www.iea.org/weo2017/ (last attempt 07.02.2018).

[21] Y. Jiang, J. Xu, Y. Sun, C. Wei, J. Wang, S. Liao, D. Ke, X. Li, J. Yang and X. Peng, “Coordinated operation of gas-electricity integrated distribution system with multi-CCHP and distributed renewable energy sources,” *Applied Energy,* no. 211, pp. 237-248, 2018.

[22] export.gov Helping U.S. Companies Export, [Online]. Available: https://www.export.gov/article?id=Portugal-Renewable-Energy (last attempt 15.02.2018).

[23] The Guardian, [Online]. Available: https://www.theguardian.com/environment/2016/may/18/portugal-runs-for-four-days-straight-on-renewable-energy-alone (last attempt 15.02.2018).

[24] APREN, [Online]. Available: http://www.apren.pt/en/renewable-energies/highlights and othersections (last attempt 17.02.2018).

[25] Endogenous Energies of Portugal, [Online]. Available: http://e2p.inegi.up.pt/ (last attempt 19.02.2018).

[26] S. Ferreira, N. A. Moreira and E. Monteiro, “Bioenergy overview for Portugal,” *Biomass and bioenergy,* no. 33, pp. 1567-1576, 2009.

[27] S. Ferreira, E. Monteiro, P. Brito and C. Vilarinho, “Biomass resources in Portugal: Current status and prospects,” *Renewable and Sustainable Energy Reviews,* no. 78, p. 1221–1235, 2017.

[28] G. Leonzio, „An innovative trigeneration system using the biogas as renewable energy,” *Chinese Journal of Chemical Engineering,* pp. 1-35, 2017.

[29] S. Li, J. Sui, H. Jin and J. Zheng, “Full chain energy performance for a combined cooling, heating and power system running with methanol and solar energy,” *Applied Energy,* no. 112, pp. 673-681, 2013.

[30] R. Leiva-Illanes, R. Escobar, J. M. Cardemil and D. C. A. Padilla, “Thermoeconomic assessment of a solar polygeneration plant for electricity, water, cooling and heating in high direct normal irradiation conditions,” *Energy Conversion and Management,* no. 151, pp. 538-552, 2017.

[31] F. Liu, G. Chen, B. Yan, W. Ma, Z. Cheng and L. Hou, “Exergy analysis of a new lignocellulosic biomass-based polygeneration system,” *Energy,* no. 140, pp. 1087-1095, 2017.

[32] N. Kabalina, M. Costa, W. Yang and A. Martin, “Energy and economic assessment of a polygeneration district heating and cooling system based on gasification of refuse derived fuels,” *Energy,* no. 137, pp. 696-705, 2017.

[33] Climaespaço Engie, *data gathered from the company,* 2017.

[34] D. M. Q. Correia, Technoeconomic analysis of a trigeneration system based on biomass gasification, Libon: IST, 2017.

[35] Blomeyer & Sanz, Guadalajara in partnership with CSIL, Centre for Industrial Studies, Milan, Integrated Solid Waste Management in Northern Lisbon, Milan, 2012.

[36] EnergyPLAN, [Online]. Available: http://www.energyplan.eu/ (last attempt 09.03.2018).

[37] 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,* no. 87, p. 1059–1082, 2010.

[38] P. A. Østergaard, „Reviewing EnergyPLAN simulations and performance indicatorapplications in EnergyPLAN simulations,” *Applied Energy,* nr 154, pp. 921-933, 2015.

[39] H. Lund, „EnergyPLAN Advanced Energy Systems Analysis Computer Model Documentation Version 12,” 2015.

[40] D. Connolly, „Finding and Inputting Data into EnergyPLAN (The FIDE Guide),” Aalborg University, 2015.

[41] Solar radiation data, [Online]. Available: http://www.soda-pro.com/web-services/radiation/helioclim-3-archives-for-free (last attempt 22.03.2018).

[42] Photovoltaic-software, [Online]. Available: http://photovoltaic-software.com/PV-solar-energy-calculation.php (last attempt 22.03.2018).

[43] Google maps, “https://www.google.pl/maps/,” [Online]. Available: https://www.google.pl/maps/@38.7827626,-9.0989756,116m/data=!3m1!1e3 (last attempt 22.03.2018).

[44] Eocycle, [Online]. Available: https://eocycle.com/small-wind-turbine/ (last attempt 22.03.2018).

[45] HOMER, [Online]. Available: https://www.homerenergy.com/products/pro/index.html (last attempt

22.03.2018).

[46] Investopedia, [Online]. Available: https://www.investopedia.com/terms/n/npv.asp (last attempt 13.03.2018).

[47] Investopedia, [Online]. Available: https://www.investopedia.com/terms/i/irr.asp (last attempt 13.03.2018).

[48] Energia, [Online]. Available: http://www.energia.eco.pl/EKONOM/ASPEKT/WSKAZ.HTM (last attempt 13.03.2018).

[49] ERSE, [Online]. Available: http://www.erse.pt/pt/electricidade/tarifaseprecos/2018/Documents/Tarifas%20e%20Pre%C3%A7os%202018.pdf (last attempt 28.03.2018).

[50] J. L. H. Miranda and L. A. A. López, "PIPING DESIGN: THE FUNDAMENTALS," page 1,11 2011. [Online]. Available: https://orkustofnun.is/gogn/unu-gtp-sc/UNU-GTP-SC-12-36.pdf (last attempt 06.05.2018).

[51] T. Nussbaumer and S. Thalmann, "Sensitivity of System Design on Heat Distribution Cost in District Heating," page 15 2014. [Online]. Available: http://task32.ieabioenergy.com/wp-content/uploads/2017/03/IEA_Task32_DHS_Cost_Analysis.pdf (last attempt 06.05.2018).

[52] Bloomberg, [Online]. Available: https://www.bloomberg.com/quote/EURUSD:CUR (last attempt 28.03.2018).

[53] Swagelok Energy Advisors, Inc., "Steam System Thermal Cycle Efficiency — Part One," page 4. [Online]. Available: https://chicago.swagelok.com/Services/Energy-Services/~/media/Distributor%20Media/C-G/Chicago/Services/ES%20-%20Thermal%20Cycle%20Efficiency_BP_33.ashx (last attempt 06.05.2018).

[54] T. Koskela, "Local energy solutions for industry and communities," page 26. [Online]. Available: http://www.lsta.lt/files/seminarai/120508_WARTZILA/Local%20energy%20solutions%20for%20industry%20Teemu%20Koskela%20ENG.pdf (last attempt 06.05.2018).

[55] The Baltic Times, [Online]. Available: https://www.baltictimes.com/news/articles/27108/ (last attempt 21.02.2018).

[56] M. Helin, page 5 2005. [Online]. Available: http://www.karelia.fi/bioenergia/nwh/woodfuel_production_technology/woodfuel/material/Helin_2005_Drying_of_wood_chips.pdf (last attempt 05.05.2018).

[57] Wood for Energy Production, page 52. [Online]. Available: http://www.videncenter.dk/Groenne%20trae%20haefte/Groen_Engelsk/Kap_09.pdf (last attempt 21.03.2018).

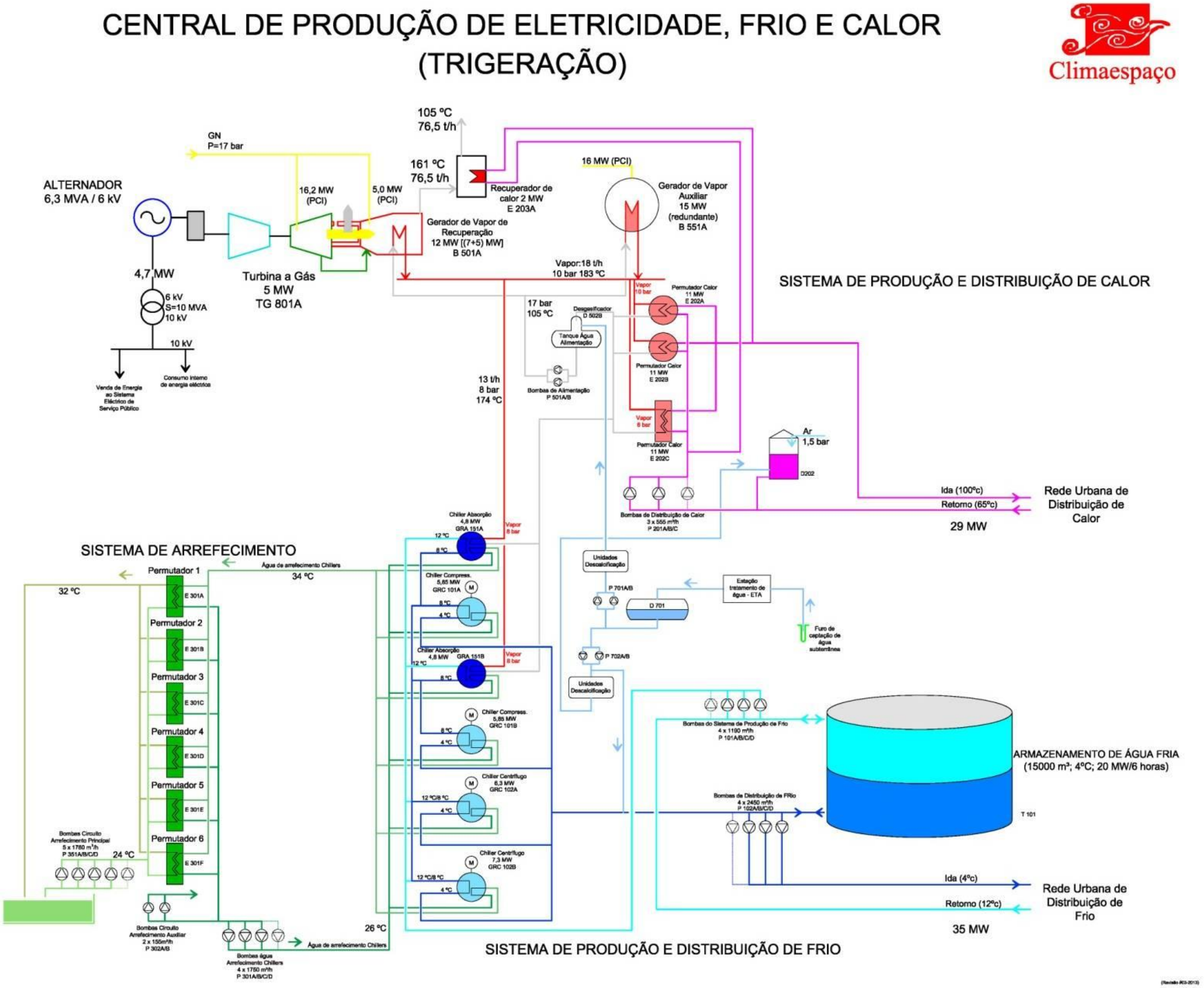
[58] A. Uslu, J. v. Stralen, L. Beurskens and F. D. Longa, "Use of sustainable biomass to produce electricity, heat and transport fuels in EU27," page 26 2012. [Online]. Available: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/biomass_futures_use_of_biomass_electricity_heat_transport_fuel_en.pdf (last attempt 06.05.2018).

[59] J. F. R. P. Behrens, T. Brás and C. Silva, "Environmental, economic, and social impacts of feed-in tariffs: A Portuguese perspective 2000–2010," *Applied Energy,* no. 173, pp. 309-319, 2016.

[60] Enerdata, [Online]. Available: https://www.enerdata.net/publications/daily-energy-news/portugal-publishes-reference-tariff-its-new-res-support-scheme.html (last attempt 29.03.2018).

[61] Eurostat, [Online]. Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics (last attempt 28.03.2018).

APPENDIX



Detailed scheme of Climaespaço plant [33]