# POLITECNICO DI TORINO

**MASTER's Degree in ENERGY AND NUCLEAR ENGINEERING**

**MASTER's Degree Thesis**

# Decarbonization in district heating sector: strategies to reduce environmental impact with cost-effective solutions

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# Summary

The effects of climate changes resulting from human activities are becoming more frequent and more impactful, therefore the energy transition consisting in moving from non-renewables to renewable energy sources has to be undertaken as quickly as possible. What is limiting this shift is often the economical aspect, since at least for now, in much part of the world is still more economically convenient to produce energy with fossil fuels.

The aim of this thesis is to study if it is possible to find a solution to reduce the environmental impact, while taking into account economic aspect, taking as a case study a district heating network. First chapters of the thesis are focused on international climate agreements and keywords related to energy transition, later system configuration is analysed, by focusing on energy demand, machinery typology of the plant and amount of costs and CO2 emissions released associated with them. Eventually, using XEMS13, an energy management tool that optimizes energy generation in hybrid power plants, and Gurobi, a mathematical optimization solver, several simulations will be computed, both with an economic optimization, which aims to reduce operating costs of the plant, and an environmental optimization, whose goal is to decrease CO2 emission released, in order to compare results firstly of the standard configuration and subsequently of new ones, which will be computed taking into consideration White, Certificates, thermal storages, and biomethane.

# Acknowledgements

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# Acronyms

**5GDHC**

$5^{th}$ Generation Distric Heating Cooling

**ARERA**

Autorità di regolazione per Energia,Reti e Ambiente

**CAR**

Cogenerazione ad Alto Rendimento

**CB**

Certificati Bianchi

**CC**

Combined Cycle

**CCS**

Carbon Capture and Sequestration

**CCU**

Carbon Capture and Utilization

**CCUS**

Carbon Capture Utilization and Storage

**CDM**

Clean Development Mechanism

**$CH_4$**

Methane

**CHP**

Combined Heat and Power

**CO**

Carbon Monoxide

**$CO_2$**

Carbon Dioxide

**COP**

Conference Of Parties

**DHW**

Domestic Hot Water

**DSM**

Demand Side Management

**EGD**

European Green Deal

**EF**

Emission Factor

**EGDIP**

European Green Deal Investment Plan

**EOR**

Enhanced Oil Recovery

**ETS**

Emission Trading System

**EU**

European Union

**GME**

Gestore dei Mercati Energetici

**GO**

Garanzie d'Origine

**GSE**

Gestore dei Servizi Energetici

**$H_2S$**

Hydrogen sulfide

**HFC**

Hydrochlorofluorocarbons

**ICE**

Internal Combustion Engine

**IEA**

International Energy Agency

**IETS**

International Emission Trading System

**JTM**

Just Transition Mechanism

**KP**

Kyoto Protocol

**LCA**

Life Cycle Analysis

**LCOE**

Levelised Cost Of Electricity

**MILP**

Mixed Integer Linear programming

**MIT**

Ministero delle Infrastrutture e dei Trasporti

**NDC**

National Determined Contribution

**NGO**

Non Governative Organisation

**$NO_x$**

Nitrogen Oxides

**OECD**

Organisation for Economic Co-Operation and Development

**OFMSW**

Organic Fraction Of Municipal Solid Waste

**PA**

Paris Agreement

**PCM**

Phase Change Material

**PES**

Primary Energy Supply

**PFC**

Perfluorochemicals

**ppm**

Parts Per Million

**PR**

Performance Ratio

**PUN**

Prezzo Unico Nazionale

**PV**

Photovoltaic

**RMP**

Raw material price

**SCR**

Selective Cathalitic Reduction

**SMC**

Standard Cubic Meter

**$SO_x$**

Sulfur Oxides

**SP**

Selling price

**SSE**

Società di Servizi Energetici

**TEE**

Titoli di efficienza energetica

**tep**

Tonnellate di Petrolio Equivalente

**TES**

Thermal Energy Storage

**THT**

Tetrahydrothiophene

**TTES**

Tank Thermal energy storage

**UNCED**

United Nations Conference on Environment and Development

**UNCHE**

United Nations Conference of Human Environment

**UNFCCC**

United Nations Framework Convention on Climate Change

**USD**

United States Dollar

**VOC**

Volatile Organic Compound

# Chapter 1

# Introduction

EU has defined a set of very ambitious goals in the field of environmental protection and fight against climate change. These themes start to be treated globally only from 1992 during the UNCED in Rio de Janeiro. This conference was held on the $20^{th}$ anniversary of the UNCHE in Stockholm in which for the first time it was stated that respect for human rights goes hand in hand with the environmental friendliness as reported in the principles presented in its report [1]:

> Man has the fundamental right to freedom, equality and adequate conditions of life, in an environment of a quality that permits a life of dignity and well-being, and he bears a solemn responsibility to protect and improve the environment for present and future generations[...]Man has a special responsibility and wisely manage the heritage of wildlife and its habitat, which are now gravelly imperilled by a combination of adverse factor. Nature conservation, including wildlife, must therefore receive importance in planning for economic development.

Rio de Janeiro summit saw the presence of political leaders, diplomats, scientists, representatives of the media and NGOs from 179 countries in the world [2] to decrease the destructive impact of human presence with its activity on Earth. At the end of this conference, it was established that since that moment the concept of sustainable development must be put before every political decision and so, to integrate and balance economic, social and environmental issues, it is fundamental to think back to the way in which we produce, and we live. It results in writing of a list of important documents in which focus is on goals to be reached and strategies that must be implemented to achieve them. This convention, through its 26 articles, aims at establish the concentration of green house gases at a level not harmful for the Earth's climate, through the adoption of a list of precautionary measures which minimize the effect of climate change, a list of commitments which goes from the diffusion of technologies and process that prevent or reduce anthropogenic emissions by sources of all greenhouse gases not included in the Montreal Protocol, to the formulation of national programs in which are present measures to mitigate climate change and to adapt to it. All of them are not binding but it is specified that they can be improved or made binding in future conferences called COP[3].

According to the Article 7 of [3] COP has two important duties to accomplish: it has a supervisory role over the policy implemented by each country, assessing the overall effects of the measures taken and suggesting further improvements, while the second role has to do with interaction between countries, since it has to promote cooperation and share of information between developed and developing countries. In fact, the latter, which are for example small island countries or countries located in arid areas, are less responsible for climate change and they access to fewer resources to face it, but they are the most affected by it, due to the increase of sea level and desertification. The first COP was held in Berlin in 1995, from that moment on every year a COP is held, this year was the turn of Scotland which host the event from November 1$^{th}$ to November 12$^{th}$ in Glasgow, but of all the conference occurred up to now, two of them are the most important: COP-3, held in Kyoto in 1997, which ends in the writing of KP, and COP-21 held in Paris in 2015, as a result of which PA is defined

## 1.1 Kyoto Protocol

The main results of COP-3 were the well-known KP. It is concluded with the aim of reducing global warming effects through the reduction of greenhouse gases concentration, listed in Annex A of this treaty, which are not only those included in Montreal Protocol such as $HCF_s$ and $PFC_s$, but also $CO_2$, $CH_4$, $N_2O$ and $SF_6$. Limits on emissions was not the same for all countries, as it is recognised that individual countries have different capability to face climate change, so they were divided in a group of industrialised country which are kept reducing their emissions on average of 5.2% with respect to 1990, while developing countries are not obliged to respect any limits. This is the first criticism of KP, given that countries such as China or India, already responsible of an increasing quantity of emissions released in the atmosphere at that time which culminates in 2019, when total $CO_2$ emissions produced by these two countries has exceed $CO_2$ emission produced by all OECD members, equal to 11318 Mt $CO_2$ [4], as represented in figure [4.9]. The second criticality has to do with its mechanism of entry into force. In fact, even if this protocol was adopted in 1997, it entered into force only in 2005, through the accession of Russia, since, as reported in article 25 of the treaty, this Protocol would become valid nine days after the date on which not less than 55 included in Annex I of KP, which accounted in total for at least 55 per cent of the total carbon dioxide emissions for 1990, deposit their instruments of ratification,

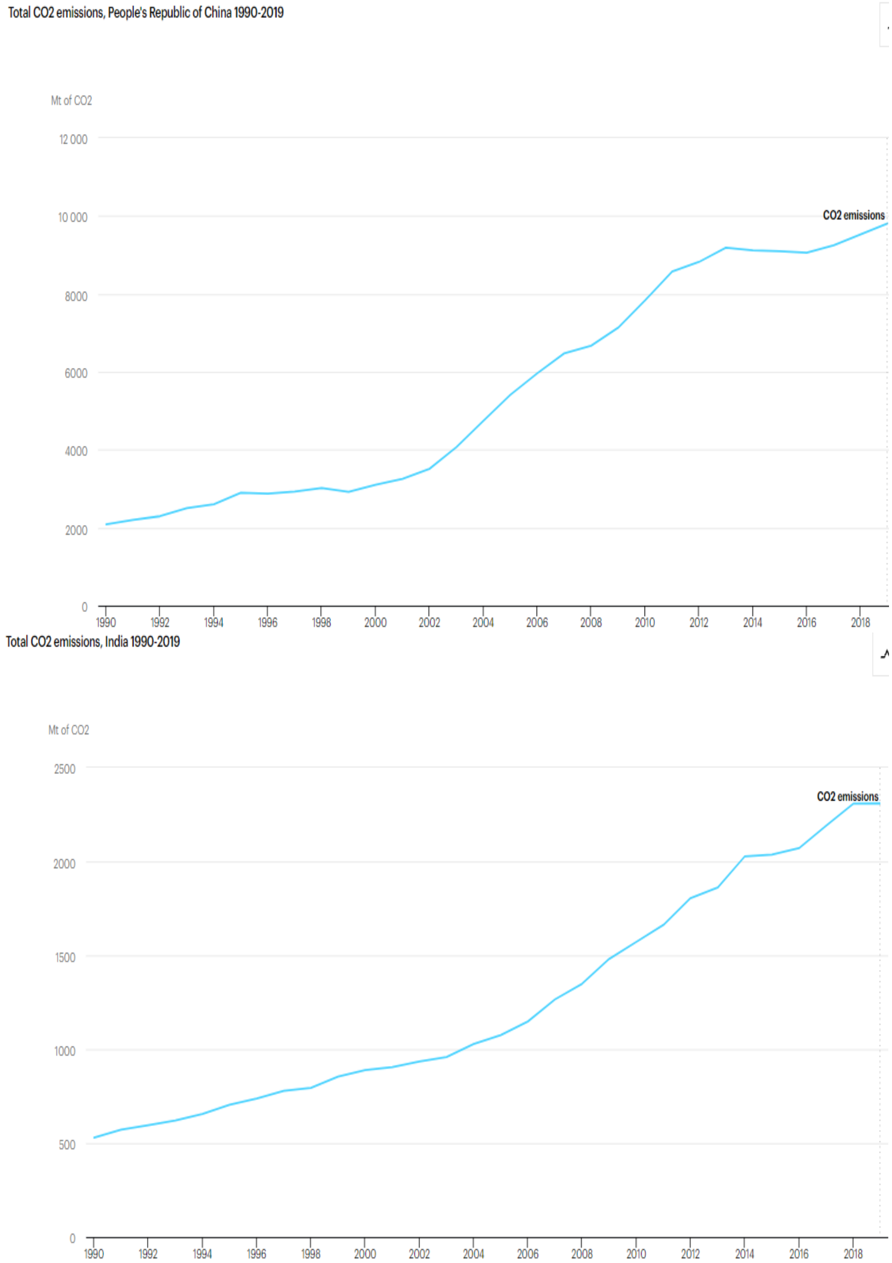


**Figure 1.1:** Trend of $CO_2$ emissions in China, India from 1990 to 2019: first graph from [5],second graph from [6]

acceptance, approval or accession, and United States, which accounted for 36.4% of total $CO_2$ emission, signed the agreement during the presidency of Bill Clinton, but his successor George W.Bush didn't ratify it.

KP establishes three different mechanisms to reduce greenhouse gas emissions:

- IETS: it is specified in Article 17 of the treaty [3]. Since global warming is precisely a global issue, this mechanism allows countries that exceeds in carbon emission to "sell" their emissions to countries which were over their targets, so a carbon market is created. Regardless of philosophical issue of giving a price on something which is not owned, Simon Caney and Cameron Hepburn in their report [7], underlines several other concerns. First of all, it deregulates industrialised country to promote sustainable development policies, palming their responsibility on other countries and this will lead to wider differences between industrialised and developing country if the latter have not a government facility able to invest finances to help poorer people. Finally, emission trading can guarantee a specific limit on emission, but not a reduction in emission in comparison with business as usual, as business as usual emission are unpredictable. In fact, this mechanism is strictly correlated to the economic performance of a given period, for an example, in a recession economic, activities went bust and similarly emission related to them. In this case, also cost price of sold emission price will decrease and this will give this will not make this mechanism cost-efficient.

- Clean Development Mechanism: it is defined in Article 12 of the treaty [3]. The purposes of this mechanism is to help developing countries in achieving sustainable development and to assist industrialised country in achieving compliance with their reduction emission target. First criticality is due to additionality of project, in which emission reduction must be additional to those which will made in the absence of KP. In fact, in a study published by Stanford University [8], Chinese situation is described, where in the early 2000's, Chinese government implemented a series of adopted measures to reduce its dependence on coal and to decrease the environmental impact of electricity generation. This led to the construction of many hydro, wind, nuclear (which is not included in this mechanism) and natural gas power plants to diversify energy mix. Industrialised countries economically support China, but, considering that China from 2005 to 2006 has constructed 200 GW of new capapity and with this ratio would catch up the total generating capacity of U.S, it is obvious that many of these plants would have been carried even without CDM. The fitting of equipment to remove $HFC_s$ contained in refrigerants was considered an additional solution, but here it came to surface the second problem. In fact, $HFC_s$ production was very cheap compared to the sale of carbon credits, and this implied that industrialised countries produce refrigerants in order to produce waste $HFC_s$, capture them and obtain a lot of credits. These problems means that this mechanism is easily exploited, so careful check must be performed, but this would slow down practices' approval, mainly due to the time spent to instruct people in developing countries about the effectiveness of proposed measures.

- Joint Implementation: it is described in Article 6 of the treaty[3]. It defines the possibility for an industrialised country to invest in a project to reduce greenhouse gas emissions in another industrialised country, instead of doing it on its territory. In this way country invest in place where reducing emissions is cheaper, and Russia has been often the place in which these projects took place, such as the Modeling and Optimization of Grid Operation of the Gas Transportation System "Ushgorod Corridor" of Volgotransgas", realised with the help of Germany[9]. With respect to the previous mechanism, this process took place in a country which is obliged to reduce its emissions but, here too problems related to addionality can arise in countries where projects are realised.

## 1.2 Paris Agreement

Eighteen years later, it is the turn of COP-21 in Paris. To assess if KP has a positive impact, it is sufficient to have a look on graphs represented in figure 1.2. The first graph of figure 1.2 represented that total final consumption of fossil

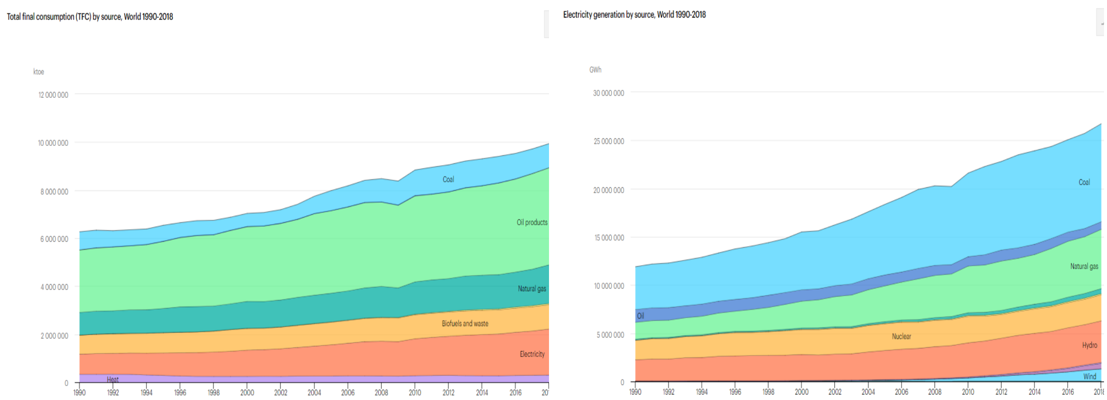


**Figure 1.2:** Historical trend from 1990 to 2018 of consumption and electricity generation by source: first graph from [10], second graph from[11]

fuels such as oil, natural gas or coal has increased after KP signature, except in 2009 due to financial crisis of 2007-2008. We also see an increase of electricity in accordance with environmental commitments but, having a focus on energy mix used to produce it, in the second graph of figure 1.2, an increased used of fossil fuel can be noticed. This led to an increase of $CO_2$ emission, which passes from 20516 Mt of $CO_2$ in 2018 to 33513.3 Mt of $CO_2$ in 2018 [12]. To stop this increase, several global meeting are organised, but precisely it is during COP-21 that the most important decisions are made. Thirteen days of meeting and negotiations brought to the writing of Paris Agreement, in which three main long term goals are established: a temperature goal, which entails in holding the increase in the global average temperature to well below 2 ˚C compared to the temperatures which characterised pre-industrial period or even to 1.5 ˚C, an adaption goal, in which it is underlined the importance of increasing the ability to face the adverse impact of climate change and reduce vulnerability, and a goal of "low emissions" finance flows, which consists in investing money with a pathway towards low greenhouse gas emission. These goals are specified in the second part of the twenty-nine articles that compose PA, which can be summarized in three different blocks:

1. Articles from Article 3 to Article 8 are related to action, they specify the three fundamental concept of mitigation, adaptation, and loss and damage.Mitigation refers to the efforts to reduce emissions and increase sinks, such as forests, while adaption is referred to strengthen resilience and reducing vulnerability. There is not a unique solution to pursue this last objective, you can for example focus on economic diversification, switching to drought-resistant crops, up to the adoption of more efficient warning system in case of hurricane and typhoons. Finally, loss and damage concept is similar to previous one, it refers to the importance of averting or minimising the loss and damage due to climate change and it can be realized, for example, thanks to the adoption of early warning system for cyclones or hurricanes.

2. Articles from Article 9 to 11 are related to support, within them concepts of finance, technology development and transfer and capacity-building are explained. With regard to the first concept, it is established that developed countries must provide financial means to assist developing countries with respect to both mitigation and adaption. The aid is not only made from a financial point of view, but as specified in the second concept, also transferring technological knowledge to developing in order to strengthen cooperation. Finally, the union of these two supports should promote the third support, namely, to enhance the capacity and ability of developing countries to adopt mitigation and adaptation measures on their own.

3. Articles from Article 13 to Article 21 concern procedures. Article 13 stressed the importance of furnishing transparent information in order to enhance confidence in the Agreement to track process, similarly Article 14 requires of a global stocktake, whose outcome is to inform countries in updating and increasing their action. All other articles deal with compliance, meeting, and entry into force of the Agreement and specify for example data and conditions of ratification, and an organization chart with duties and power of all competent bodies

Remaining articles contains information of a legislative nature. Is the PA enough? The answer would appear to be negative according to [13], which estimates a 2.7 $^{\circ}$C rise by the end of the century, even assuming that countries bring to completion their commitments. A possible cause of this can be the central element of PA, namely the "pledge and review" mechanism, with which member states submit their NDC that listed their prefixed climate action. A criticality can be detected in both words which constitute the mechanism. As regards review, with this configuration, countries impose by themselves their NDC instead of having targets imposed by above, so there is a shift from a top-down approach, characteristic of KP, in which targets where legally bound, to a bottom up approach, in which goals are politically encouraged and the committee responsible for facilitating implementation of PA provisions, operates in a non-punitive manner, resulting in advice or help for non-compliance country [13].On the subject of pledge, it is useful to read this report [14], in which current commitments of 184 PA ratifying states to reduce emissions are analysed and 128 of these are considered partially or completely insufficient, as represented in figure 1.3. Also the idea of progression and ambition of climate

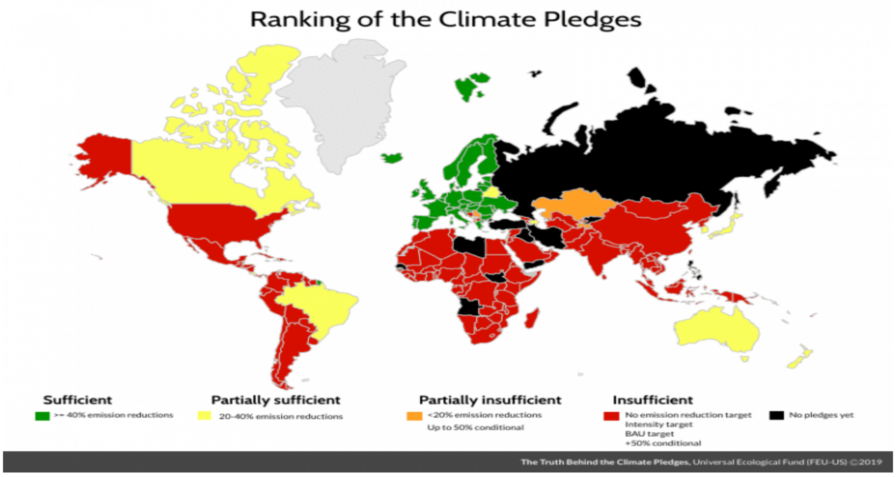


**Figure 1.3:** Ranking of climate pledges of PA ratifying countries: image from [14]

pledges is dragging its feet, as,after the first revision of them, 97% of countries pledges are the same of those initially submitted in 2015/2016 [14].

## 1.3 European Green Deal

On the heels of previous treaty but with the awareness that what has been done was not enough, EU decided to move on their own and, on 19$^{th}$ December 2019, presents the EGD. Few days earlier the European Commission president, Ursula Von der Layen, states:

> "The European Green Deal is on the one hand our vision for a climate neutral continent in 2050 and it is on the other hand a very dedicated roadmap to this goal.[...] Our goal is to reconcile the economy with our planet, to reconcile the way we produce and the way we consume with our planet and to make it work for our people.[...] We do not have all the answers yet. Today is the start of a journey. But this is Europe's 'man on the moon' moment.[15]"

It aims of making Europe the first climate neutral continent in 2050 with already a reduction of $CO_2$ of 55%, with respect to 1990, in 2030. It fits into a context in which EU has already attempt to move on their own to stop climate changes with the adoption of the "2020 climate and energy package", a set of measures adopted by each country to obtain by 2020 a 20% cut in greenhouse gas emissions from 1990 levels, 20% of EU energy from renewables and 20% improvement in energy efficiency [16] and of the "2030 climate and energy framework", that aims to cut the greenhouse gas emission about 40%, a 32% share of renewable energy and a 32.5% improvement in energy efficiency [17]. Its implementation has been undoubtedly favoured by Green Parties results in 2019 European elections. Green deal is not a law, it is a framework where all countries can take inspiration for laws, so this means that EU points the way and then each member state is responsible to translate indications into laws. Aspects to environment protection are linked to economic development because ecological transition must be accompanied by an economic growth decoupled from resource use in which no person or place are left behind. In figure 1.4, key elements of green deal are represented.

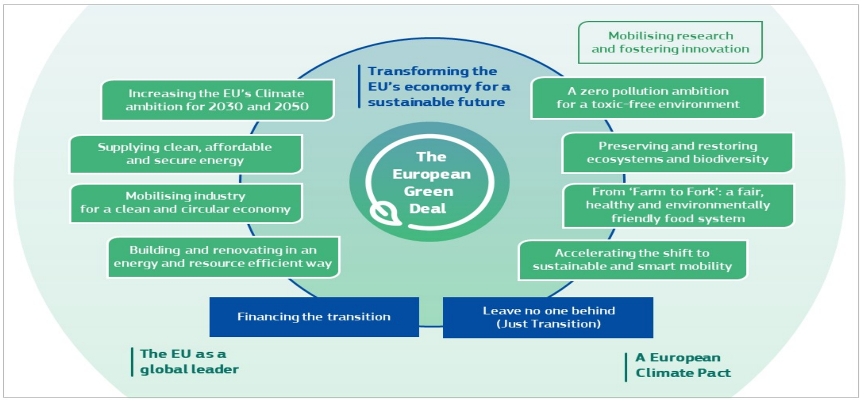


**Figure 1.4:** Key elements of EGD: image from [18]

All intervention areas belong to different sectors, but at the same time they are all connected to each other. Let's see in detail all key elements of EGD:

1. Increasing the EU's climate ambition for 2030 and to 2050: assessment process of plans to reduce emissions presented by countries must be realised with frequency, in order to stimulate them to adopt more ambitious measures. To do this, it will be necessary to adopt an IETS, to ensure effective carbon pricing throughout the economy. This could bring to carbon leakage phenomena, for which EU countries relocate their activity to countries with less stringent environmental duties which could cause also economic damage due to job losses. To prevent this, in accordance with WTO and respecting EU's international duties, EU is realising a carbon border adjustment mechanism for which prices of imported products more reflect their carbon content.Finally, considering that climate change is already showing its dramatic effects, it is important to implement a more ambitious EU strategy on adaptation to climate change.

2. Supplying clean, affordable and secure energy: these three adjectives must always go with the word energy for a complete energy transition. Energy must be clean because energy and heat production is still the biggest cause of $CO_2$ emissions, so it is necessary to develop a power sector based on large renewable power plants to decarbonise energy mix, with the aim to eliminate fossil fuels from it within 2050. Energy must also be affordable, looking for fixing a ceiling price for energy to afford key energy services that guarantees basic standards of living and eliminate the issue of energy poverty. In conclusion, energy must be secure, and this has been always a problem for EU, because it has always relied on foreign country with unstable political conditions or undemocratic regimes and nuclear energy has never fully widespread. So, given the uncertainty connected to the implementation of renewable energy sources, it is necessary to be equipped with a network infrastructure able to manage energy, for example composed of smart grids and energy storage.

3. Mobilising industry for a clean and circular economy: the strategy to be used in this sector proceeds on two parallel: on one side it is necessary to make fundamental industrial process such as steel or paper less energy-consuming and more sustainable, reaching a complete decarbonization through co/trigeneration (technology used to generate with one fuel two or three energy vectors such as heat, electricity and chilled water) and electrification of industrial process, presuming that electricity is produced with renewable energy sources. The other track to follow brings to the diffusion of circular economy with a plan which aims at placing on the market reusable and repairable products, promoting a clear and unambiguous set of information to reduce the risk of "green washing". This policy could the additional benefit to reduce waste significantly.

4. Building and renovating in an energy and resource efficient way: here too, this

project involves the inclusion of buildings in IETS and to create a platform which brings together members of building sector, architects, and local authorities to rethink to a new concept of building itself, putting effort especially to public building such as school and hospital to support education and public health.

5. Accelerating the shift to sustainable and smart mobility: several strategies can be implemented to achieve this goal, starting from multimodal transport, a combination of at least two different modes to move your cargo from countries and even though various modes for transportation are included, they fall under the same bill of lading [19] with the help of automated mobility and in this way communication and coordination expenses are minimized. As regards fuels, funding for fossil fuels should stopped and in parallel while alternative transport fuels, such as hydrogen fuel cells and biodiesel should ramp up.

6. From 'Farm to Fork': designing a fair, healthy and environmentally friendly food system: also, the way in which we feed has a deep impact on the climate, suffice it to say that the use of pesticides and fertilizers used in most of the crops that must be abandoned. At the same time, it is important to promote sustainable food consumption and promote healthy food for all.

7. Preserving and restoring ecosystems and biodiversity: this aim is about both forests and oceans. Forested area needs to improve both in quantity and in quality to help the absorption of $CO_2$ and reduce the extent of forest fire, while action on oceans deal with the arrest of their acidification, which has consequences on the ocean itself, but also on marine organism and on man.

8. A zero pollution ambition for a toxic-free environment: to guarantee a toxic free environment, EU commission will present a chemical strategy for sustainability to protect citizens and environment against hazardous chemicals based on scientific evidence on the risk posed by them in products.

As represented by the circle in figure 1.4, to afford all that, it is fundamental the financing of the transition by which no one will be left behind. The EGDIP is the investment pillar of the EGD and will guarantee €1 trillion in sustainable investments over the next decade to reach EGD goals. A part of the plan, at least €100 million in investments over the period 2021-2027, is used to aim at supporting regions facing the greatest difficulty associated to energy transition (Poland still relies on coal to produce nearly 75% of its electricity [20]) through the JTM. Money invested will need to support project on small scale the construction of a waste-to-energy plant in Olsztyn, Poland,to help with waste-management and guarantee with a single fuel both electricity and heat thanks to this cogeneration power plant financed with more than €180 million [21] to a large scale such as the promotion and financing of energy efficiency modernisation process across Lithuania through the installation of solar panels on private homes, the renovation of multi-apartment buildings and increase of energy efficiency of Lithuanian industries mainly focused on the installation of efficient lighting financed overall financed with €37.5 million [22].

Also EGD is not without critics, starting with the JTM. On the one hand, countries which strongly rely on coal, such as Poland, claim that it is necessary to more diversify pace by which achieve climate neutrality according to the starting point of each country, complaining about the fact that funds are unfairly distributed and with the current breakdown will effect Polish competitiveness, but on the other hand Spain, investing since the 2000s on wind power plant and decuplicating electricity produced with these plant from 2000 to 2019 [23], complains about this, claiming that with this mechanism country which have previously invested without imposition of EU treaty are not rewarded. With regard to Spain, in recent month when gas price was rapidly increasing, it has been criticised its decision to limit bill increases with funds that were destined to companies which produce energy from gas alternatives, that, according to Jacob Kirkegaard, risk to reduce confidence in green economy [24]. This is not the only flaw from the economic point of view of EGD. In fact, it is based on the idea that decoupling economic growth and environmental impact is possible. Supporting this, it is taken as example that between 1990 and 2017 emissions decreased by 22% while the economy grew by 58% [25], but the price spent by EU in imports from China increases more rapidly, multiplying by five in the same period [26], which means that emission source is simply moved. In conclusion, a technological limit is represented by the material used to obtain renewable energy, such as PV panels or batteries, which are realized with scarce raw material such as lithium or nickel, that could lead to a rapid shortage of these material, whose over exploitation could raise the price sky-high of them but can also bring environmental damages to the people which live in the mines area.

# Chapter 2

# Keyword

Focusing on the second point of the European Green Deal, based on clean, affordable, and secure energy, it is necessary to go more into detail on the subject of the keyword listed such as cogeneration, electrification, decarbonisation. -ation suffix comes from Latin suffix -*ātiō* and indicates the result of an action or a process, in this case the result when a system is or electrified, cogenerated or decarbonised. The single actions or their union result in another word which ends in -ation, which is optimization. Below, these four keywords are analyzed, to better understand their mechanisms and their potentiality for an energy transition.

## 2.1 Cogeneration

CHP is a technology in which a single plant is able to generate heat and electricity at the same time, using a single fuel. In the most common configuration, as you will see later, several combinations are possible, a fuel, typically gas, is burnt in a boiler room to boil water and produce high pressure steam, that expands in a steam turbine which converts thermal energy into mechanical energy, and then, thanks to alternator, electricity is produced and sent out to the power grid. After this step, steam still has an high heat content, so instead of being dissipated, so it is sent to a condenser, an heat exchanger used to transfer heat from an hotter fluid to a colder one. Steam is the hotter fluid, while water is the colder one and after being heated, according to the temperature, it can be used by industrial or residential utilities. In latest plant, if steam is still warm enough, it can be used in absorption chiller to produce chilled water and you go from cogeneration to trigeneration. Today, cogeneration supplies 11% of electricity and 15% of heat consumed in Europe [27]. The choice of joining two cycles brings numerous advantages from the point of view of the increase of energy efficiency, since it is evaluated as the sum electrical and thermal efficiency, which implies a smaller amount of fuel to produce the same amount of energy and a $CO_2$ emission reduction. This last quantity can be further reduced substituting natural gas with waste biomass or biofuels. There are also advantage from an economic point of view. To partially cover construction and operational cost, GSE, releases a number of CB assessed by PES and RISP index, two parameters that will explained better later, which quantify primary energy saving, that binds fuel due to cogeneration, with respect to the fuel necessary to produce the same amount of electrical and thermal energy with separate production. There are several technologies by which cogeneration is possible, according to [28]

- CC: most of energy produced from cogeneration in Italy comes from CC. A CC power plant is a plant in which two thermodynamic cycles in series are presents. First one is a Bryton-Joule cycle, in which exhaust gas, after being expanded in a gas turbine and having produced mechanical energy, are still characterized by an high thermal content, so they can be exploitable in a second cycle, Rankine cycle, to heat water and make steam, that will be expanded in a steam turbine to produce again mechanical energy. Power values of these two turbines are similar, even if steam turbines operates at lower temperature values. Gas turbines have very low $NO_x$ emissions, thanks to dry low-$NO_x$ combustors and SCR, equal to 25 ppm, and simultaneous low CO emission in the 10 to 50 ppm, and they are mainly used in power generation to cover peak load for their readiness to use. Instead, steam turbine does not directly convert fuel to electric energy, so steam production can take place using a large variety of fuels from natural gas to waste, including all types of coal, wood, wood waste and agricultural products.They are suited for medium-large applications, so in addition to cogeneration, can be used for example for district heating. Steam turbines has a long service life, but they have longer start up with respect to gas turbine, so they cannot follow grid peaks and they are used to cover base load.

- ICE: this technology is the most numerically widespread technology in Italy even if its energy produced is a quarter of that produced by CC. This mainly due to the fact that their operational range is one of the highest between CHP technologies, which implies that their usage is not limited to CHP, but also for vehicles and emergency shutdown generators, but its power range (10 kW-10 MW) considerably less than gas or or steam turbine. In any case, an ICE starts quickly and can operate at partial load ensuring good partial load efficiency, while other limits are the relatively high $NO_x$ emissions and their maintenance cost are higher than comparable gas turbines.

- Microturbines: microturbines are small combustion turbines which burn gaseous or liquid fuels. The operating principle is the as previous turbine with the difference that, besides the smaller size which implies a lower power, they operate with lower compression ratio and combustion, while comparing them with ICE which have similar power, they have an higher power density and lower emissions but their start is less sudden. They are used in commercial buildings and small industries, so they are particularly suitable for promoting distributed generation application and smart grid.

- Fuel cells: between all technologies described, fuel cells are those which offer the potential for clean energy. Their working principle is the following: an electrolyte separates an anode and a cathode, in the first electrode hydrogen is reacted with a catalyst, resulting in the following reaction:

$$H_2 \rightarrow 2H^+ + 2e^-$$

The electrolyte, characterised by an high protonic conductivity, allows the passage of protons just obtained towards, while electrons migrate through an external circuit connected to a load to provide electricity, and then to the oxygen electrode where the second reaction occurs:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O + heat$$

So with hydrogen and oxygen it is possible to produce electricity, water and heat without any emission, with the exception of those caused by the production of hydrogen, that in 95% of cases it is produced from fossil fuels, such as natural gas. What hurdles the full dissemination of this technology is certainly its elevated cost but there are also difficulties related to its storage. In fact due to its low density, it is necessary to store it at extreme condition of temperature and pressure to keep it in liquid state (700 bar in a typical hydrogen car [29] and even in the case of liquid hydrogen, are necessary to bring it to -253°C.

## 2.2 Electrification

Electrification consists in a process wherein there is a replacement of the technologies utilizing fossil fuels with those which exploit electricity. There are several reasons associated to this choice: firstly, to be more reliant on electricity allows to improve the security of own energy mix, since electricity can be produced by a list of energy carriers on national territory and allows to reduce fossil fuels dependence on other country. Moreover, relying on electricity allows to make own energy even more sustainable, because electricity price produced from renewable sources is becoming more comparable with that produced by fossil fuels, with the electricity weighted average global cost that had, between 2010-2019, a drop of 82% for photovoltaic, a drop of 29% for offshore wind, and a drop of 40% for onshore wind [30]. As you will see after, electrification can be applied to all sectors, thus ensuring an overall increase of efficiency and better air quality thanks to the reduced pollutant emissions. Moreover, it promotes the widespread of digitalisation into power sector, allowing people to consume less electricity thanks for example to the development of distributed energy resources and of the DSM mechanism.

Enel Foundation, with the collaboration of Energy Center of Politecnico di Torino and MIT, has published a report in which are represented possible electrification pathways up to 2050 for the three main sectors of building, transportation and industry, and it seeks to introduce an energy paradigm based on the exploitation of renewable energy source. In this study, the starting point taken into account is the 19% of electricity of total energy consumption spent in 2019. This increase will reach 46% in 2050 [31] and it will be accompanied by a rise of renewable energy sources to produce electricity, that will pass from 48% in 2019 to 85.6% [31]. There are several benefits connected to this solution: first of all, you will have a more than a half reduction of $CO_2$ emissions, that will imply an increase public health saving due to a minor premature mortality. You will see also a diminution of primary energy consumption, that results in an increase of energy efficiency and a diminishing of weight of energy bills for household

As previously mentioned, the three policy areas are buildings, transportation and industry. The latter has the lower room for improvement, both because it is the one which already exploits more electricity, but also because temperature and pressure requested are difficult to be achieved using only electricity. The technological solution which will help to increase the penetration of electricity is having recourse to low to medium temperature heat pumps, whose temperature range also reaches 200˚C. For greater temperature available technologies such as electric arc furnaces, which reach temperatures even higher than 1500˚C, are mature and competitive only with natural gas, also because hydrogen usage is still not convenient due to high costs.

With regards to transport, electrification widespread is closely linked to study progress in the field of batteries and energy storage, since maximum autonomy of an electric car is represented by 840 km crossed by Tesla Model S Plaid+ [32], significantly below the potential number of kilometers crossed by the diesel and gasoline car with more autonomy (up to 1590 km of the Volskwagen Passat [33] and up to 1060 of Citroen DS3 [34]) and this aspect, coupled with the fact that charging stations are not evenly distributed on Italian territory, is slowing down their spread. Of course private cars is not the only transportation sector in which electrification is possible. From this point of view, rail transport is the sector in which electrification has the largest penetration, whereas road public transport and light freight transport too will see an increase in their electrification. For all other mode of transport, several technological limits slow down electrification penetration.

Heavy trucks has the limit of low mass capacity ratio of their batteries that will require several thousand of high power charging columns, and moreover, there is not a specified plan under design as for a wide network of electric highways. Also air and water transport are far away from a shift towards electrification in next decades, due to the even higher energy density of batteries. As regards flight, the first attempt is of substituting hydraulic system of flight controls of planes with an electric one, while for the second one small ferries between near island are becoming electrified, but in any case their contribution towards electrification pathway by 2050 will be negligible, as represented in the first graph of figure 2.1. Nevertheless electrification does not include in an uniform way all transport typologies and the increase of transportation demand is expected to be in average proportional to GDP increase, the total primary energy consumption will expect to decrease from 1523 PJ in 2015 to 748 PJ in 2050 [31], as pictured in the second graph of figure 2.1, to emphasize electrification benefits.

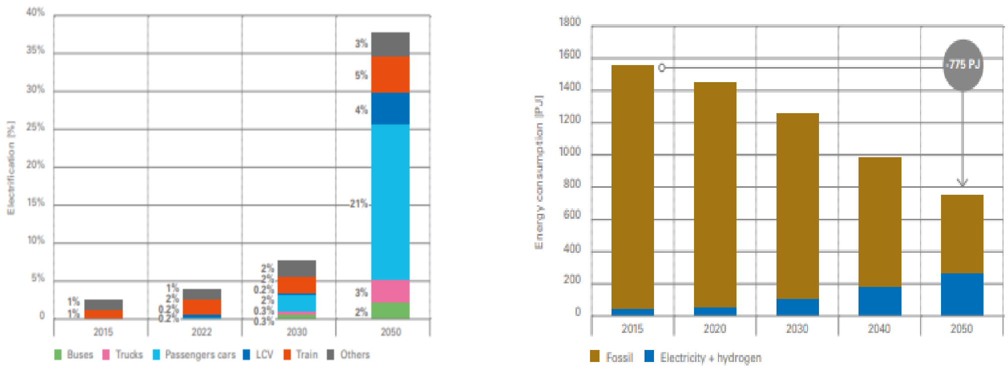


**Figure 2.1:** Percentage of electrification in each transport sector and transportation consumption from today to 2050: graphs from [31]

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In conclusion, building sector is composed by residential and non-residential sector. The latter, which includes offices and commercial activities, is already widely electrified due to use of electrical appliances and air-conditioning system, so efforts are addressed to residential buildings. Areas where consumption is highest in residential building are space heating and water heating, so technologies available to introduce electricity in this sector are condensing boiler, biomass boiler and heat pump for space heating, not forgetting that biomass boiler and heat pumps must be coupled with a thermal storage. For both application, in 2050, the dominant role will be allocated to heat pumps as represented in figure 2.2, whose electricity will be produced thanks to PV panels, this will ensure that in 2050 electricity will the most used energy drivers, and consequently a decrement of final energy consumption in residential sector. In particular, electricity in space heating will

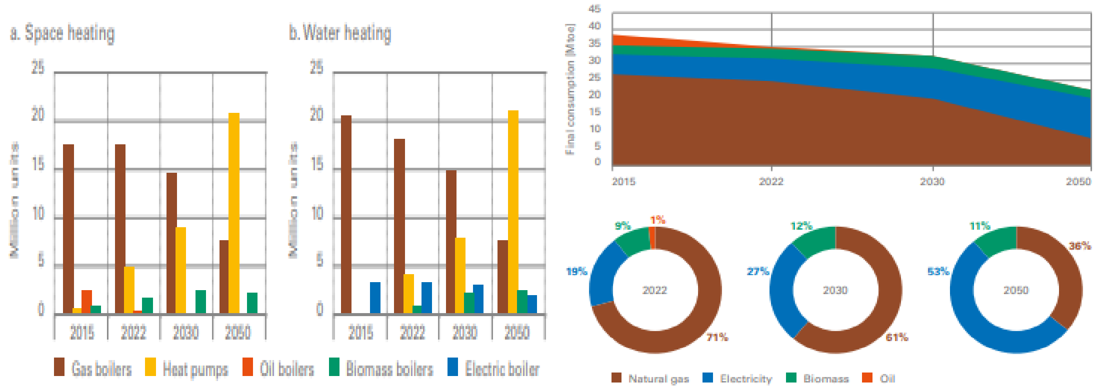


**Figure 2.2:** Changing technology and percentage consumption in residential sector from today to 2050: graphs from [31]

increase from 3.6% in 2022 to 36.3% in 2050, while electricity in water heating will pass from 17.4% in 2022 to 50.3% [31]. It is to important to underline that even cooking, even if it has , will be affected by electrification thanks to induction stove.

## 2.3 Decarbonisation

Decarbonisation refers to the process of decreasing carbon intensity of something, namely reducing the emission released in the atmosphere resulting from a process. How it has been mentioned in previous paragraph, CHP and electrification are two possible strategies to decarbonise, but are mainly related to the power sector and regards on a smaller scale other sectors, such as chemical one, which is built on hydrocarbons as a feedstock and as a source of energy. Even taking into account that production of chemical industries, particularly those which deal with plastics should decrease, plastic-made products will continue to be realized so a possible solution to reduce their environmental impact is to use CCS and CCU, sometimes combined together in CCUS.

CCS is a technique for trapping carbon dioxide before it reaches the atmosphere, transporting and storing it into geological sites. Published scenarios indicated that CCS has a fundamental role to reach net zero $CO_2$ emission by 2050, quantifying also that to contain temperature increase to 1.5 ˚C in 2050, as clamored in PA, in 2030 $CO_2$ captured by CCS has to be of 230/400 Mt $CO_2$/yr, increasing to 930/1200 Mt $CO_2$/yr in 2050 [35].There are 51 CCS plant across five continents [36], in Italy Enel is currently developing a small-scale pilot project at the Brindisi power station in order to test CCS capture before application to the full-scale demonstration project at Porto Tolle.

As represented in figure 2.3, $CO_2$ can be captured before combustion using $CO_2$

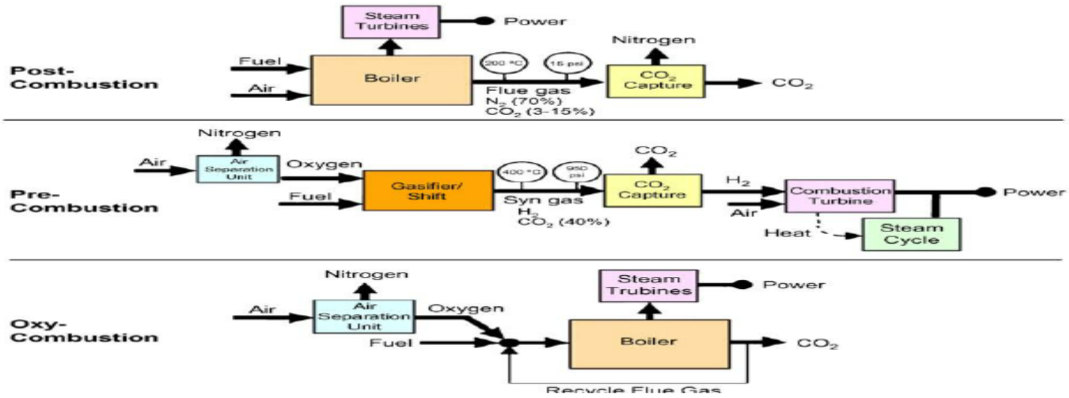


**Figure 2.3:** Scheme of different CCS techniques: figure from [37]

physical absorption system or after combustion using $CO_2$ chemical absorption system. In the first case, fuel is converted into $CO_2$ and $H_2$ through gasification,a process in which by reacting fuel with an oxiding agent such $O_2$, you get a mixture named syngas composed of CO and $H_2$. Then, following a transition across a catalytic reactor in which CO, it reacts with water vapour, with the aim to obtain $CO_2$ and further $H_2$. After this $CO_2$ is transported and stored, while $H_2$ can be used as fuel to produce electricity or to feed hydrogen cars [38]. Post combustion capture implies that exhaust gas are put in contact with solvents such as ammonia. This reaction allows the formation of a chemical compound that, if it is heated, allows the release of purer $CO_2$, while ammonia is cycled to be used again [39].You have a third chance to capture $CO_2$ with oxycombustion, namely using pure $O_2$ in the combustion in order to obtain purer $CO_2$ but this solution is extremely expensive and and has been only tested on smaller scale plant [39]. Of course, first typology is more complex, but it realises a better separation of $CO_2$ and it is possible to obtain $H_2$.

Cost related problem is not just about oxycombustion technique, but it regards also the other two technologies. Australian government publish a report in which, even underlining the fundamental importance of reducing carbon emission states that: "There is not one example of a CCS project anywhere in the world that offers a financial justification for investing in CCS.[40]". This strong affirmation, even coming from a country which in 2019 produces 58% of electricity using coal [41] and so would suffer an increase in the price of electricity if severe limits on $CO_2$ were put(in U.S,in 2016, it has been estimated that electricity price would pass from 94.6$/MWh to 136.2$/MWh [42] for a coal power plant without or with CCS), it is important to go into detail of this affirmation. Possible issues that must be faced regards not only technological problems due to the big amount of energy necessary to transport and storage which reduce efficiency of CCS and the storage itself, since place where $CO_2$ is injected, is not always a secure place according to seismic activity, but in fact there also critical element related to the economic point of view. According to this report [40], there is no economic sense in investing on CCS if there is not a whole emission price supported by carbon border taxes.

In the footsteps of this limit, the idea of CCU, sometimes CCUS, for which $CO_2$, instead of being stored, is converted into commercial products, takes hold. The most relevant application is methane production by reacting $CO_2$ with $H_2$ produced by water via electrolysis, but also methanol, an alternative fossil fuel, can be easily synthesized from them. Moreover, $CO_2$ can be used to produce biofuels from microalgae or carbonates, when it reacts with MgO or CaO, and can be used for EOR. Another possible application is EOR, in which $CO_2$ is injected in liquid state in reservoirs, so the oil swells reducing its viscosity allowing it to flow more easily through the interconnected pore spaces towards the production well which can result which can result in 10/30 % more oil production. During this process $CO_2$ becomes trapped in the rock and is permanently stored in pore spaces [43]. It may seem counter intuitive to adopt this choice, since obviously this does not result in a net carbon positive to the atmosphere, but the energy requirement to produce all these products is lower than that would be needed to produce without CCU. In this regard, a study has been done to assess LCA of products mentioned before realized with or without CCU [44]. A summary of obtained results is reported into the following table 2.1. To properly analyse results obtained it is important to specify

| Product | $CO_2$ produced without CCU | $CO_2$ produced with CCU |
|---|---|---|
| $MgCO_3$ | 1000/1115 [$kgCO_2/tCO_2$removed] | 524/1073 [$kgCO_2/tCO_2$removed] |
| DMC | 132 [$kgCO_2$/kg DMC] | 31 [$kgCO_2$/kg DMC] |
| EOR | 1100 [$kgCO_2/tCO_2$removed] | 575/625 [$kgCO_2/tCO_2$removed] |
| Biodiesel | 85 [$kgCO_2$/MJ] | 19/534 [$kgCO_2$/MJ] |

**Table 2.1:** Amount of $CO_2$ produced for each product with or without CCU: table from [44]

that different values for a determinate product are due to different study which considers different techniques of processing $CO_2$. In particular, interval emission for biofuels varies according to the environment in which process is realised. They are also the only product for which actually it is not convenient to produce them with CCU due to the predefined condition to make it.

## 2.4 Optimization

The set of these actions combined together, if properly implemented, commit that energy system becomes more sustainable and convenient, in other words it is optimized. An optimization problem can be defined in the following way:

Given a function $f\colon A \to \mathbb{R}$ it is requested to find an element $x_0$ such that $f(x_0) \leq f(x) \forall x \in A$ (minimization) or $f(x_0) \geq f(x) \forall x \in A$ (maximization)

In simpler terms, an optimization consists in the determination of a minimum or a maximum of a function, varying the values of its independent variable. Function $f$ to be minimised or maximised can be of a thermodynamic, an economical, a technological or an environmental nature. According to the sectors, values of independent variable vary and, since optimization often involves two or more function of different nature simultaneously (multi-objective optimization), an economical optimization and an environmental one will probably be different between them. This leads to a kind of competition between objective functions for which optimizing with respect to only one function, values which are obtained do not optimize the second function. With only two functions, it is usual to represent optimized solution with a Pareto Curve as represented in the first graph of figure 2.4. In this case, present in the publication [45], a low carbon supply chain network is designed, focusing on the trade off to decrease both $CO_2$ emission and cost. Point A represent the condition which minimises the cost, while point D is the one which minimises emission. All intermediate points are obtained varying the weights of the two functions, in particular point B, known as elbow point, represent the point at which emission and cost are more decreased at the same time, while point C is the point following which a cost increase has a negligible effect on $CO_2$ emission reduction.

Optimization methods can be divided according to the features of the objective function itself, (which can be continuous or non-continuous, linear or non linear, single-decision or multi decision), the variables (which can be real, integer or a combination of both) and constraints (linear or non linear). Optimization algorithms list is very long, in any case in engineering problems dealing with energy system optimization, continuous and integer variable are involved, so this approaches are mainly used. Linear programming is used to solve problems characterized by a linear behaviour used to simplify system. A general linear programming is described in the following way:

$$\begin{gathered}\min \mathrm{c}^{\mathrm{T}} \cdot \mathrm{x} \\ \mathrm{a_i}^{\mathrm{T}} \cdot \mathrm{x} = \mathrm{b_i} \\ \mathrm{a_j}^{\mathrm{T}} \cdot x \geq \mathrm{b_j} \\ \mathrm{x_k} \geq 0\end{gathered}$$

where $\mathrm{c}^{\mathrm{T}} \cdot \mathrm{x}$ is the function to be minimised, while following equalities and inequalities are the constraints of the system, whose union create an area which defines a feasible area, as represented in the second image of 2.4. This yellow area represent the set of all possible solution of this optimization problem. In this figure it is also possible to distinguish between linear programming and integer linear programming, one of its subset, since in this last case the solution is represented by integer values, while in the first one it is possible to choose any decimal number. Mixed integer linear programming is the union of this two previous methods, it is used when some of the variables have an integer solution while some other variables are decimal. In conclusion, the last typology is that of "Mixed integer linear programming, which is the most difficult case to optimize, due to the presence of non linear functions.

The most utilised linear programming algorithm is branch and bound algorithm. It can be applied to all previous typology if the objective function is convex. The method is based on problem partitioning and lower bound, a way to avoid solving some of the sub problems which originate from the problem partitioning, which means that if some of possible sub problems are not possible for the solution. In the first solution a real value is accepted, even if the aim is to obtain integer values. Then, starting from this solution, problem is ramified going towards solution with integer values. When the real solution is found, to determine integer one, it is necessary to add two constraints: the first is that solution found must be lower or equal to the integer value closer and lower than the value obtained, while the second problem want to identify the closest integer larger than the solution. Branching problem ends with an integer solution for all design variable is found or the solution is unfeasible, in a process which continuously improve the objective function.

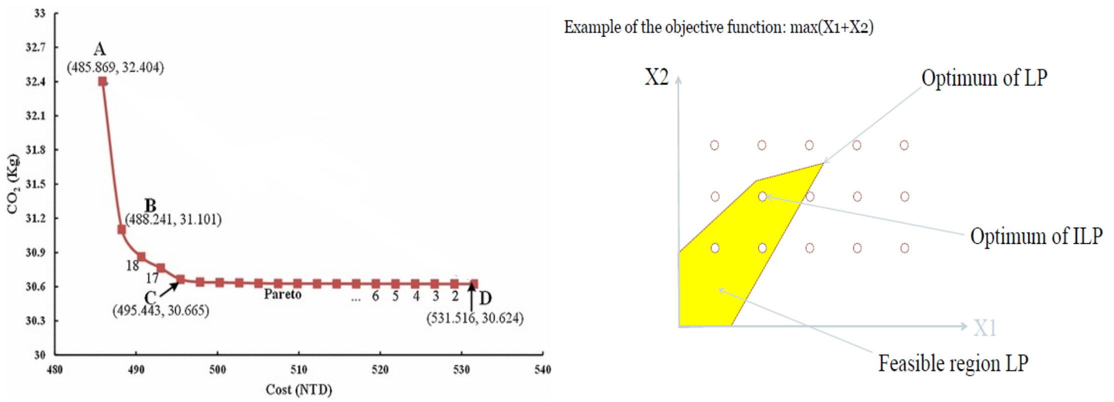


**Figure 2.4:** Pareto curve of two functions and differences between linear programming and integer linear programming: First image from [45], second image from [46]

# Chapter 3

# Case study

## 3.1 Case study description

Case study which is examined is related to an industrial company in Piedmont which plans to connect with a district heating network in project. Customer's request was to find the best solution between five alternatives configuration plants, which all have in common the usage of CHP, to exploit the advantages motivated in section 2.1. Consequently, the reasons which will convince to choose a configuration rather than another, are both of economic and environmental nature, which coincide with the search of two minimum points of two different objective functions: first one is to decrease operational cost, while second one is a reduction in $CO_2$ emission. After first two optimisation in standard condition, three different improvements will be assessed: first one is to introduce inside the optimization CB mechanism, making sure that economic gain due to recognition of CB is taken out of maintenance cost of each cogeneration machine. Second one will introduce thermal storage in the system, while third one will cover an increasing percentage of biomethane in substitution to natural gas, while taking into account that its usage is limited by technological reasons, as it is not possible today receive from the market an unlimited amount of biomethane. To begin the analysis, the most important information are those related to load profiles of final users and to machinery, in addiction to project information of the district heating network:

- Flow temperature: 90°C
- Return temperature: 65°C
- Working pressure: 6 bar
- Expected connected volumetry: 3000000 cu m.
- Expected network length: 30 km

## 3.2 District heating

District heating technology has its roots since the late 1870's and is seen as one of the most convenient solutions to decrease environmental impact of building sector in densely populated urban areas. It is defined as a system in which heat is generated in a centralized location and it is distributed with a system of insulating pipes to end users, properly designed to maintain the water temperature when in transit, and so avoiding heat losses, to improve final energy efficiency. Through this network water arrives in connected building to provide room/floor heating or domestic hot water. Whether it is used directly or pass through a heat exchanger, supply water decreases its temperature, and it returns to district heating plant, endlessly circulating in this network. Some district heating also use steam as distribution energy vector for industrial processes, but its disadvantage is that it has higher heat losses than water, with losses ranging from 10% to 30% or more in the most inefficient systems[47]. Heat generation is frequently obtained using cogeneration, but it can be produced also with renewable energy sources and from waste heat from nuclear power plants or industry. Compared to individual heating system, such as boilers and hot water boilers, district heating plants are better at reducing emissions since they have more efficient pollution control equipment, besides the fact that heat can be produced with renewable energy sources, ensuring better external air quality. But advantages are also connected to the safety, as there is less risk of fire, explosion, or CO build-up. Advantages for consumers are also of an economic nature, as heat is already delivered to them in a usable form, so it is not necessary to install boilers and there are no maintenance or operational costs related to their usage. Moreover, district heating usage plays a role also in the increase of energetic rating of a building, consequently increasing its economic value. In conclusion, it is important to underline that district heating benefits from economy of scale, in particular as regards distribution, as cost of pipes is directly proportional to pipe size, while transmission capacity increases with the square of the pipe size [48] and even specific investment cost decreases with size. As mentioned above, one of the main strengths of district heating systems is their capacity to integrate several energy sources, such as waste heat and renewables, but their usage is still limited as they made up 8%, equal to 16 EJ of heat, of energy inputs for district heat production in 2020 of globally [47]. The situation is better at European level, but in the Net Zero Emissions by 2050 Scenario, produced by IEA and compared with 2020, renewable production jumps to more than 20% in 2030, nearly tripling today's level, the share of electricity produced with electric pumps also grows to around 12%, and finally while fossil fuels use decreases by more than 40%[49].

These goals will allow reaching of realisation of 5GDHC. A 5GDHC grid is based on the exchange of thermal energy between buildings with diverse needs. Its scheme is represented in figure 3.1. Main feature of this innovative technology is that heat is circulated at temperature close to the ambient one, in order to reduce at minimum heat losses, which can even reach 5% of heat produced [50]. Key elements of 5GDHC are the following: heat pumps, two pipes grid and storage system. In this new network typology, heat is not delivered to a heat exchanger but to heat pumps, which are able to generate the required temperature, while for DHW is necessary a booster heat pump. This implies that grid transports thermal energy, but it does not need to deliver it at the required temperature, since it is the task of heat pump to modify thermal level. Another fundamental element is the two pipes grid. In previous technology supply and return line are well defined, while in this case best definition is of "warm" pipe and cold pipe. Energy stations which need heat, will take water from the warm pipe, extract heat and return it to the cold pipe, while for cooling it will occur the opposite. Temperature in pipes is not fixed, but it can vary within a certain range, in both cases from 10˚C to 25℃. Final step to realize a 5GDHC concerns the sizing and the installation of a storage system, which can be centralized or decentralized, in which surplus heat and cold can be stored and kept for a later time when it can be used by final users. The largest 5GDHC is located in Mijnwater in Heerlen, the Netherlands, where more than 350 homes and nine large office buildings, are currently connected [51].

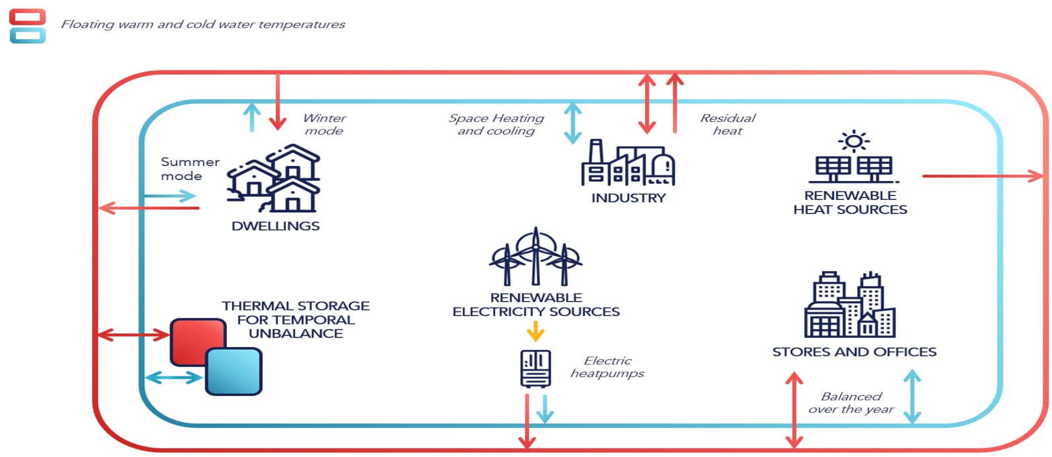


**Figure 3.1:** Scheme of 5GDHC: image from [50]

With respect to Italian situation and considering only residential sector, district heating covers 2% of heating and DHW demand, equal to 11.9 TWh, and energy mix with which is realized is largely composed by natural gas (63%), followed by renewable energy and waste heat sources (25%) and other fossil fuels [52]. In parallel with district heating and in lights of climate change effects, district cooling begins to catch on.

## 3.3 Load profile

The company has to cover two different loads, electrical load and thermal load. To cope with this request, electricity is produced with cogenerative engines, and a photovoltaic system located on the company premises, while thermal energy is produced by the same cogenerative engines and integration boilers, which come to the aid of them when they cannot satisfy thermal energy demand on their own. When these energy vectors are over-produced, electricity is sold to the grid, while thermal energy is stored or dissipated. In conclusion, likewise electricity is sold to the grid when production exceeds demand, it is purchased from the grid itself in the opposite situation.

To determine electricity and hot water load, EGEA has provided load-profile of a district heating network with similar design features, reported in figure 3.2 and normalized with respect to the maximum value of the load profile, hour by hour. Looking at figure 3.2, it is easy to distinguish a typical hot water load profile in climatic zone E, where heating season last from 15$^{th}$ October to 15$^{th}$ April, while in the remaining part of the year district heating is mainly used to provide domestic hot water. Following a process of visual and numerical comparison, a reference week for each month has been chosen to be used in the simulation, in addition a second week in April and October to consider switching on and off of district heating, and a second week in August to take into account planned shutdown are added, for a total of 15 weeks. The decision of choosing reference weeks can seem approximate but, if properly done, it can bring to a good estimate of annual demand after the multiplication of the sum of weekly values for a coefficient which considers the number of day in each month (in this case the difference between real and calculated is 0.1% lower than). Numerical values has been reported in a csv file in which are also contained information about its date, specifying the year, the month of the year, the i-th day of year, the reference day and hour of the week. A similar process has been done also for profiles related to renewable energy sources, concerning for example electricity production from PV panels, and electricity price profile sold and purchased, while that of gas is not provided, as its price is kept constant for the whole simulation, since it is not affected by hourly variations.

### 3.3.1 Electricity and gas price

It is necessary to distinguish two different prices related to electricity, that of electricity sold to the grid and that of electricity purchased from the grid. First one is determined from PUN of the reference year increased by 2.3% to take into account grid losses, while purchase price, in addition to considering previous contribution, is composed also by dispatching cost, charges due to transportation and measures, which varies in function of voltage connection and the amount of energy consumed,

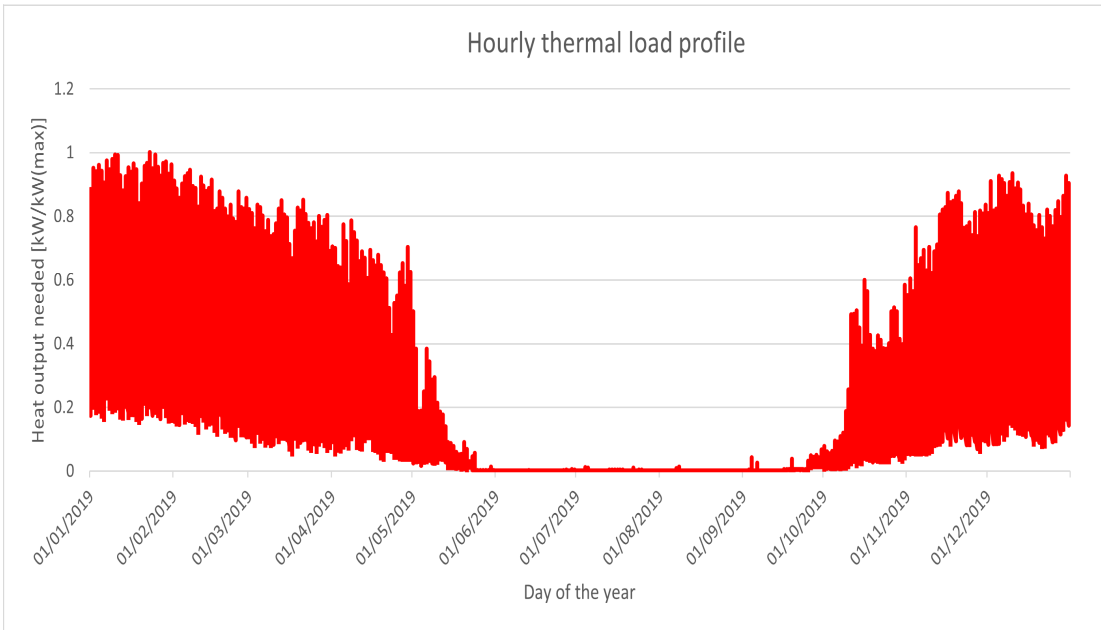


**Figure 3.2:** 2019 thermal load hour per hour

which classify an industry as energy-consuming or not, excise duties and prices increase due to GO. As far as concerns gas price, knowing the amount of natural gas consumed, price of 0.2511 €/smc is imposed. This price is increased taking account excise duties on not tax-free natural gas,$CO_2$ quotes and GO.

| Energy vector | Raw material price | Selling price | Selling price with GO |
|---|---|---|---|
| Electricity | 1.023*PUN | RMP+70.66€/MWh | SP+1€/MWh |
| Natural gas | 0.2511 €/smc | 0.3860 €/smc | 0.4360 €/smc |

**Table 3.1:** Cost of purchased electricity and natural gas

### 3.3.2 Garanzie d'origine

Growing interest on the part of companies to consume electricity produced with renewable electricity brought to the need of a guaranteed system which certifies the electricity origin. In this regard, GO are implemented in Italy with ARERA. GO refers to an electronic certification which attests the renewable origin of energy sources used, a GO is released for each MWh fed into the grid from such system. They are used by operators to prove the truthfulness of the electricity energy mix they provide, insofar as each company by 31$^{th}$ March of following year in which electricity is sold with the guarantee of being produced with renewable energy sources, is kept purchasing an amount of GO equal to the electricity sold as renewable. GO can be bargained through a special platform prepared by GME through periodic session at least every three months. GO must indicate:

- Energy sources used and data of start and end of its production.
- Name, location, typology, and capacity of reference power plant.
- If plant has benefited from investment support
- Data of commissioning
- Realising data

GO is characterized by a variable price depending on the energy sources used, but as represented in figure 3.3, its price has been around 1€/MWh, while GO of natural gas consist in biomethane purchase and are equal to 0,05 €/smc. When simulation is executed, after adding GO, it is expected to have compared with a rise of raw material cost, to a decrease of$CO_2$ emissions.

### 3.3.3 $CO_2$ quotes

$CO_2$ quotes consist of authorisation to emit an equivalent ton of $CO_2$ and they can be purchased on the ETS market, which had been spoken of in chapter section 2.3. Looking at European ETS market, to this day, there are more than 31000 companies involved [53] and they are allowed to buy $CO_2$ quotes in three different ways: buying from companies which have a surplus of them, from a stockbroker or from appropriate stock exchange. Number of $CO_2$ has an upper limit to maintain high prices to induce companies to produce less, but after year of economic crisis, in which several companies have reduced their production, $CO_2$ quotes plunged to a low of 3€/ton [54]. To face this situation, EU has introduced a series of amendments to the norm of the system with [54]. to reduce more decisively $CO_2$ emission during phase 4 of ETS. Key points of this are the following:

1. Linear increase of reduction factor at 2.2% against a previous rate of 1.74%, to emphasize rarity-effect, for which $CO_2$ quote price is sustained even during crisis periods.
2. Revision of assignment modes of free $CO_2$ quotes for sector which are deemed to be exposed to a significant risk of carbon leakage, cutting by a third the number of sector which are entitled to access to 100% of free $CO_2$ quotes to keep economic competitiveness, excluding for example extraction of iron and chemical industry, and progressively reduce free $CO_2$ up to 0 for other less exposed sectors.

3. Strengthening of market stability reserve, a rule-based mechanism allows the supply of allowances to respond to changes in demand [54], maintaining the balance in the EU ETS carbon market, in details number of set aside $CO_2$ quotes will duplicate, reaching 42% of $CO_2$ quotes in circulation.

4. Grant funding from EU to support industry in the transition towards a less-polluting economy.

| Tipologia certificato | | Quantità assegnate | Prezzo di assegnazione (€/GO) | | |
|---|---|---|---|---|---|
| | | | Min | Max | Media ponderata |
| Altro | Altri Mesi | 31.000 | 0,83 | 0,86 | 0,85 |
| Eolico | Altri Mesi | 98.000 | 1,26 | 1,27 | 1,27 |
| Idroelettrico | Altri Mesi | 321.764 | 0,80 | 0,82 | 0,81 |
| Solare | Altri Mesi | 339.414 | 1,07 | 1,15 | 1,11 |


**Figure 3.3:** Cost of GO and $CO_2$ quotes: first chart from [55], while second one from [56]

## 3.4 Components

Each component in the plant configuration must be defined with a set of parameters:

- Cogenerative engines/boilers: it is necessary to specify the heating value of the fuel burnt to produce different energy vectors, the minimum number of hours for which a machine must be activated or stowed, different power level of each energy vector according to the load factor and hourly emission. As regards power level, values are taken from datasheet machinery and in case a specific load factor is not present, resulting values are obtained through interpolation. Electric and thermal power value are in turn used to determine hourly emission which is evaluated in kg/h, starting from the emission factor of each machinery. It is also necessary to evaluate for cogenerative engines maintenance cost connected with their use and expressed in €/kWh and a coefficient to consider the volume of tax-free natural gas in cogenerative planning equal to 0.22 which means that 22% of total generated electricity is produced with tax-free gas. Maintenance cost is lower than cost associated to fuel or electricity, but it is important when CB calculation will be implemented in the software.

- Electric heater/Heat pump: in this is case it is sufficient to determine rated power and its efficiency (expressed as COP for heat pumps). In addition, pumps are also characterized by a minimum number of hours for which a machine must be activated or stowed and the minimum value of power, set as the half of rated power.
- Thermal storage: for this component it is sufficient to indicate its capacity in kWh and its efficiency.
- Photovoltaic or solar panels: there are two ways to indicate them. As previously mentioned, it is sufficient to build a profile in which for each hour it is possible to read the power produced, while the second possibility consists in creating a new component, indicating its efficiency, its covered area, its peak power and its PR.

As mentioned above, five different configurations will be simulated, both with an economic optimization and an environmental optimization. Configuration are composed as follows:

- Configuration 1: Two co-generating units, first one with rated power of 10.9 $MW_{el}$, while second one with rated power of 12.4 $MW_{el}$, and integration boilers for hot water production.
- Configuration 2: Two co-generating units, first one with rated power of 10.9 $MW_{e}$, while second one with rated power of 12.4 $MW_{el}$, an electric boiler with rate power of 30 $MW_{el}$ and integration boilers.
- Configuration 3: A co-generating unit, with rated power of 16.5 $MW_{el}$ and integration boilers
- Configuration 4: A co-generating unit, with rated power of 16.5 $MW_{el}$, a heat pump with rated power of 15MW $_{th}$, an electric heater of 10 $MW_{el}$ and integration boilers.
- Configuration 5: Five co-generating units with rated power equal to 3.36 $MW_{el}$ and integration boilers.

In all these scenarios, it is always considered the same amount of electricity from PV panels. When simulation is performed, several files are generated: in fact, for each week, it is achieved an .xml file which contains the values of the two objective functions, values of all kind of energy considered in the system, which can be produced, sold, purchased, stored and dissipated and all other values which contribute to system description, and a .csv file for each energy vector. in which, in a tabular form, it is reported its energy balance [57]. This data visualization allows to analyse all weeks in detail, but it does not provide a global visualization of energy annual values, since the simulation is often about only one week in a month. To tackle this problem, a Python code, starting from a pre-existing one, has been realized.

# Chapter 4

# Simulation and results post processing

## 4.1 XEMS13

Energy systems, in which an energy vector can be produced with more technologies, are spreading, so it is possible to choose, on the basis of external climate condition or prices associated to energy vectors, which is the best technology to use to maximise or minimise a predetermined objective function. Furthermore, the presence of more technologies requires a management system which manages to start power plant in determined conditions, looking for maximise energy from renewable source or to produce. A tool which is useful to achieve this goal is XEMS13, an open tool developed in the Energy Department of Politecnico di Torino in collaboration with the company Sampol Ingenieria y Obras (Spain). Its feature is precisely to optimize energy generation in hybrid power plant which has to cover an electric or thermal load, scheduling dispatchable and non-dispatchable energy generation to create operation and management strategies to fulfil customer need in the most efficiency way [58].

In XEMS13, after having defined load profiles, prices and components features, it is necessary to define several inputs to prepare a netlist, a .txt document which resumes the following information:

- List of components in the assessed configuration: defines which .xml file is necessary to upload to include the list of components.
- Length and conversion factor of the simulation: it contains the number of intervals in which is divided a single simulation and its time basis (168 hours which represent the number of hours in a week) and a factor to convert €/MWh into €/kWh.

- Optimization typology: specifies according to which criteria the optimization is performed. ENVI is used for an environmental optimization, while ECOENVI is requested for an economical optimization. In an environmental optimization the objective function aims to reduce $CO_2$ emissions released by cogenerative units and integration boilers, while in the economic one the goal is to reduce the sum of operational cost, which includes cost of the fuel and maintenance cost. In any case, both optimization technique also indicates the value of the other non-optimized parameter depending on the different optimization, so it is possible to assess the cost of the environmental optimization and the amount of $CO_2$ released in the economic one.

- Nominal system voltage: it indicates the system voltage of the grid, to which is connected to the plant.

- Input list: it displays all inputs of the plant, it can be divided in dispatchable and non-dispatchable electric input, dispatchable and non-dispatchable thermal input, and dispatchable steam input, as appropriate. For each input, a list of machines used to produce that input and in case that more than one machinery is present for a given input, it is useful to specify intervention priorities which mean that a machine is activated before than the others.

- Output list: it flags up loads which must be covered related to different energy vectors.

- Price and of energy vectors: it signals the price of sold and purchased electricity, the cost of tax-deferred and non tax-deferred natural gas and its heating value.

- Solver definition: it states which solver performs the optimization; in this case all optimizations are made with GUROBI.

Equations which describe this problem are common balance equation, assuming for convention that outgoing flux of the system are characterized by a positive sign, while incoming flux into the system with a negative sign. Hence, in electrical balance electricity produced from cogenerative engines, renewable energy sources and electricity purchased have positive sign, while electricity sold, electricity consumed, and electricity requested from final users have a negative sign. In the same way, as far as concern hot water balance, thermal energy produced from cogeneration and boiler have a positive sign, while thermal energy dissipated, and thermal energy requested by final users have negative one. Once the problem is linearized and equations, boundaries, and constraints are set, an '.mps' file is created and delivered to GUROBI, a MILP solver. Results are expressed into two file typologies: first of all, an .xml file is generated, in which are contained values of two objective function, hourly energies produced by each component and all other values which helps system description. Later, a .csv file for each energy vector is provided, in which energy values which defines energy balance are provided hour by hour. XEMS 13 has been developed on MATLAB, but an executable has been prepared in order to execute it also with computer without a MATLAB, using for example Spyder. In figure 4.1, it is represented the flow chart of the process.

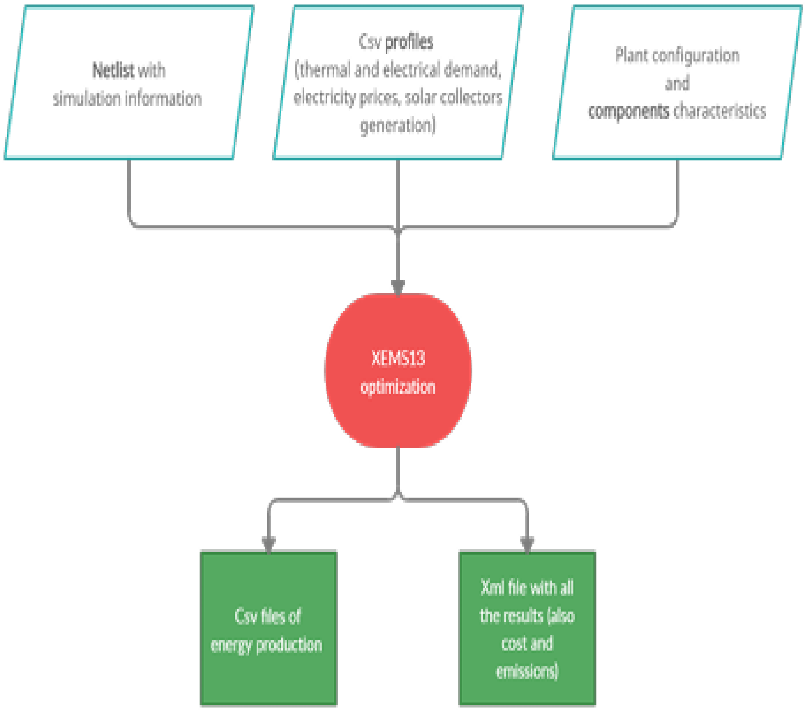


**Figure 4.1:** Input and output of the simulation: image from [57]

As results are represented in .xml format to have maximum flexibility, their visualization is not easy, so, using Spyder, a code is created in order to gather numerical values present in .xml files, to order them according to the reference machinery and reference week, and insert them in a .csv file, both at monthly and at yearly level, supposing reference week profile faithfully represent monthly one. Relation between monthly and weekly values is assumed to be linear and proportionality coefficient is equal to the ratio between number of days in that precise month and the number of days in a week, namely 7. To the required needs, a .csv file is created for all machinery which characterize a power plant production, which are:

- CHPS: a cogenerative engine which produces electricity, heating, and steam.

- CHPLE: a cogenerative engine which produces electricity, heating and low-enthalpy heating, whose heat degree can be enhanced by an HPLE.
- CHP: a cogenerative engine which produces both electricity and heating.
- HPLE: a heat pump which increases thermal level of a low-enthalpy thermal energy
- HP: a heat pump which transfers thermal energy of a thermal energy
- SBoiler: a boiler typology which is in charge of producing steam.
- Boiler: a boiler typology which is in charge of producing heating.
- Stt: a storage in which heat is stored when its production exceeds needs and released when the latter are higher than production.
- EH: a boiler typology which produces heating with electricity.
- PV: a photovoltaic system which produces electricity through solar radiation.
- SH: a solar panels system which produces thermal energy through solar radiation.
- SHLE: a solar panels system which produces low thermal energy through solar radiation.
- HEX: a device which transfers thermal energy between two fluids at different temperatures.

Then these results are collected in other data frames, broken down by energy vector involved and this will bring into five other .csv files in which are collected results inherent in electricity, heating and low-enthalpy heating, steam, fuel, a recapitulation file, and a last file with information about CB. First step of this code is to import packages with their abbreviations which will be recalled and after this, a window is opened, where is possible to select the .txt file used to count the occurrences of each machinery. Chosen file name is also used to name .csv files in which data will be rearranged. According to number of machines, an appropriate number of columns for each component, with energy vectors related to it, is created. For example, regarding boilers, there are three columns for each boiler which represent the amount of heat produced, the amount of fuel consumed, and the amount of electricity spent by auxiliaries, and then these indexes are attached to .csv files. At this point, the program is ready to read all .xml files in which are contained energy flux involved in plant configuration, whose number vary according to the number of identified reference weeks in the simulation. All 15 weeks has 168 hourly values for each energy flux, so to obtain monthly value it will be necessary to multiply for a correction factor which considers number of days for each month. In conclusion, all these values are copied in appropriate .csv files, both in those related to machinery and those related to energy vectors, and several chart such stacked bar plot or scatter plot, with useful quantities for the analysis are created.

## 4.2 Result analysis

After having run all simulations, results are ready to be analysed on related graphics. Charts represented below are a scatter plot with on x-axis operational cost and on y-axis $CO_2$ emissions, while stacked bar plot is the chart typology in which ratios between energy produced with or without cogeneration and correlated quantities are depicted. Cost and emissions are normalized with respect to maximum values of each parameter, as well as other parameters are normalized with the respect to the sum of all quantities involved. From this moment on, according to a chromatic convention, energy produced with cogeneration is associated with orange while energy not produced with cogeneration is associated with light blue. As far as concern electricity, it will be used different shades of green, for thermal energy reference colour will be red and finally fuel will be associated to purple. Acronyms with which simulation were built are the following

- 1A: Economic optimization of Configuration 1.
- 1B: Environmental optimization of Configuration 1.
- 2A: Economic optimization of Configuration 2.
- 2B: Environmental optimization of Configuration 2.
- 3A: Economic optimization of Configuration 3.
- 3B: Environmental optimization of Configuration 3.
- 4A: Economic optimization of Configuration 4.
- 4B: Environmental optimization of Configuration 4.
- 5A: Economic optimization of Configuration 5.
- 5B: Environmental optimization of Configuration 5.

Starting from scatter plot of figure 4.2, it is possible to find three different areas: economical optimization solutions are located at the centre of the graph, environmental optimization without electric heater or heat pumps are a little bit

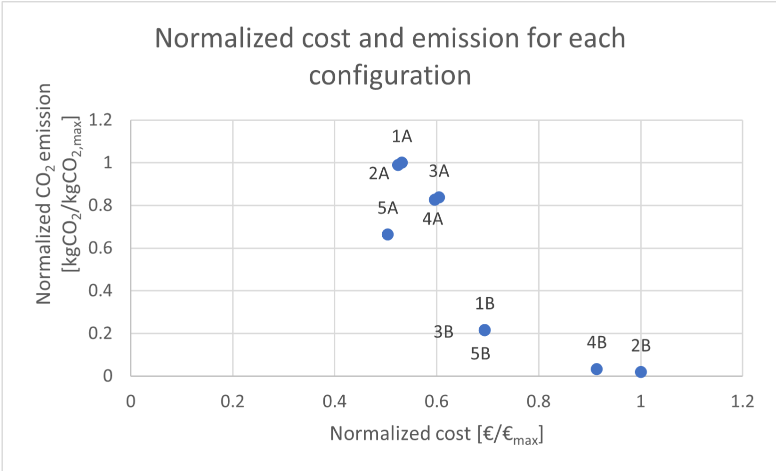


**Figure 4.2:** Cost and $CO_2$emissions released for each plant configuration

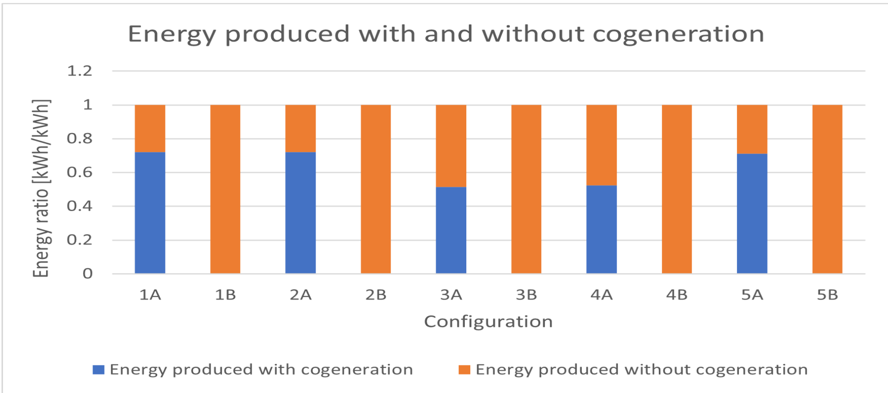


**Figure 4.3:** Cogeneration use for each plant configuration

down right, while remaining environmental optimization are in the right end corner. As regards economic aspect, the best solution is that of 5$^{th}$ configuration, that besides having the lowest between all economic optimization, is even that which have a lower environmental impact. As far as concern, environmental optimization, 1$^{th}$,3$^{th}$ and 5$^{th}$ configuration has the same value of cost and of $CO_2$ emission released. What may seem like a mistake, is actually due to the fact that while in an economic optimization has to choose between electricity and natural gas depending on their price, in this case the choice is between the emission factor of each component, and since there is the possibility to purchase electricity from the grid with GO, namely with an emission factor equal to 0, the solver decide to purchase all electricity from it. Since then, all cost profiles and thermal load are the same for each configuration and electricity demand has been already covered,

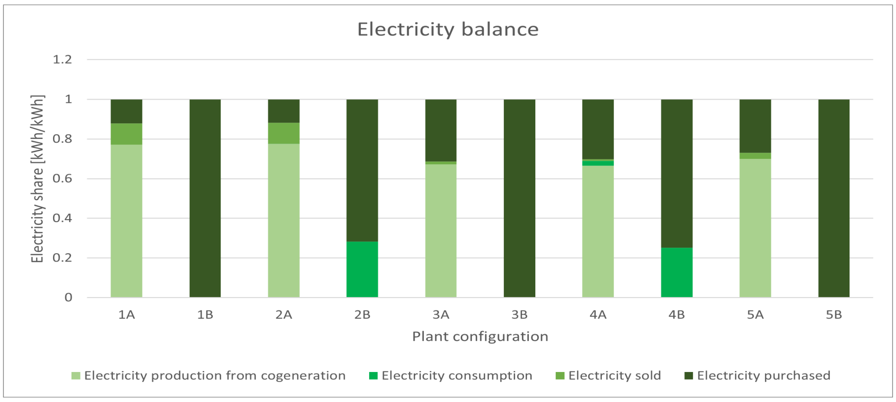


**Figure 4.4:** Different electricity use for each plant configuration

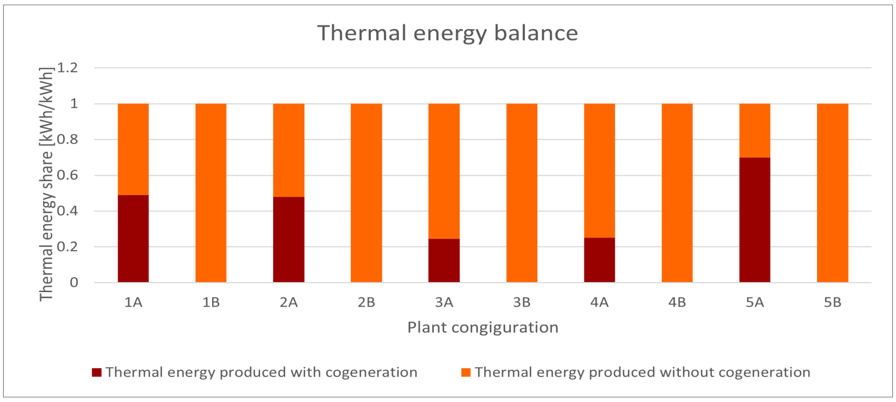


**Figure 4.5:** Thermal energy produced and without cogeneration for each plant configuration

Gurobi does not taken on cogenerative that would produce more electricity, but it chooses to operate integration boilers. The possibility to produce thermal energy with electricity implies that in the two remaining configurations, $CO_2$ are further reduced, in the face of a cost increase since electricity price is higher than natural gas one. These optimization criteria are reflected also in other quantities. As represented in figure 4.3, cogeneration is never used in environmental optimization, and separate production of energy vectors is resorted, purchasing electricity from grid and thermal energy with integration boilers or, if any, with electric heaters and heat pumps. These two last machines, as represented in figure 4.4, only work in environmental optimization due to the high-cost difference, even at industrial level, between electricity and natural gas price. Remaining on 4.4,it is possible to check that combined production is preferred over separate production in an economical optimization with respect to an environmental, since it is possible to

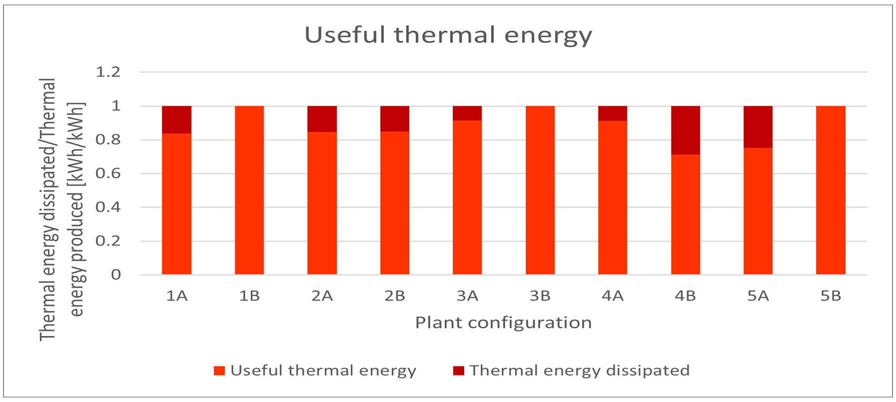


**Figure 4.6:** Useful and dissipated thermal energy for each plant configuration

sell electricity to the grid, hence cogenerative engines are often fully-loaded, also because of a low price of natural gas. The last aspect to be stressed is related to thermal dissipation: the expectation is to find higher values of thermal dissipation in economical dissipation than the environmental one, and this occurs in $1^{th}$,$3^{th}$ and $5^{th}$ configuration, but not for the remaining configuration. This can be explained by the fact that, in the eyes of solver, this thermal energy dissipated does not bring with it an increase in $CO_2$ released since electricity is provided with an emission factor equal to 0.

These and other chart are showed to the industry to help them in the choice of the best configuration. $5^{th}$ configuration was the best solution on both ends and, from this moment on, this will be the only configuration analysed.

## 4.3 Influence of GO and $CO_2$ quotes on final results

Once determined which is the best configuration, it is interesting to determine how much GO and $CO_2$ quotes impact on final solution in terms of cost and emission. In this regard, six different configurations of chosen structure are created:

- A:Economic optimization assuming no GO for electricity and no $CO_2$ quotes natural gas
- B:Environmental optimization assuming no GO for electricity and no $CO_2$ quotes for natural gas
- C:Economic optimization assuming GO for electricity, but no $CO_2$ quotes for natural gas

- D:Environmental optimization assuming GO for electricity, but no$CO_2$ quotes for natural gas
- E:Economic optimization assuming GO for electricity and $CO_2$ quotes for natural gas
- F:Environmental optimization assuming GO for electricity and $CO_2$ quotes for natural gas

Even in this case, cost and emissions are normalized with respect to maximum values of each parameter, while other parameters are normalized with the respect to the sum of all quantities involved. Looking at the chart in figure 4.9, three different areas are visible: that of economic optimization in the top centre of the chart without $CO_2$ quotes on natural gas, that of environmental optimization with GO on electricity and that of economic optimization with $CO_2$ quotes on natural gas located below and the right, and a third area located halfway of the above with the remaining ones. It is evident that, GO on electricity affects cogeneration usage, annulling cogeneration contribution on energy production, while $CO_2$ quotes mainly has an effect of increasing natural gas price, with an null effect on environmental optimization. In fact, possible $CO_2$ reduction are explained by the fact that solver prefers to purchase a share of electricity from the grid instead of producing it with cogenerative engines, underline once again that economic and environmental goals are difficult to match.

Starting from ratio between energy from cogeneration and energy not from cogeneration, it is immediately evident the difference between environmental optimization in which GO are considered or not. In fact, in 1B scenario, which is the only environmental optimization not having GO, the share of energy produced with cogeneration is far below than that of economical optimization, but it is different from zero.

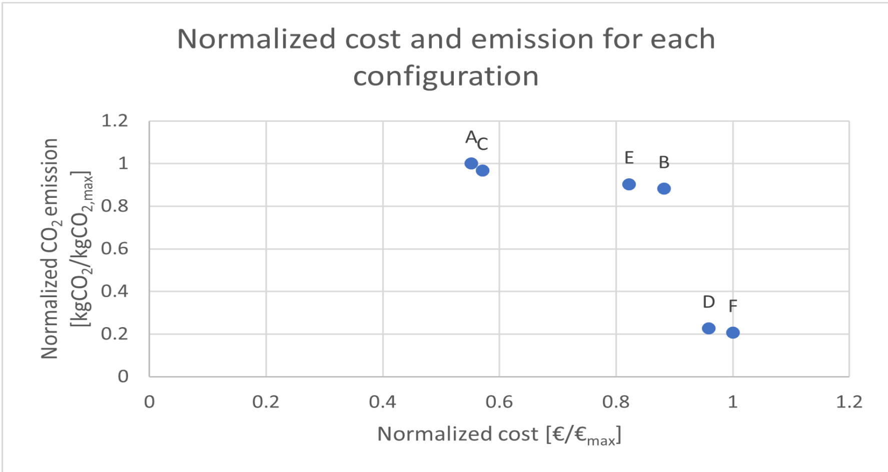


**Figure 4.7:** Pareto curve with cost and emission associated to each configuration

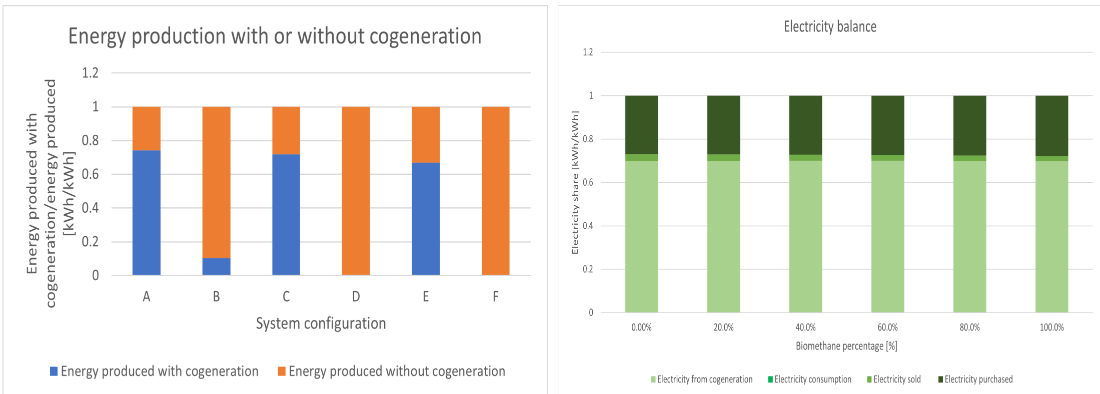


**Figure 4.8:** Pareto curve and ratio between energy produced with or without cogeneration

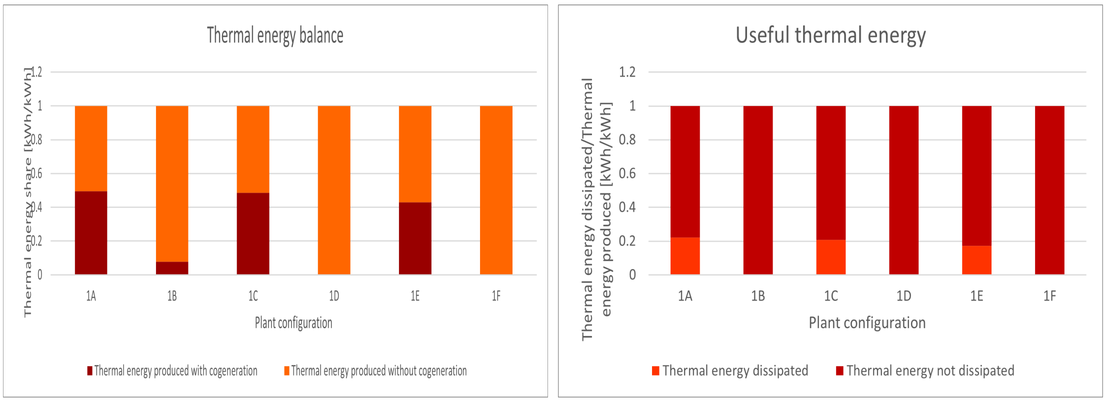


**Figure 4.9:** Pareto curve and ratio between energy produced with or without cogeneration

# Chapter 5

# White Certificates and thermal storage

The common feature of all economic scenario is the high amount of thermal energy dissipated, which in view of CB can reduce gain from them, since only useful thermal energy is considered in that mechanism. To reach this reduction goal two different paths have been followed: first one is to already implement in XEMS 13 CB and not only calculating them after the simulation, while second one is to use thermal storages, which can store thermal energy over produced.

## 5.1 White Certificates mechanism

What these two optimization typology, whether or not they consider GO and $CO_2$ quotes, have in common is that at present CB mechanism is not properly exploited both in economical optimization because only useful thermal energy is for the purpose of calculating of Obtainable CB, and all economical optimization, thermal energy dissipated plays a significant role. At the same time, in environmental optimization, cogeneration is put into the background, by hampering the access to CB, despite thermal energy dissipation are close to zero. CB, or TEE, are the means by which it is certified the implementation of the energy saving measures to which they are obliged to fulfil, according to [59], electricity and gas distribution companies with over fifty thousand customers connected. A TEE equals to an energy saving of 1 tep (41.480 GJ). For the purpose of access to CB mechanism, energy efficiency project are considered eligible when they respect these five conditions: their realization cannot precede the data in which access to CB mechanism was requested, they must generate additional energy savings with respect to previous condition, they must be realized with components that have never had access to CB mechanism, they must be correctly prepared and communicated to GSE and finally they must be classifiable between intervention typology. Project can be realised by the distribution companies themselves or by other actors such as third-party companies which does not have any kind of oblige, such as SSE. In this last case CB mechanism is processed in the following way: an SSE suggests an energy saving efficiency intervention among those which are eligible, to an user, promising him revenues from lower consumption after a determined time period. Once it has been carried out, the SSE requires the GSE to issue TEE through GME, and after this, it can put them in the stock exchange of GME, where they are purchased from distribution company. After having bought them, the distribution companies present to GSE purchased title and recover their cost with tariff contribution in bills. There are four typologies of TEE:

- Type 1: they attest primary energy savings through intervention which implies an electricity final consumption reduction.
- Type 2: they attest primary energy savings through intervention which implies a natural gas final consumption reduction, among which there are those related to CAR, which will be the typology in which we are interested in.
- Type 3: they attest primary energy savings different from natural gas and electricity in all sectors with the exception of transportation sector
- Type 4: they attest energy savings of primary energy different from natural gas and electricity in transportation sector.

## 5.2 White Certificates in XEMS13

As it has been explained in section 2.1, reference was made to PES, as fundamental parameter to access to CB. This incentive is given when cogeneration is CAR, namely its PES is higher than 10% for plants with nominal power bigger than $1MW_{el}$ and higher than 0% for small and micro cogeneration. Another important parameter is the global efficiency, given by the sum of electrical and heat efficiency, which must be higher than 0.8 if technology used is condensing turbines with steam extraction and gas turbine with combined cycle and heat recovery, for all other types of system this value is set to 0.75. The aim of this procedure is to assess CB effects inside the simulation, in order to obtain better results in term of heat dissipation and cogeneration use. The easiest way to determine their contribution is to subtract to maintenance cost of each cogeneration machine the economic gain in €/kWh related to CB, in order to obtain a new maintenance cost and compute a new simulation. In fact, maintenance cost, expressed in €/kWh, includes the expenses that a machine incurs for ordinary and extraordinary maintenance due to its use, such as the substitution of lubricating oil and spark plug cleaning, so if cogeneration is CAR and the co-generating unit is working, it must bear maintenance cost, but, at the same time, it can earn from CB mechanism. The procedure will therefore be iterative and will be performed as follows:

1. At first iteration, code executes the first optimization and with values obtained calculates white certificate gain, updating the maintenance cost.

2. This new maintenance cost will be used to execute again the optimization and with this a new value of gain thanks to CB: two different parameters are chosen to stop the iteration:, first one is called $\beta$ and it is equal to the average of ratios of each machine of heat dissipated and heat produced, while the second parameter is called RISP and it is equal to the average of RISP of each machine which is equal to:

$$RISP = \frac{E_{\text{chp}}}{\eta_{\text{E,RIF}}} + \frac{H_{\text{chp}}}{\eta_{\text{H,RIF}}} - F_{\text{chp}} \tag{5.1}$$

   equal to the difference between the amount of fuel that would be necessary to produce $\text{E}_{\text{chp}}$ and $\text{H}_{\text{chp}}$ with or without cogeneration. In this case $\eta_{\text{E,RIF}}$ is adjusted using a factor which considers connection voltage and amount of electricity self-consumed, while $\eta_{\text{E,RIF}}$ remain constant for each machine, with respect to efficiency used in PES calculation which for example depends on year construction of the plant and fuel typology.

3. Conditions to interrupt iterations are the following: after two iterations, if percentage change between $\beta_{\text{m}}$ in n and n-1 iteration is lower than 0.001, the iterative procedure is stopped. Choice goes towards an absolute difference instead of a relative since for small numbers negligible variation would have been too much influential and would have generated unnecessary iterations. Small values occur especially during winter months or in case of the presence of a storage in the system, and in this case *beta* is nearly or equal to 0, so difference between two consecutive $\beta$ can be lower than 0.01 even after two iterations. To overcome this problem, relative gap between two consecutive RISP is assessed, and if this parameter is lower than 0.01, iteration is interrupted. If, after a prefixed number of iterations, convergence is not yet achieved, the program stops, informing the user that the maximum of iterations has been reached. Difference between two consecutive RISP is generally higher than $\beta$, so in this case a relative difference is chosen.

Overall code used to include CB is composed by four different sub-codes: `Cb_Final`, `Find_in_netlist_Final`, `Modify_maint_Final`, `Restore_maint_Final` and `Result_for_CB_final`. First four files, apart from slight changes, were already present, so a brief description is given hereafter, while for `Result_for_CB_final` is intended a separate paragraph.

- `Cb_Final`: This is the first part of the code which is recalled. In this part, the first information is about the number of iterations, whose size will increase according to the complexity of each scenario. So, the first simulation starts and, after this, two .txt. files are opened. First file is called "XEMS13cfg.txt" and it contains setup about the window dialogue or the .csv delimiter, while second file called "defaultDIR.txt" contains within paths of file, such as that of profile or components which are used for the simulation. That way files are stored, and it is not necessary to recall them during following iterations, since they are always the same. After having recalled two other files, the first of two reads, on an appropriate file, information about components in the simulation, while the second returns a list of parameters used during the iterative procedure, a csv is created with headers of the simulation parameter, for each machinery. Then the loop starts. During the first iteration nothings happens, apart from the addition of useful parameters in the csv file and the update of maintenance value, while for following ones, besides the steps, the list of parameters used during the iterative procedure is modified taking into account new maintenance cost. After having carried out checks on $\beta$ and RISP, referred to above, csv files are added in the netlist and XEMS13cfg.txt is modified in order to start a new simulation and maintenance cost of each machine it is updated to the initial value.

- `Find_in_netlist_Final`: this file requires in input netlist and components path and with two functions named`Find_components_list_name` `Find_CHP_name` search the name of components file and save the rows containing information about the cogenerators.

- Modify_maint_Final: the function parses the components .xml file previously chosen of the components .xml. Subsequently, for each cogenerator inside the lists, it searches the one with the same modality and typology inside the .xml and substitutes its maintenance value.

- `Restore_maint_Final`: after iterations stop, this program once again parses the components .xml file previously chosen to restore initial value of maintenance of considered components.

It was finally added a .txt file, named "Useful Parameters", in which are indicated parameters which are used in the simulation, such as the year of construction of the plant and the fuel used by it. In this way, during the execution, the program reads the txt. file the first time, stores them and it is not necessary to insert them every time an iteration is made. It is necessary to insert a number of parameter equal to the number of components in each simulation, so for example if there are three CHP plants, in the txt. file it should be written: Year_of_construcion=2012 2012 2012.

## 5.3 Result_CB_final

This code is the core of the program, inside all parameters used to determine CB specific cost is calculated. Main function of this program is called 'result' and contains in turn other functions:

1. eta_lim_el: starting from the year of construction of the plant and the typology of used, it calculates the harmonized efficiency reference values for separate electricity production, available in Annex 1 of [60]. These values are based on low heating value and evaluated at standard ISO atmospheric conditions. For different condition, a correction is necessary.

2. eta_lim_th: starting from the year of construction of the plant and the typology of used, it calculates the harmonized efficiency reference values for separate thermal production, available in Annex 1 of [60]. These values are based on low heating value and evaluated at standard ISO atmospheric conditions. For different condition, a correction is necessary.

3. K_calculation: starting from the number of hours in which cogeneration engines are used and their nominal electric power, it is possible to calculate the average power of each CHP. Later, the harmonisation factor K is evaluated, through empirical coefficients in [61] multiplied by the average power of each order. This parameter is necessary to assess RISP and it is equal to 1 if a revamping is carried out.

Code follows steps represented in figure 5.1: after having recalled from previous files useful parameters, it all parses all .xml files given in order to divide different contributions. In this case, it is not necessary all of the prior coding, but just contributions from CHP of electricity, heat and fuel, thermal dissipation, electrical user, electricity sold to the grid. Later on, useful thermal energy for each machinery is calculated, knowing overall dissipation for each plant configuration, since, with respect to electricity, not all thermal energy produced is charged as CAR, but only that share which is actually used. In addition, if power plant produces also steam, useful energy from it should be further reduced by the contribution of the discharged condensation. Useful thermal energy calculation is developed under the following with the following procedure: let us suppose to have to have in an hypothetical hour, the conditions reported in table 5.1, where all values are in [$kW_{th}$].

Since XEMS13 does not automatically provide dissipation for each machinery, it is necessary to proceed as follows: given a hypothetical hour, first machine responsible for the dissipation are those which are put into operation later and then we proceed back. Hence in this case, comparing value of the overall dissipation and that of $P_{th,CHP5}$, their difference is lower than zero, so there is not an useful thermal

| Diss | Ut | $P_{th,CHP1}$ | $P_{th,CHP2}$ | $P_{th,CHP3}$ | $P_{th,CHP4}$ | $P_{th,CHP5}$ |
|---|---|---|---|---|---|---|
| 1475 | 13131 | 3410 | 3410 | 3410 | 3410 | 966 |

**Table 5.1:** Thermal energy production in a hypothetical hour

energy associated with it. At that point, overall thermal energy dissipated is reduced, and it is compared this updated value with of $P_{th,CHP4}$. Now the difference is higher than zero, so this means that not all the thermal energy produced is accounted for as useful thermal energy. Nevertheless, now dissipation become equal to 0, so all thermal energy produced by remaining machinery is considered useful. The new situation is updated in table 5.2

| Diss | Ut | $P_{th,CHP1}$ | $P_{th,CHP2}$ | $P_{th,CHP3}$ | $P_{th,CHP4}$ | $P_{th,CHP5}$ |
|---|---|---|---|---|---|---|
| 1475 | 13131 | 3410 | 3410 | 3410 | 2901 | 0 |

**Table 5.2:** Useful thermal energy in a hypothetical hour

At this point, electric and heat efficiency are calculated and summed up, in order to obtain global efficiency. If this sum is higher than the efficiency limit value which has been mentioned before, all energy produced is considered into CB mechanism, if not, a virtual machine is introduced. Virtual machine is a machine that, given the useful heat of the process, produces an amount of electricity that ensures that global efficiency is equal to efficiency limit. Electricity produced which is considered CAR is equal to:

$$E_{\text{CHP}} = H_{\text{CHP}} * C_{\text{eff}} \tag{5.2}$$

where $C_{\text{eff}}$ is a function of electrical and limit efficiency, which reducesCAR electricity. With this new value of electricity all other values such as fuel consumption and efficiency will be recalculated in order to obtain a global efficiency equal to limit efficiency. Subsequently, eta_lim_el and eta_lim_th are recalled to calculate their efficiency reference values. These values could be modified in certain conditions. According to the Italiano region, in which it is located the plant, electrical efficiency reference values must be corrected as a function of the external temperature, and in this case it will be increased of 0.00369. Moreover, it is also necessary a correction depending on the connection voltage of the plant and on the quantity of electricity produced which is also consumed. For the same connection voltage, you get a bigger reduction with increasing self-consumed electricity, instead, retaining ratio between self-consumed and sold electricity, electrical efficiency more reduces with decreasing connection voltage. Hot water efficiency does not require corrections, instead steam efficiency, if condensation backflow in previous calculations is not included, must be increased of 0.05. Heat efficiency is a weighted average between hot water and steam energy produced with cogeneration.

It can therefore be possible to evaluate both RISP as:

$$RISP = \frac{E_{\text{car}}}{\eta_{\text{E,RIF}}} + \frac{H_{\text{car}}}{\eta_{\text{H,RIF}}} - F_{\text{car}} \tag{5.3}$$

where $\text{E}_{\text{car}}$, $\text{H}_{\text{car}}$ and $\text{F}_{\text{car}}$ are energy amounts on CAR mode, while $eta_{\text{E,RIF}}$ and $eta_{\text{E,RIF}}$ is the average conventional efficiency of Italian electrical and thermal production park. It is important to underline that this efficiency are different to those which were previously calculated, since they equal to 0.46 for electric efficiency and equal to 0.90 in case of hot water and steam, and 0.82 in case of direct usage of exhaust gases. Electric efficiency must be corrected taking into account connection voltage. PES is defined as:

$$PES = 1 - \frac{1}{\frac{\eta_{\text{el,CHP}}}{\eta_{\text{el,s}}} + \frac{\eta_{\text{th,CHP}}}{\eta_{\text{th,s}}}} \tag{5.4}$$

where $\eta_{\text{el,CHP}}$ and $\eta_{\text{th,CHP}}$ are electrical and thermal efficiencies on CHP mode, while $\eta_{\text{el,s}}$ and $\eta_{\text{th,s}}$ are harmonized efficiency reference values for separate electricity and heat production. If PES does not respect limit value, reference machine cannot access to CB mechanism, otherwise the value of K is calculated. It is now possible to calculate the amount of CB obtained and its economic value, as:

$$CB_{\text{obt}} = \alpha \cdot K \cdot RISP \tag{5.5}$$

$$e_{\text{CB}} = CB_{\text{obt}} * CB_{\text{val}} \tag{5.6}$$

where $\alpha$ is equal to 0.0086, which corresponds to the conversion factor between kWh and tep, while $\text{CB}_{\text{val}}$ is the price for a single CB, whose trend price is reported in figure 5.2. Eventually it is calculated the specific price of CB and the new maintenance cost, given by the subtraction between old maintenance one and specific price of CB. At this point CB calculation ends, and other sub codes are recalled. Output of these codes are the same of previous XEMS13 simulations, namely an .xml file and a .csv for each energy vector, which are updated after each iteration. In addition, as CB are evaluated on each machine, another .csv for each machine is created in order to know related CB. These values obtained are related again to weekly values and not annual. As regards these last .csv files a new code is created, which takes the last line of each file, which corresponds to the last iteration, and collect them in a new csv file, where values are multiplied by a correction factor which takes into account number of days in the month of reference week. It is necessary to precise that this code is usable only for machine whose limit efficiency is 0.75 and not 0.80, due to difficulties to evaluate $\beta$ for steam turbines with extraction and condensation in design phase, which represents the missing electricity production to the advantage of thermal energy, and it is evaluated knowing the size of the turbines, steam placing and extraction condition.

## 5.4 Results of White Certificates mechanism

In this section, results between initial configuration without CB and CB implementation are compared. Scenario with CB has been implemented only with economic optimization, since from the environmental point of view, CB does not influence $CO_2$ emission, as, comparing different emission factor, those related to grid and integration boilers are lower than cogeneration one. Things are different in economical optimization. Having decreased maintenance cost of cogenerative units, this results in an increase of energy produced from cogeneration, both electricity and thermal energy, and consequently, of fuel used. Keeping fixed electricity and thermal load, this will imply a decrease of energy produced without cogeneration but at the same time, having this latter lower emission factor, there will be an increase in $CO_2$ emissions released. Overall operational cost will decrease, besides, in addition to having lower maintenance cost and keeping the same fuel cost, electricity overproduced is sold to the grid.Unexpectedly, thermal dissipation increases, in spite of the goal prefixed. Explanation of what is the following: electric efficiency of this cogenerative engine is quite high, of consequence PES is kept over the threshold value even in case of low thermal efficiency, to ensure that CB mechanism is still activated. What happens is therefore that during each iteration, the model tries to maximise thermal energy produced from cogenerative engine by operating as little as possible integration boilers, as on them CB mechanism is not considered. At that point, useful thermal energy from cogeneration will be greater with respect the previous case, that means an increase in the electricity produced. This double increase will guarantee a greater RISP and consequently, a greater gain from CB, despite PES decreases due to the reduction of heat efficiency, which considers only the useful thermal energy, not the total produced one, in contrast with electricity.

## 5.5 Storage

Another possible strategy to reduce dissipation is dealing with storage usage. Specifically, TES are used when thermal production exceeds its demand. In that case thermal energy can be dissipated with dry coolers, to which is associated an electricity consumption, or it can be stored and used in a second moment, helping to decouple demand from immediate generation, increasing renewable energy sources usage, and improving system flexibility. This system acts a sink when surplus of energy is available and as a source when surplus of energy is requested. In district heating system, there are physical reasons for which generation and demand occurs at different time mainly for physical one such as for the intermittent feature of solar energy, and it is expected that TES will provide an annual energy saving up to 7.8% in the European Union [63], since their use can prevent boiler intervention in case of peaks, also reducing the size of CHP plants, by making them work at full load for an higher number of hours. It also reduces operational cost of pumping system, it allows to increase custumers without modifying network design, saving him money shifting consumption in off-peak hours. District heating already incorporates sensible heat technologies such as TTES, but in the next years a development of PCM and thermochemical storage system is expected, which will guarantee smaller volumes and thermal losses. TES can be subdivided according to different criteria:

- Storage duration: short term storage is used to fill daily peak request, while long term storage allows storing energy from one season to another. Short term storage is in turn divided in pressurized and atmospheric TES. First kind of system is used with elevated temperature district heating, in this case it is necessary to work with pressures higher than the atmospheric one, since working with temperature up to 100°C can lead to evaporation. In this way pressured vessel is directly connected to the district heating network, so storage and pipeline operates at the same pressure level. In terms of control mechanism, this configuration is simpler than atmospheric TES, as represented in figure 5.4. In fact, in this storage typology, a valve and pump system is fundamental to ensure the correct pressure difference between the pipeline and the TES. With regard to long term TES, they are used in combination with solar panels with the aim to store heat during summers when an high solar radiation coincides with a lower demand. They are divided into TESs for direct usage in which the temperature of the storage is the same of supply line and TESs for indirect usage, which deals with temperature storage lower than the supply line, and so use an heat pump to increase the temperature.

- Physical phenomenon used for storing heat: As mentioned above there are three main phenomena in thermal storage field, and among these, sensible heat is the most widespread. In this case, the temperature increase or decrease of the medium is used to store heat and, between available material, the one which is most used is water for its low cost, its high specific heat and availability, it can be easily carried and ,as liquid, it allows a more efficient heat exchange. The negative aspect of this storage typology is the lower heat storage density, which requires a larger volume to store the same amount of energy with respect to a medium which, in addition to use sensible heat, it makes use of latent heat. To give an example Glauber's salt, whose fusion temperature of 32°C, which is well suited for low temperature district heating, has an energy density equal to 104 kWh/smc, instead increasing water of 50°C only guarantees 59 kWh/smc [65], and the advantage to deal with fusion temperature allows to work always with the same temperature. You have a lot of available materials with this feature, called PCM,which can be divided in organic, inorganic and eutectic material, but the choice is restricted because due to problems such as subcooling and segregation, that disrupt the material properties, and more generally, it does not exist the perfect PCM: organic PCM such as paraffins, are inexpensive and has a long life cycle, but they have a low conductivity. while inorganic PCM are characterized by an higher conductivity, but subcooling and segregation are strongly manifested. These two physical phenomena are related to a direct storage, which implies that, for each heat flux, it is associated an entropy flux according to the 2$^{nd}$ principle of thermodynamic and consequent heat losses. Instead, indirect thermal configuration includes the addition of a converter which has the task of separate heat and entropy flux, ceding the latter to the external environment. This occurs during charging phase, while in discharging one the exergy flux to upgrade heat at the requested temperature. This last typology involves or a chemical reversible reaction, endothermical when heat is excess and exothermical when heat is requested, or through the phenomena of absorption and adsorption.

Last criteria to subdivide TES are those concerning their spread, since it is possible to have few big or several small storages.

## 5.6 Storage in XEMS13

In section 3.4, parameters necessary to characterize a thermal storage were described. Between them, the most important one is probably the capacity, expressed in MWh. Optimal capacity of the tank could depend on several parameters, in this case it has been chosen the variation of operational cost with respect to the devoid of storage configuration. To select border value in which find the solution hourly ans daily thermal dissipation were selected, so, thermal capacity varies approximately from 0 MWh to 300 MWh, and this interval has been divided in five slices. However, as represented in figure 5.5, between 60 MWh to 300 MWh difference is null. The reason for this arises from the fact that to make sure that the thermal storage provides an effective improvement of the system is important that the reference week has been characterized both by an high request by the user and by a great level of dissipated thermal energy. So, in winter week of the year the reduced or null quantity of dissipated energy entails a small difference of produced and requested thermal energy. A different reasoning, which however brings to the same conclusion, can be done for summer weeks, when due to the reduced hot water demand dissipated energy remains unused. So, it is necessary to find the optimal size between 0 60 MWh. Applying the elbow method to the cost function, which consists in setting the optimal value of a function when following values remains nearly constant even with an increase in the independent variable, in this case the thermal storage size, optimal value is set as 30 MWh. To have an idea in terms of size, volume of a thermal storage can be determined as:

$$V = \frac{E}{\rho * c_{\mathrm{p}} * \Delta T} \tag{5.7}$$

Supposing $\rho$ equal to 990 kg/smc, $c_p$ equal to 4.186 kJ/kgK and $\Delta T$=40˚C , storage volume is equal to:

$$V = \frac{30000 * 3600}{1000 * 4.186 * 40} = 645m^3 \tag{5.8}$$

Storage usage does not only bring to an operational cost reduction. In fact, as represented in figure 5.6, the possibility to store thermal energy brings to an increase of cogeneration use, and consequently an increase in its capacity factor, and a decrease in boiler use. Even $CO_2$ emission decrease, but this occur only for values near the optimal one, because in case of large volumes, cogenerative engines works at full load to sell electricity to grid, knowing that thermal energy contemporarily produced will not be lost and it will not require additional power from boilers.Even in this case, environmental optimization is not affected since integration boilers are expected to work until reaching thermal and not later than.

This solution manages to reduce thermal dissipation, but on the environment front, nothing changes. Reminding us that in an environmental optimization all thermal energy is produced with integration boilers, from the point of view of the model, there is no difference between emitting when thermal production exceeds demand and store thermal energy in order to use it later and emitting in times of need, hence the two simulations will be the same. Then, to see differences in environmental optimization it is not enough to add new components in the system, but it is necessary to reason on the scale of fuels.

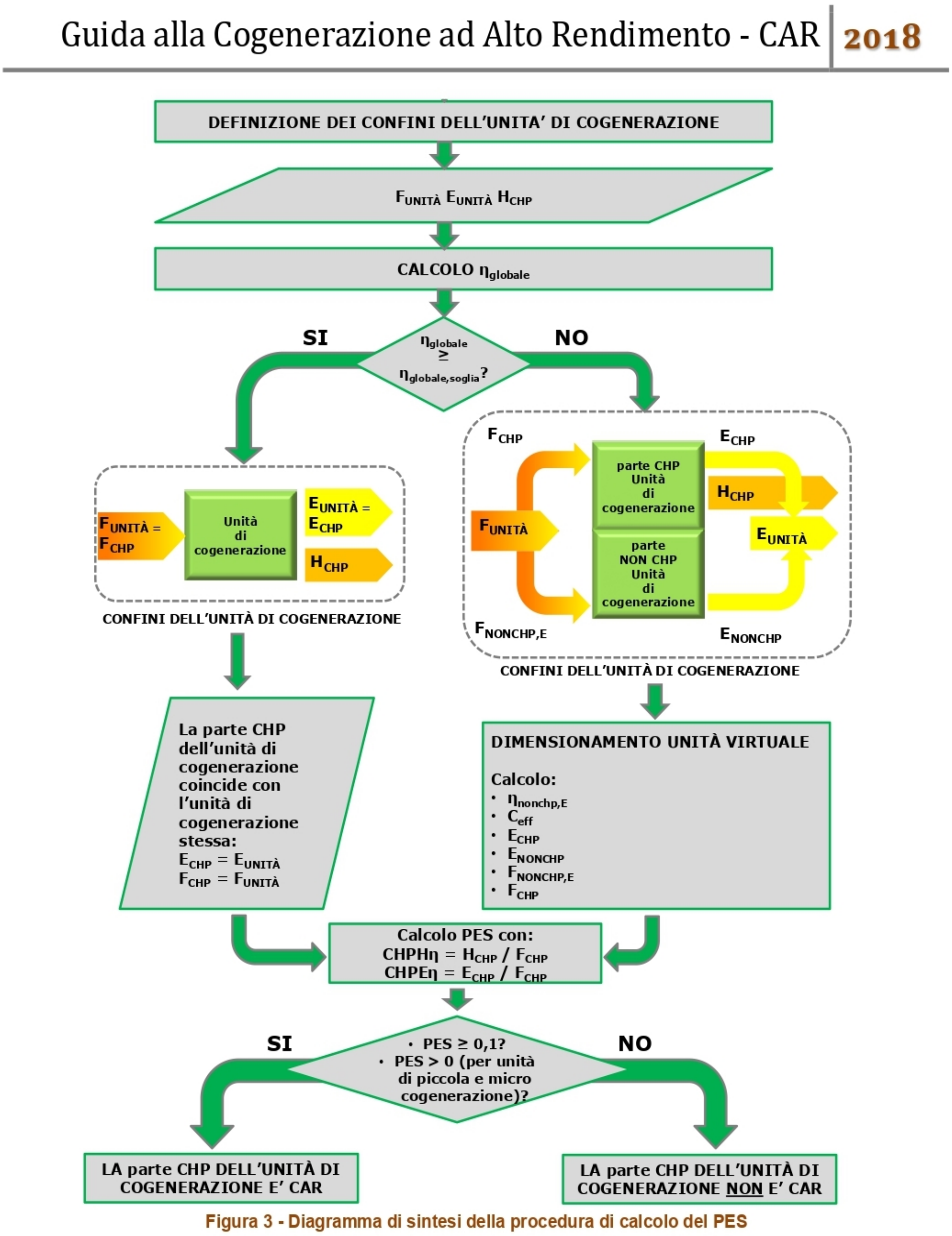


**Figure 5.1:** Scheme of CB mechanism: image from [61]

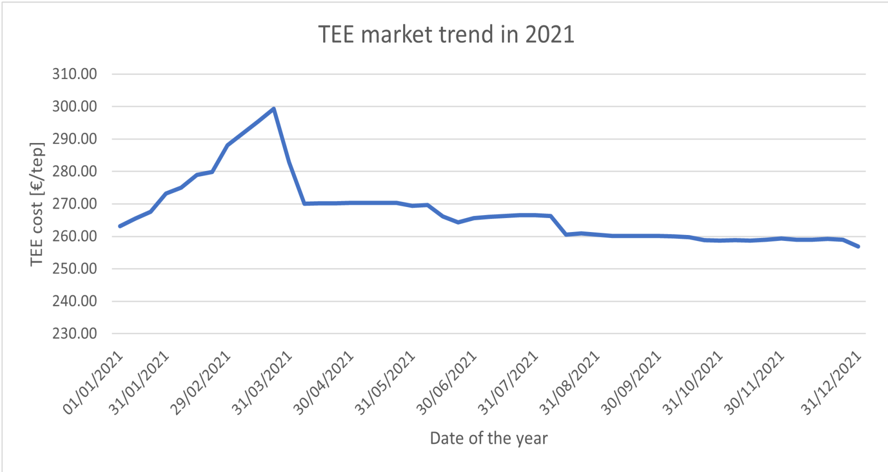


**Figure 5.2:** CB price variation in 2021: data used in this image are from [62]

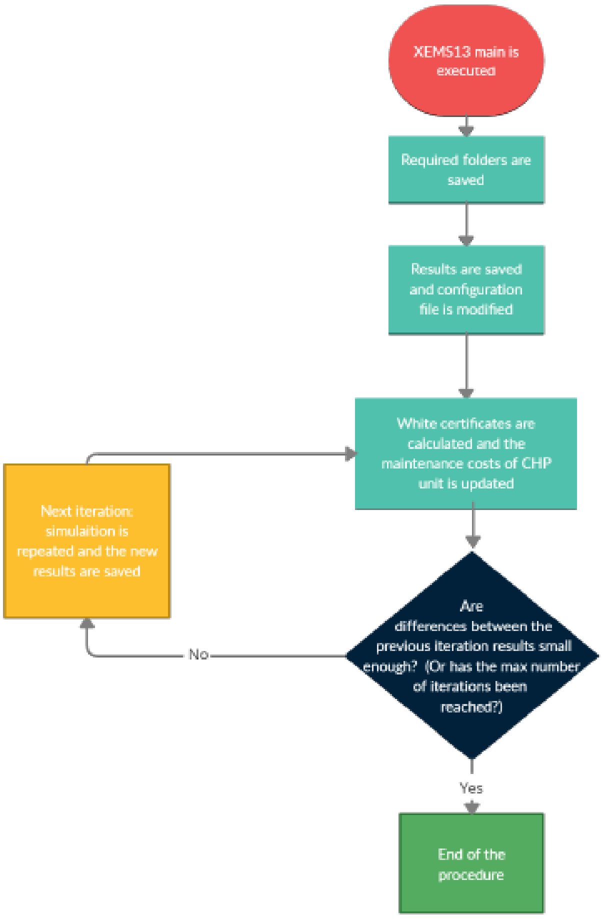


**Figure 5.3:** Iterative procedure flow diagram: image from [57]

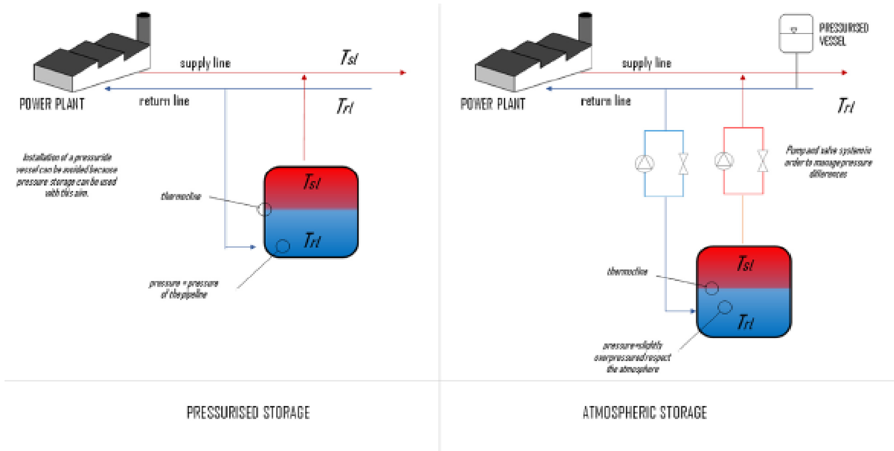


**Figure 5.4:** Scheme of connection with district heating network of pressurized thermal storage and atmospheric thermal storage: image from [64]

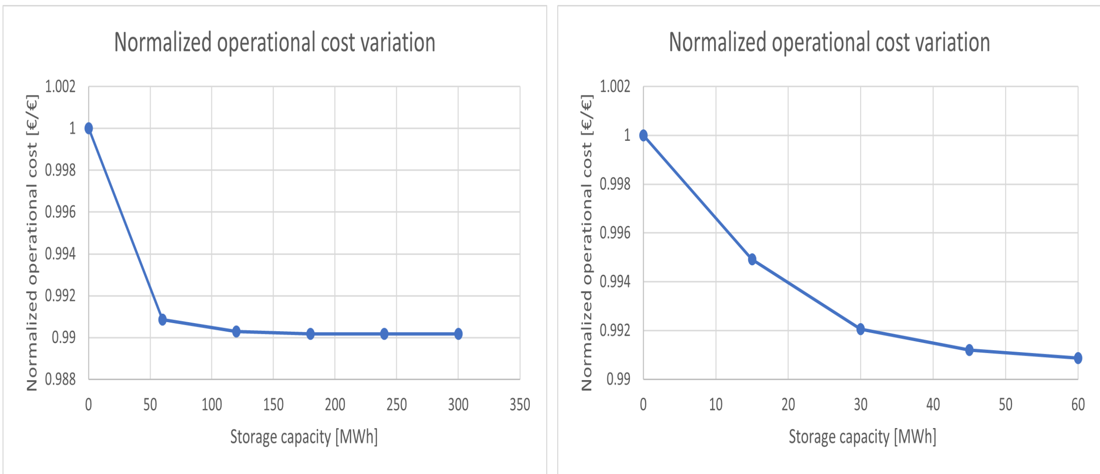


**Figure 5.5:** Operational cost variation with increasing thermal storage capacity

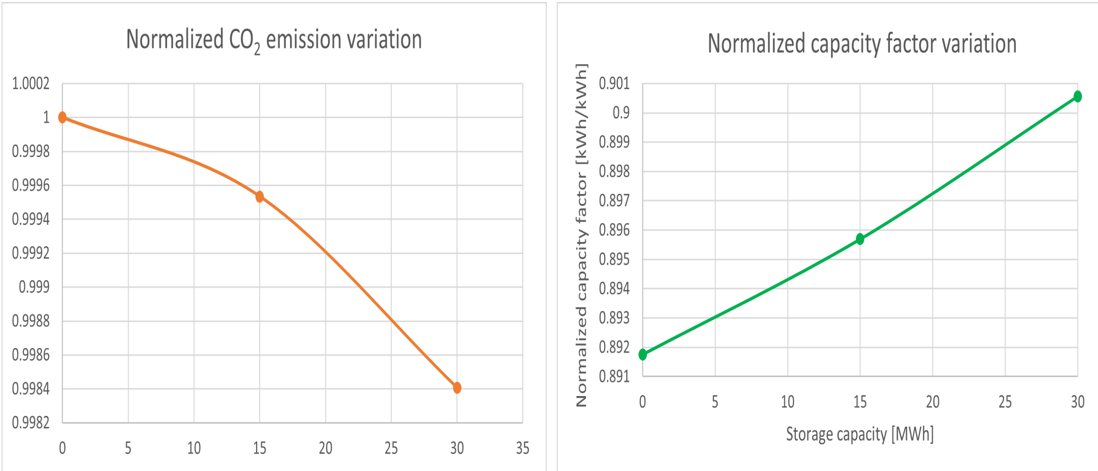


**Figure 5.6:** capacity factor and $CO_2$ emission released variation with increasing thermal storage capacity

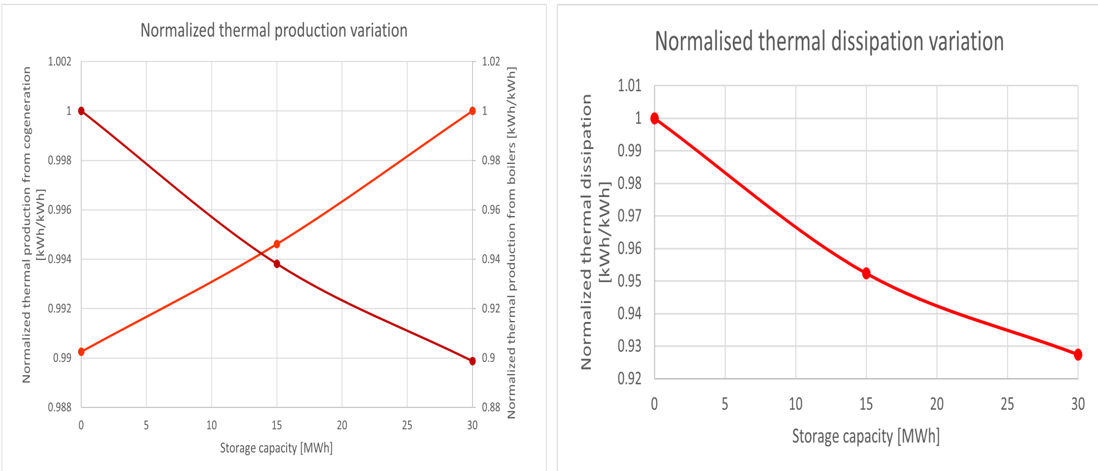


**Figure 5.7:** Production method of thermal energy and thermal energy dissiapted variation increasing thermal storage capacity

# Chapter 6

# Biomethane

Based on results of chapter 5 it is possible to say that, in an environmental optimization, CB mechanism and TES effect is null, so, it is necessary to introduce an element which provide a lower environmental impact related to cogeneration, substituting natural gas with biomethane.

## 6.1 Biomethane

As seen in section 2.2 in some sector such as industrial one, it cannot be addressed without reference to natural gas for certain uses. Hence, in this context it is necessary to reduce its environmental impact, by relying on biomethane.

Biomethane is a renewable energy source produced from agricultural biomass, such as dedicated crops or agricultural and animal waste, waste from food process chain and OFMSW. Biomethane is obtained in two separate phases: biogas production and subsequent removal of $CO_2$. Biogas is a mixture of methane, $CO_2$, and other gas produced during the process of anaerobic digestion of organic matter in an oxygen-free environment called biodigesters. Inside them organic material, diluted in water, is broken down by naturally occurring micro-organisms and after having removed contaminants and moisture biogas can be used to produce electricity or heat. Its methane content varies from 45% to 75% [66] according to its composition and the technology with which it is produced and this implies a variation in its heating value. To obtain biomethane it is necessary to remove $CO_2$ from biogas and it is accomplished with a process which is called upgrading, based on membrane technologies. In this process, after having been produced, biogas is cooled and dehumidified, it is transported in a double activated carbon filter that serves as a pre-treater, where VOC and $H_2S$ are removed, to avoid condensation which can cause corrosion.Additionally, $H_2S$ removal allows also to prevent excessive wear of mechanical parts [67]. After this, biogas is compressed up to 12-16 bar for the three-stage membrane system. The first stage is characterized by a high selectivity for $CO_2$, in order to separate biogas in a $CH_4$ rich gas and a $CO_2$ rich gas. $CH_4$ rich gas contains a 98% of $CH_4$ must undergo a purification process to be injected into the network, with propane addiction, and then THT is injected into to give the gas its characteristic smell. Around 90% of biomethane production is from upgrading biogas [66], while the remaining part is produced with thermal gasification of biomass. In this moment there are only some small plants, mostly at demonstration scale, which use this technique, which consists in which biomass is broken down at high temperature and pressure in a low-oxygen environment where it is converted in a mixture of gases called syngas. To obtain biomethane, it is necessary to remove from it corrosive components and then through the methanation reaction:

$$3CO + 3H_2 \rightarrow CH_4 + H_2O \tag{6.1}$$

it is possible to produce it. Production process of biogas and biomethane is represented in figure 6.1. Its adoption brings with it advantages in many ways: besides the environmental aspect for which fuel used does not have related $CO_2$ emissions, biomethane usage is convenient from an economic point of view, firstly because waste disposal cost decreases and secondly because biomethane is not the only product from its production process. As it is represented in figure 6.1, once biogas it is produced, inside a biodigester remains another product which is called digestate, the remaining part of organic matter, which is rich in nutrients and commonly used as an organic fertilizer. Moreover $CO_2$, after being separated from $CH_4$, it can be liquified and reused in several sectors, such as again the agricultural one, to obtain carbon fertilisation in greenhouses, generating circular economy mechanism. In alternative, $CO_2$ can be stored underground, driving biomethane a $CO_2$-negative source of energy, knowing that with $CO_2$-negative means a process which involves a permanent removal of $CO_2$ from the ecosystem. It must not neglected social aspect, as biogas, is produced especially in agricultural context and it allows to improve growth process of trees and crops and the usage of this new technologies can help to repopulate those territories.LCOE from biogas varies, according to the technology used to produce it, from 50USD/MWh to 195 USD/MWh [66], a cost considerably higher than LCOE from photovoltaic panels which is around to 30USD/MWh [68], which implies that biogas can become more economically only with a appropriate policy system, which highlights its strengths, as the greater flexibility within which they can provide energy with respect to solar panels or wind turbines.

First decree about biomethane has been issued on $5^{\text{th}}$ December 2013, and it concerned not only the electricity production in CAR plants, but also its use in transportation sector or simply injected into the network.

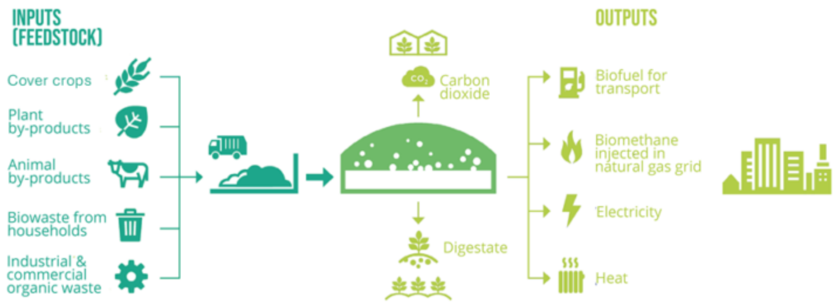


**Figure 6.1:** Schematic overview of input and outputs of the biogas and biomethane production process: image from [69]

## 6.2 Biomethane in XEMS13

Biomethane is used to make sure that cogeneration is exploited even in environmental optimization, in order to access to CB mechanism when GO are taken into account. The main goal of this section is to find which is the minimum percentage of biomethane in fuel mix, that implies a convenience even from an environmental point of view to have cogeneration instead of separate production. To do these five different scenarios will be executed which corresponds to difference percentage of biomethane in the system, passing from 20% to 100%, with a 20% increase. Once known energy associated to fuel in each scenario and knowing that biomethane heating value is equal to that of natural gas, it will be possible to assess the amount of natural gas in smc necessary and to compare it with amount available. These simulations are computed under the hypothesis that biomethane is used only for cogeneration engines, even if it is not the case in reality since natural gas and biomethane are introduced distribution network. This hypothesis is necessary, however, since if biomethane would be used also for boilers, output will be the same of previous environmental optimizations, since for the same thermal energy produced, thermal energy efficiency of industrial boiler is nearly twice as much as cogenerative units one. From this it is deduced that it will be necessary a lower amount of fuel and consequently, a lower number of $CO_2$ emissions. Different scenario will be characterised by the fact that, with increasing biomethane percentage, cost will increase by the same percentage, so adding up 1c€/smc in each simulation, likewise $CO_2$ will decrease by the same percentage. In XEMS 13 this difference is represented by defining two fuels with the same heating value, but with different name and price: first one is intended to integration boilers and its price will be kept constant at 38.60c€/smc in each simulation with increasing biomethane percentage, instead, the second fuel, used from cogeneration engines, is ideally composed of two fuels, the first of which is just natural gas and the second is biomethane, whose price must be increased considering GO, equal to 5c€/smc, which added to natural gas price, implies that natural gas price in is equal to 43.60c€/smc. This fuel mix will have a single price, which will be more influenced by biomethane price with increasing biomethane fraction in fuel mix. To be clearer, for example, scenario in which biomethane fraction x is equal to 20%, fuel price used by cogeneration boiler will be equal to:

$$c_{\text{fuel}} = c_{\text{bm}} * x + c_{\text{ng}} * (1 - x) = 43.60 * 0.2 + 38.60 * 0.8 = 39.60c€/smc \quad (6.2)$$

All other conditions will remain the same of previous simulation. It is possible to produce a first estimate of the proportion of biomethane beyond which cogeneration becomes more convenient from the environmental point of view. An equal amount of $CO_2$ released can be written as:

$$kg_{\text{CO}_2,\text{cogeneration}} = kg_{\text{CO}_2,\text{boiler}} \quad (6.3)$$

Since $CO_2$ released depends on fuel typology and considering that cogeneration involves both natural gas and biomethane, called x the ratio of biomethane, 1-x will be the ratio of natural gas. Since it is possible to define an emission factor $\mu$ for each component, given by the ratio between kg of $CO_2$ emission released, and thermal energy associated to that emission

$$x = 1 - \frac{\mu_{\text{boiler}}}{\mu_{\text{cogeneration}}} \quad (6.4)$$

Knowing from available data that $\mu_{\text{boiler}}$=0.24 $\text{kg}_{\text{CO}_2}/\text{kWh}_{\text{th}}$ and $\mu_{\text{cogeneration}}$=0.49 $\text{kg}_{\text{CO}_2}/\text{kWh}_{\text{th}}$, it is possible to provide a first estimate of x:

$$x = 1 - \frac{0.24}{0.49} = 0.52 \quad (6.5)$$

So, the expectation is that before this percentage CHP is not used and after this value, there will be an increase of this share.

## 6.3 Results

Let's start to compare the simulation starting from the difference between cost and emission in each simulation. In this case there are two different charts, one for the economic optimization and the other for the environmental one, in order to better underline by varying the amount of biomethane available. As regards economic optimization, represented in figure 6.2, we see that biomethane increase involves a cost increase, but even a $CO_2$ emission reduction. While emission reduction is greater and decreases with a trend nearly linear, due to the fact that $CO_2$ emissions vary linearly between scenarios, cost increase is more is lower, highlighting how, although biomethane price is higher, it will be cheaper than electricity purchase from the grid. Consequently, with increasing biomethane, electricity from cogeneration share, and that of electricity sold, will decrease compared with a rise of electricity purchased from the grid, but as you can see in figure 6.3, difference between scenarios are negligible. The same can be said about the thermal energy production, where the non-use of cogeneration engines is compensated by integration boilers. Another goal of improved economic optimization was that of a decrease in thermal dissipation, and though it happens, it is almost not perceptible, as represented in figure 6.4. Similar to what has been done previously, it is interested to evaluate the maximum cost for which it is more convenient to purchase electricity from the grid instead of producing it with cogenerative engine. To do it, let's suppose to compare the cost to produce 1 $\mathrm{kWh_{th}}$ with cogeneration and with integration boilers, knowing that in case of cogeneration, it's possible to sell electricity to the grid, decreasing operational cost.

$$\frac{E_{\mathrm{th,cog}}}{\eta_{\mathrm{th}}}\frac{1}{H_{\mathrm{i}}} * (x * c_{\mathrm{bm}} + (1-x) * c_{\mathrm{gn}}) - E_{\mathrm{el}} * c_{\mathrm{sold}} = \frac{E_{\mathrm{th,boi}}}{\eta_{\mathrm{th}}}\frac{1}{H_{\mathrm{i}}} * c_{\mathrm{gn}} \tag{6.6}$$

where $\eta_{\mathrm{el,cog}}$ is electric efficiency of cogenerative engine, $\eta_{\mathrm{th,cog}}$ is the thermal energy efficiency of cogenerative engine, $\eta_{\mathrm{th,cog}}$ is the thermal energy efficiency of integration boilers, x is the fraction of biomethane, $c_{gn}$ is the natural gas cost, $c_{bm}$ is the biomethane cost while $H_i$ is their heating value. $c_{sold}$ can be expressed as:

$$c_{\mathrm{sold}} = \frac{\frac{E_{\mathrm{th,cog}}}{\eta_{\mathrm{th}}}\frac{1}{H_{\mathrm{i}}} * [x * c_{\mathrm{bm}} + (1-x)] * c_{\mathrm{gn}} - \frac{E_{\mathrm{th,boi}}}{\eta_{\mathrm{th}}}\frac{1}{H_{\mathrm{i}}} * c_{\mathrm{gn}}}{E_{\mathrm{el}}} \tag{6.7}$$

Let's suppose to compare the cost to produce 1 $\mathrm{kWh_{th}}$, in order to express $E_{el}$ as $\frac{\eta_{\mathrm{el,cog}}}{\eta_{\mathrm{th,cog}}}$, and knowing that $\eta_{\mathrm{el,cog}}$ is equal to 0.442, $\eta_{\mathrm{th,cog}}$ is equal to 0.493, $\eta_{\mathrm{th,boi}}$ is equal to 0.92, $c_{gn}$ is equal to 38.6 c€/smc, $c_{bm}$ is equal to 43.6 c€/smc and $H_i$ is equal to 9.59 kWh/smc, it is possible to calculate $c_s$ as a function of x, whose results are reported in table 6.1

Two aspects are immediately noticeable: first of all is that with increase of available biomethane, due to its higher cost, it increases the also electricity price to sell to the grid, but this growth is both of modest entity and it deals with electricity price extremely low, considering that in the reference year, only 139 times is lower than 35.87 €/MWh and 278 times lower than 43.45€/MWh. These prices are more present in holiday periods, especially during night, this explains why there is not an appreciable difference between simulations.

| Biomethane fraction | Price of electricity sold [€/MWh] |
|---|---|
| 20% | 35.87 |
| 40% | 37.77 |
| 60% | 39.66 |
| 80% | 41.56 |
| 100% | 43.45 |

**Table 6.1:** Electricity price beyond which cogeneration is more advantageous than boiler production

Situation is different in an environmental optimization starting from operational cost and $CO_2$ emission trend. So far, it has always been observed that cost and $CO_2$ emission had opposite trend in each scenario with both optimization criteria, but this does not occur in this case, as it is pictured in figure 6.5. In fact, using biomethane, both cost and $CO_2$ emission decrease. If for the $CO_2$ emissions the reason is obvious, it deserves a closer look what occurs for cost. Coming back to chart, the first two scenario are the same for both parameters: as it has been seen in chapter section 6.2 the minimum percentage of biomethane to access to cogeneration is 52.5%, so the model decides to buy all electricity from the grid and produce thermal energy with integration boilers. At successive step, as represented in the first chart of figure 6.6, cogenerative engines start to be used and, inside this chart, it is possible to understand the reason operational cost decreases, as, in this scenario, it appears the amount of electricity sold to the grid, hence in this case the choice to produce energy with cogeneration is even the less polluting one. It has been previously evaluated that a price increase of biomethane does not significantly affect electricity production, therefore, despite biomethane cost increases, it is fully repaid from the sale of electricity to the grid. This peculiarity is still more evident in the scenario of 80% of biomethane, in which due to the increased use of biomethane, cogeneration is still more convenient, and it allows to sell more electricity to the grid. Comparing the two optimizations with a share of biomethane equal to 80% of total fuel used, you can even see that electricity sold to the grid is higher than the economic optimization. Obviously, this does not result in a lower cost, otherwise it would subvert the concept behind an economic optimization, but it is due to the fact that total electricity produced is lower and it must be integrated with electricity from the grid part of the gain due to the sell, but also because electricity is produced with cogeneration when it would be more convenient to purchase it from the grid. The different electricity production, looking at monthly values, is present during summer weeks, in which, to the absence of thermal load, the model decides to purchase electricity instead of producing it in the environmental optimization. A negative aspect of this optimization is the increase of the thermal energy dissipated with increasing biomethane usage as represented in second chart of figure 6.7.

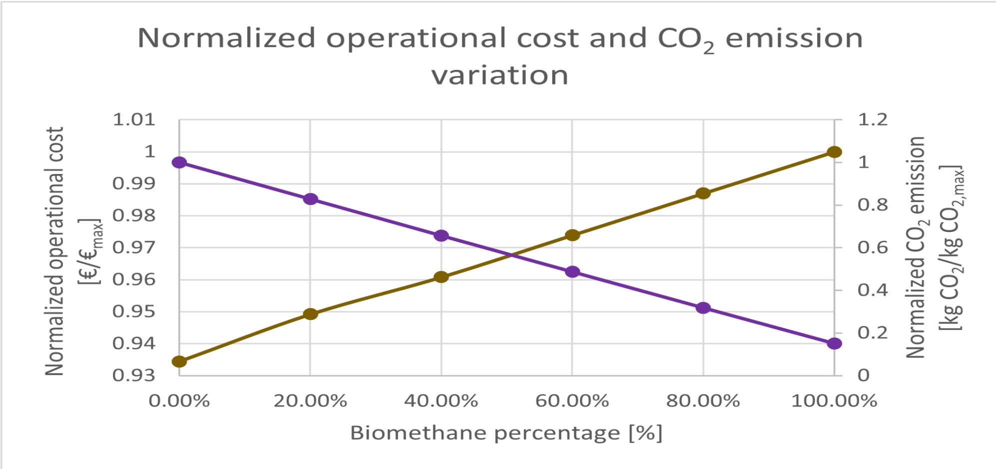


**Figure 6.2:** Operational and $CO_2$ emission variation with increasing biomethane percentage in economic optimization

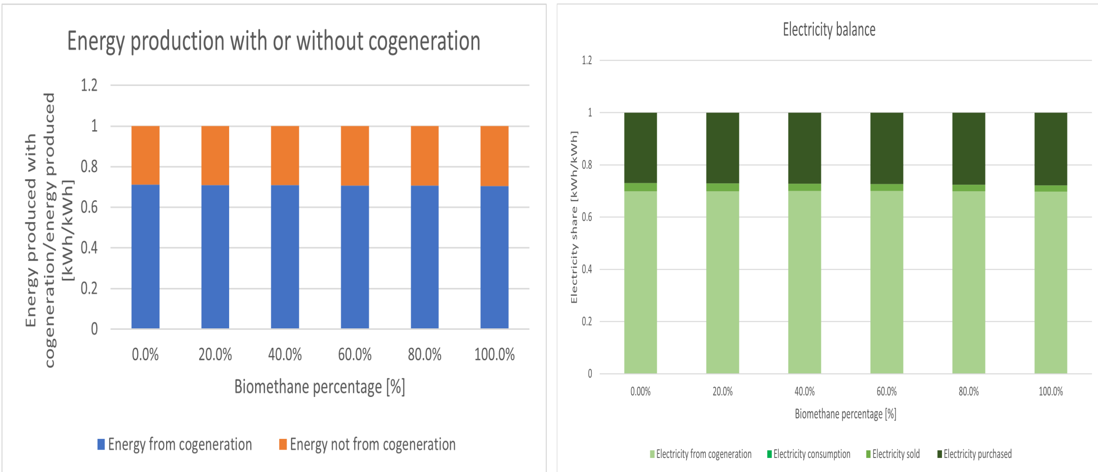


**Figure 6.3:** Cogeneration and electricity usage variation with increasing biomethane percentage in economic optimization

it is important to explain why in this case optimization has been stopped to 80% of biomethane. In the environmental optimization, it is not inserted the 100% level of biomethane, due to incongruities of the optimization process. In fact, during month in which thermal request is null and boilers do not operate, from an environmental point of view there is no difference between purchasing electricity

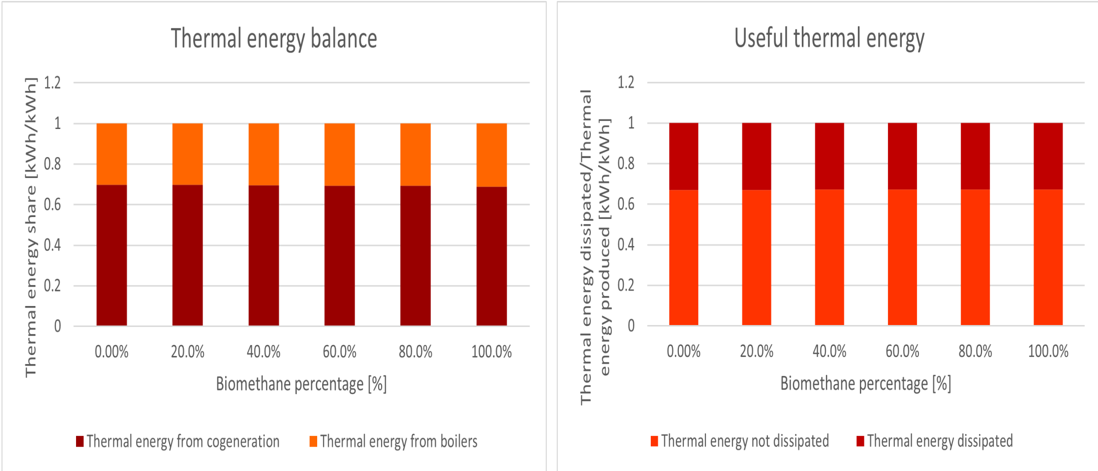


**Figure 6.4:** Thermal energy from cogeneration and thermal dissipation variation with increasing biomethane percentage in economic optimization

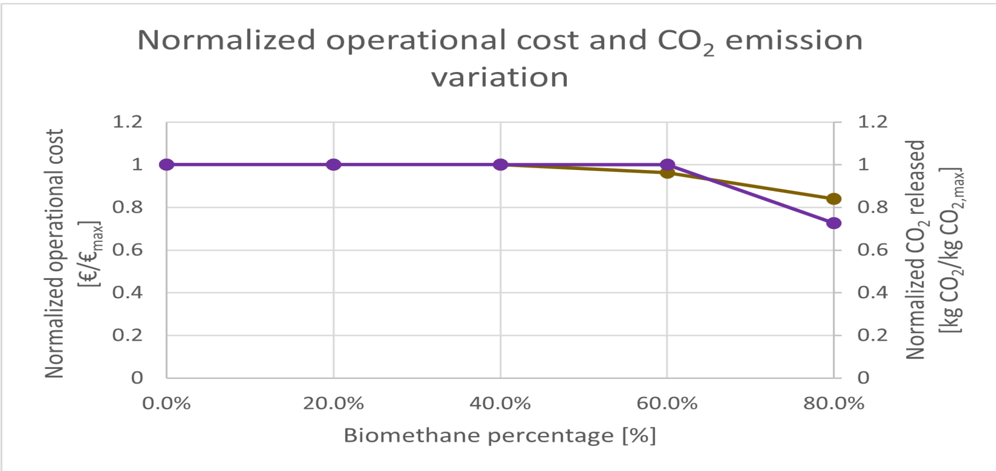


**Figure 6.5:** Operational and $CO_2$ emission variation with increasing biomethane percentage in environmental optimization

from the grid or to produce it from cogenerative units, having only biomethane as fuel, since both are $CO_2$-free and the model choose in arbitrary way how to obtain electricity. If from the point of view of emissions, the situation is equivalent, the same cannot be said about operational cost, which will be extremely different comparing the purchase of electricity from the grid and thermal production from integration boilers with respect to cogeneration. Second important point is, besides the fact that a scenario in which is present 100% is unfeasible nowadays as despite the efforts of increasing biomethane production of 2.3/2.5 Gsmc within 2030 with a

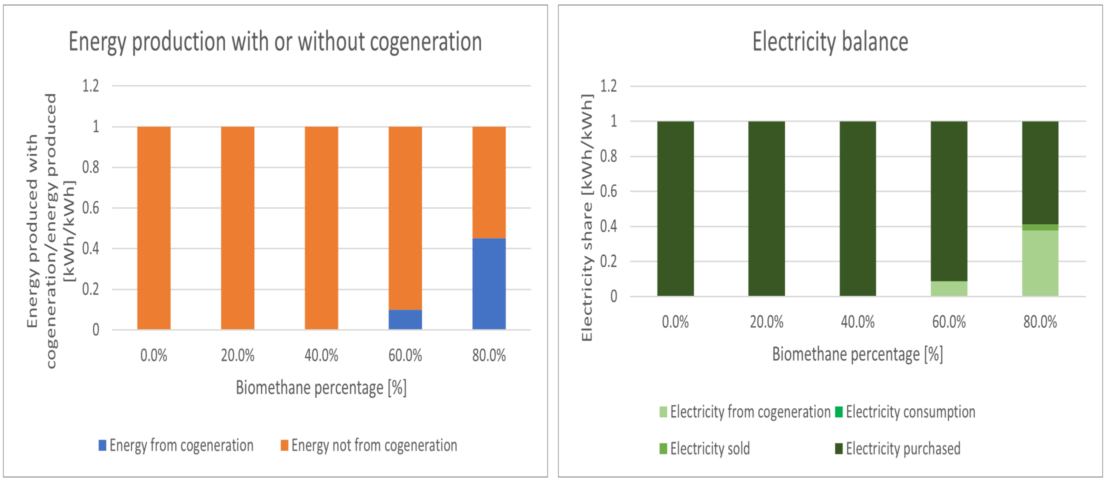


**Figure 6.6:** Cogeneration and electricity usage variation with increasing biomethane percentage in environmental optimization

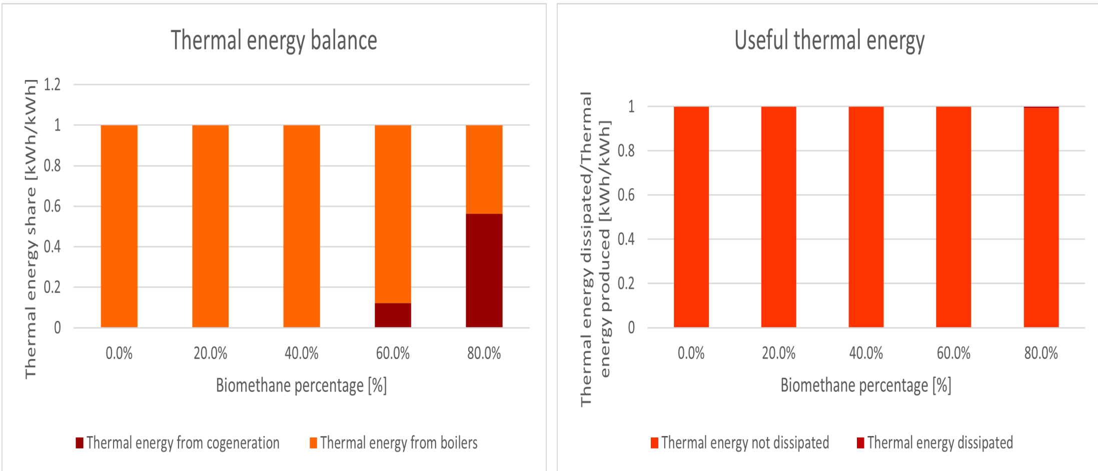


**Figure 6.7:** Thermal energy from cogeneration and thermal dissipation variation with increasing biomethane percentage in environmental optimization

total investment of €1.92 mld [70], biomethane annual production amounts to 236 Msmc [71], hence following step are evaluated considering a biomethane percentage of 60%, a value higher than 52.5% and therefore guarantee cogeneration use, but that takes into account difficulties in the biomethane supply. In any case, even in the economical optimization of the scenario with a 100% of biomethane, $CO_2$ are not reduced to 0, because cogenerative engines cannot independently cover thermal demand, so integration boilers, which consume natural, gas are required.

## 6.4 Final configuration

After having more detailed the system, in table 6.2 similarities and difference of the two systems are listed which are ready to be compute on XEMS13 to see it is possible to analyse the overall impact of changes made, while figure 6.8 graphically represents the two configurations. Looking at pictures of figure 6.9, it is noted that,

| | Initial configuration | Final configuration |
|---|---|---|
| El. prod. | 5 CHP units +PV | 5 CHP units +PV |
| Th. prod. | 5 CHP units + boilers | 5 CHP units + boilers |
| Fuel for cog. | 100% nat.gas | 60% biomethane 40% nat.gas |
| Fuel for boi. | 100% nat.gas | 100% nat.gas |
| GO on electricity | Yes | Yes |
| GO on nat.gas | No | Yes |
| $CO_2$ quotes on nat.gas | Yes | Yes |
| CB implementation | No | Yes |
| TES | No | Yes (30 MWh) |

**Table 6.2:** Comparison feature of the two configurations

by adding all interventions, the two objective function improves in both simulations, even if their drop is more visible in economic optimization. In this last, operational cost decrease is mainly due to increase of electricity produced from cogeneration, which allows to increase the amount of electricity sold to the grid and, at the same time, diminishes electricity request from the grid. Thermal energy from cogeneration itself increases, resulting in a decrease of activation time of integration boilers, and this reduction is more marked thanks to TES, which have intervention priorities in case that cogenerative units fails to cover thermal demand on their own. More in general TES allows to reduce fuel consumption and dissipation and this imply a lower amount of $CO_2$ released. Environmental optimization is less stark due to two reasons: first of all, already in first configuration, the model could rely on an energy source with an EF equal to 0 and, secondly, the fraction of biomethane in fuel mix is close to the threshold value, beyond which cogeneration is more convenient only from an environmental point of view, hence situations in which there is something more convenient from the environmental point of view are not many. This situation will occur during morning and evening hours in winter months which coincides with the greater thermal energy demand. In the rest of the year, when this demand is lower, the model behaves as in the previous case. Nevertheless, cogeneration starts to be used, ensuring gains from the sale of electricity, but also, being produced by cogeneration engines, it allows to access the mechanism of CB.

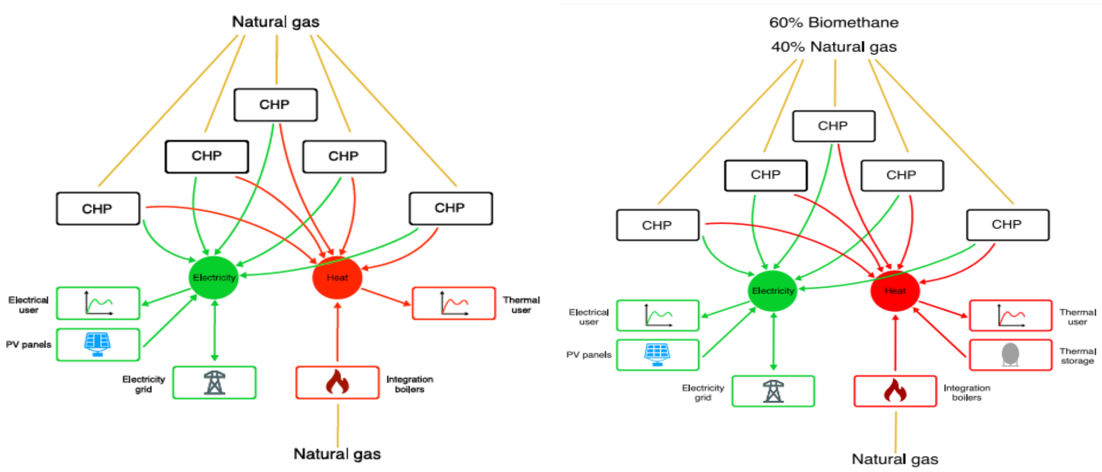


**Figure 6.8:** Comparison between initial and final configuration

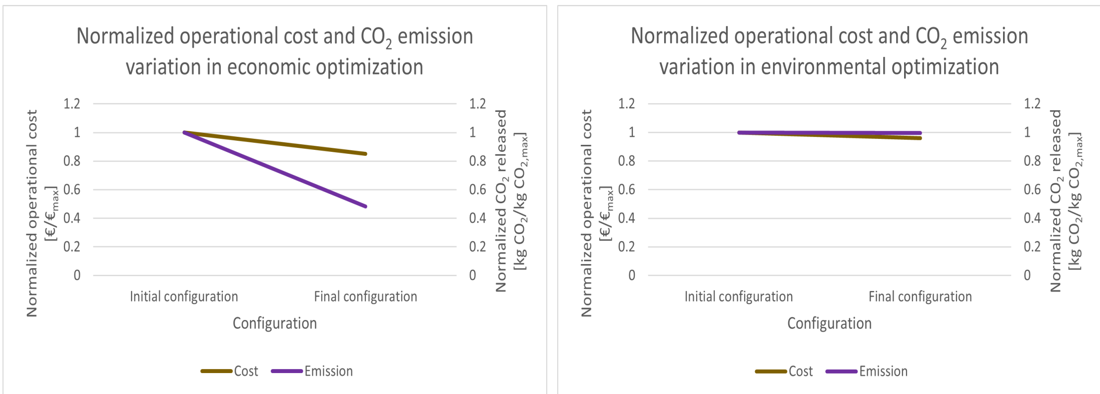


**Figure 6.9:** Comparison of operational cost and $CO_2$ emissions released between initial and final configuration in economic and environmental optimization

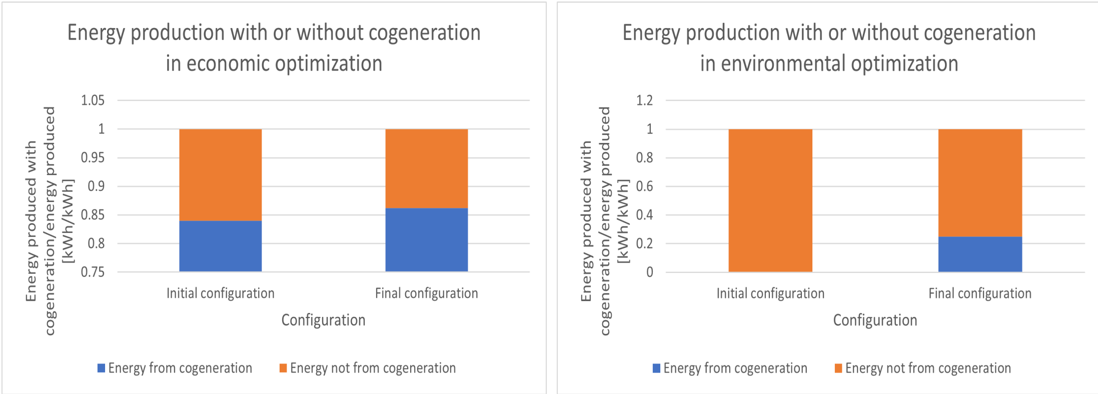


**Figure 6.10:** Comparison of energy produced with and without cogeneration between initial and final configuration in economic and environmental optimization

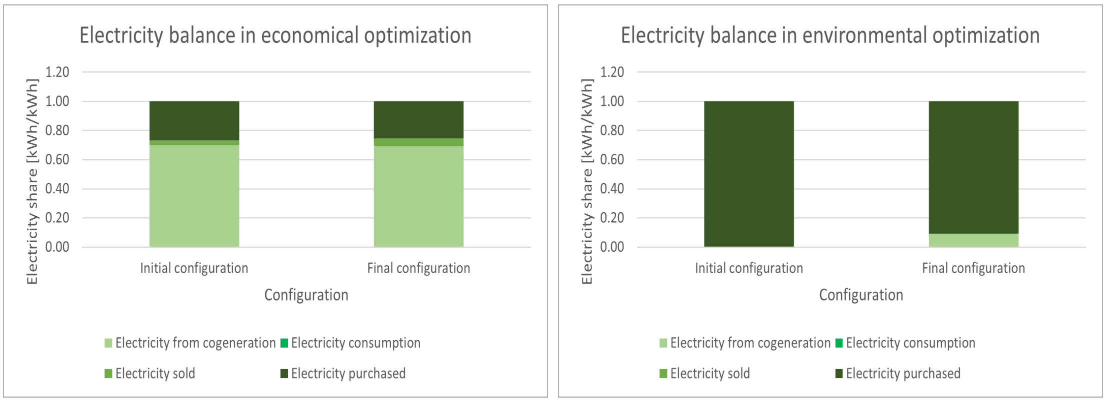


**Figure 6.11:** Comparison of electricity balance between initial and final configuration in economic and environmental optimization

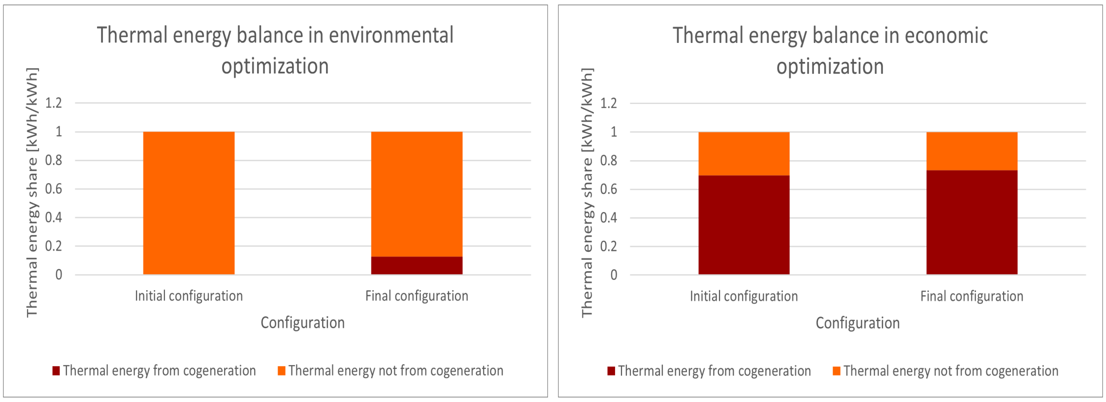


**Figure 6.12:** Comparison of thermal energy balance between initial and final configuration in economic and environmental optimization

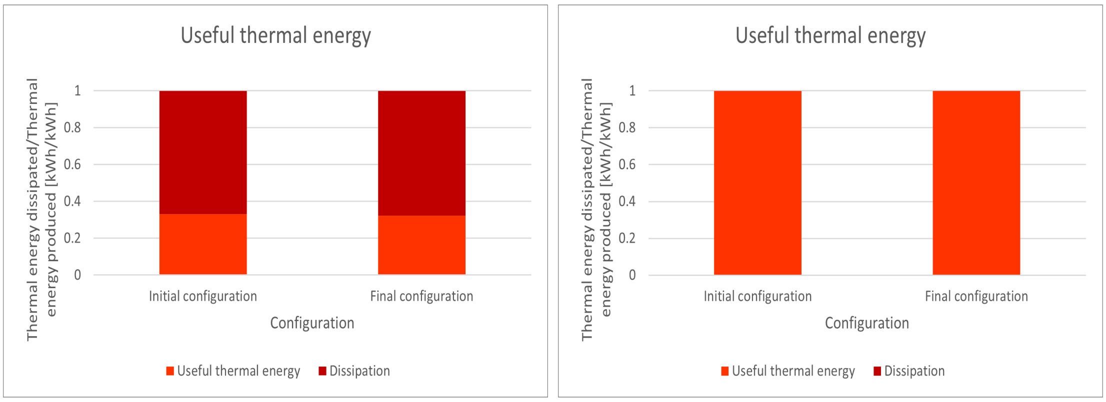


**Figure 6.13:** Comparison of thermal energy dissipated between initial and final configuration in economic and environmental optimization

# Chapter 7

# Conclusion

In this master thesis two different codes have been written and implemented with XEMS 13, in order to assess which configuration, among those available, ensure the best results in terms of reduction of operational cost and $CO_2$ emissions.

In chapter 4 the code, which will be used for all scenarios, has been described to get annual values from the weekly ones, giving the possibility to store energy quantities both for machinery and for energy vector, applying it to the base case with only GO on electricity and $CO_2$ quotes on natural gas. Chosen the best configuration which has been analysed for the rest of the thesis, it has been evaluated as GO and $CO_2$ quotes, increasing operational cost and only partially reducing $CO_2$ emissions.

In chapter 5 improvements of the system to reduce thermal dissipation and $CO_2$ released in economic optimization and to increase cogeneration contribution in environmental one to reduce operational cost, are listed, namely the code written to implement CB in XEMS13, considering also the addition of TES. In both cases, environmental optimization does not change with respect to base case, since using TES leads to the desired target. On the contrary, this does not happen with CB mechanism, which indeed increases the share of dissipated thermal energy to reach higher electric efficiency.

Finally, in chapter 6, biomethane usage is included in each scenario with rising percentage. In this case, economic optimization does not vary too much in terms of energy produced with cogeneration due to the low price of natural gas. Instead, in the environmental optimization, after a given percentage of biomethane in the fuel mix which depends on emission factor of cogenerative engines and integration boilers, cogeneration starts to be used, decreasing at the same time both operational cost and $CO_2$ emissions. Eventually, a comparison was made between the case base and the case with all improvement suggested, highlighting that a sinergy between different actions increases their advantages when taken individually, improving both objective function in both optimization kinds. It must be stressed that the use of biomethane leads to the best results, highligthing its potentiality in the decarbonisation process.

Undoubtedly, the work done leaves the room for at least three different insights:

- The procedure for selecting reference weeks of the year, can be improved by using clustering techniques, making sure that the code itself chooses number and features of representative weeks, creating subsets with high intra-class and low inter-class similarity. Most likely, number of reference weeks with clusters will be lower, providing a more accurate result with a shorter computational time.

- Focusing on XEMS13, two additions would guarantee more accurate and complete results: first improvement is related only to economic optimization and it is the addition between components list of dry cooler needed to dissipate excess heat. To these components a share of electricity would be associated, subtracted from that which would be sold to the grid or purchased from it An economical cost for each kWh of thermal energy dissipated would be associated, making sure that there is a cost to produce more thermal energy than needed if the plant has to use electricity to dissipate it. On both optimization it would be interesting to consider not only $CO_2$ emissions, but also those of other pollutants such as $NO_x$ or $SO_x$, which for some specific CHP plant has a greater weight, and which countermeasures to take in order to reduce them.

- In this analysis reference was made only about operational cost and not the investment one. This has to do with the fact that it is difficult to find such information in preliminary phases relying on datasheet available online. Therefore, once the choice is made, it is a good thing to contact the company to know this additional information, in order to carry out a more detailed analysis.

As my project work draws to an end, most of the computations here presented and performed on the basis of a stable scenario of energy prices, are surpassed by recent extraordinary changes and increases in gas and electricity costs. Even in this extreme cases, the availability of simulation tools would be useful to assess the feasibility of new energy initiatives.

# Appendix A

# Python code

## A.1 Post processing code

In this appendix it is left space for code used in thesis. First one is that explained in section 4.1, hereafter, due to its length, it is reported the procedure only related to CHPS, since for all other components and energy vector the procedure is similar.

```
    #import delle librerie necessarie per il post processing
import tkinter as tk
import os.path
import pandas as pd
import re
import matplotlib.pyplot as plt
import numpy as np
import csv
import xml.etree.ElementTree as ET
from tkinter import ttk
from tkinter import *
from tkinter import filedialog as fd

#apertura finestre per la selezione dei file di riferimento
root = tk.Tk()
root.title('File selection')
root.resizable(False, False)
root.geometry('300x150')
filenames = "undefined"
flag = 0

def select_files():                          # Ask the 14 xml files
    global filenames
    filetypes = (
        ('txt files', '*.txt'),
```

```
        ('All files', '*.*')
    )
    filenames = fd.askopenfilenames(
        title='Open files',
        initialdir='/',
        filetypes=filetypes)

open_button = ttk.Button(
    root,
    text='Choose files to post-process',
    command=select_files
)
open_button.pack(expand=True)
root.mainloop()

week = 0
n_weeks = int(0)
name = "undefined"
path = "undefined"


for filename in filenames:
    n_weeks = n_weeks + 1    # number of periods analyzed
    if name == "undefined":
        name_complete = os.path.basename(os.path.normpath(filename))
        name = name_complete.rsplit(".", 1)[0]                        #
    name of the simulation
        path = filename[0:(len(filename)-len(name_complete)-1)]+"/"
print(name)
print(path)
dire=path+name+".txt"
print(dire)

os.chdir(path)
#creazione CSV di riepilogo per ogni componente presente nella
   configurazione
name_post_processing_CHPS = name + "_post_processing_CHPS.csv"

with open(name_post_processing_CHPS, "w", newline="") as risultati:
    writer = csv.writer(risultati, delimiter=";")



#ricerca all'interno del file txt prescelto del tipologia e del
   numero dei macchinari presenti nella configurazione
with open (dire) as f:
    n_CHPS=re.findall("CHPS",f.read())


```

```
l_CHPS=len(n_CHPS)

N_CHPS=print(int(l_CHPS/2))

#formazione dei titoli delle diverse colonne che compongono i file csv a seconda dei vettori energetici che caratterizzano ogni macchinario
if int(l_CHPS/2)>0:
    y_CHPS_el=[]
    y_CHPS_th=[]
    y_CHPS_st=[]
    y_CHPS_fu=[]
    for i in range(int(l_CHPS/2)):
        y_CHPS_el.append("E_el_CHPS"+str(i+1))
        y_all_electricity_machinery.append("E_el_CHPS"+str(i+1))
    for i in range(int(l_CHPS/2)):
        y_CHPS_th.append("E_th_CHPS"+str(i+1))
        y_all_thermal_machinery.append("E_th_CHPS"+str(i+1))
    for i in range(int(l_CHPS/2)):
        y_CHPS_st.append("E_st_CHPS"+str(i+1))
        y_all_steam_machinery.append("E_st_CHPS"+str(i+1))
    for i in range(int(l_CHPS/2)):
        y_CHPS_fu.append("E_fu_CHPS"+str(i+1))
        y_all_fuel_machinery.append("E_fu_CHPS"+str(i+1))

        y_all_CHPS=[]
        y_all_CHPS=y_CHPS_el+y_CHPS_th+y_CHPS_st+y_CHPS_fu
        y_all_CHPS.insert(0,"Mese")

else:
    y_all_CHPS=[]
    a="Month"
    y_all_CHPS.append(a)
    print(y_all_CHPS)


#aggiornamento file CSV con l'aggiunta di eventuali titoli con colonne
with open(name_post_processing_CHPS, "a", newline="") as risultati:                # update csv file
                            writer = csv.writer(risultati, delimiter=";")
                            writer.writerow(y_all_CHPS)


root = tk.Tk()
root.title('File selection')
root.resizable(False, False)
root.geometry('300x150')
filenames = "undefined"
```

```
flag = 0

def select_files():                              # Ask the 14 xml files
    global filenames
    filetypes = (
        ('xml files', '*.xml'),
        ('All files', '*.*')
    )

    filenames = fd.askopenfilenames(
        title='Open files',
        initialdir='/',
        filetypes=filetypes)

open_button = ttk.Button(
    root,
    text='Choose files to post-process',
    command=select_files
)


open_button.pack(expand=True)
root.mainloop()
week = 0
n_weeks = int(0)
name = "undefined"
path = "undefined"

for filename in filenames:
    n_weeks = n_weeks + 1      # number of periods analyzed
    if name == "undefined":
        name_complete = os.path.basename(os.path.normpath(filename))
        name = name_complete.rsplit(".", 1)[0]                    # name of the simulation
        path = filename[0:(len(filename)-len(name_complete)-1)]    # path of the simulation
el_prod_CHPS=0
th_prod_CHPS=0
st_prod_CHPS=0
fu_prod_CHPS=0

if n_weeks == 15:
    for week, filename in enumerate(filenames):
        y_Pot_el_CHPS=[]

        if week <= 3:
            Month = week + 1
            Components_value_CHPS.append(Month)

```

```
        elif 3 < week <=8:
            Month = week
            Components_value_CHPS.append(Month)

        elif 8 <week<=11:
            Month = week - 1
            Components_value_CHPS.append(Month)
        else:
            Month = week - 2
            Components_value_CHPS.append(Month)


        tree = ET.parse(filename)                                  # read all values in xml file

            # legge i risultati dei CHPS
        i=0
        if week == 4 or week == 8 or week==12:
            num_mese = 14
            num_period = 7

        if week == 0 or week == 2 or week == 5 or week == 7 or week ==14:
            num_mese = 31
            num_period = 7

        elif week == 1:
            num_mese = 28
            num_period = 7

        elif week == 6 or week == 10 or week == 13:
            num_mese = 30
            num_period = 7

        elif week == 3:
            num_mese = 16
            num_period = 7

        elif week == 9:
            num_mese = 17
            num_period = 7

        elif week == 11:
            num_mese = 17
            num_period = 7

        sum_all_el_CHPS=0
        sum_all_th_CHPS=0
        sum_all_st_CHPS=0
```

```
        sum_all_fu_CHPS=0
        sum_all_el=0
        if int(l_CHPS/2)>0:
            for valore in tree.findall('.//Node_1/CHPS/istanza/Pes/VAL'):
                Pot = float(valore.text)
                y_Pot_el_CHPS.append(Pot)
            for x in range(0,len(y_Pot_el_CHPS),168):
                y_pot_el_CHPS=(y_Pot_el_CHPS[x:x+168])
                y_sum_el_CHPS=sum(float(x) for x in y_pot_el_CHPS)
                y_sum_el_CHPS=y_sum_el_CHPS*num_mese/num_period
                Components_value_CHPS.append(y_sum_el_CHPS)
                Components_value_electricity_machinery.append(y_sum_el_CHPS)
            for valore in tree.findall('.//Node_1/CHPS/istanza/Pes/VAL'):
                Pot = float(valore.text)
                sum_all_el_CHPS=sum_all_el_CHPS+Pot
            sum_all_el_CHPS=sum_all_el_CHPS*num_mese/num_period
            sum_all_el=[]
            sum_all_el.append(sum_all_el_CHPS)

            for valore in tree.findall('.//Node_1/CHPS/istanza/Pts/VAL'):
                Pot = float(valore.text)
                y_Pot_th_CHPS.append(Pot)
            for x in range(0,len(y_Pot_th_CHPS),168):
                y_pot_th_CHPS=(y_Pot_th_CHPS[x:x+168])
                y_sum_th_CHPS=sum(float(x) for x in y_pot_th_CHPS)
                y_sum_th_CHPS=y_sum_th_CHPS*num_mese/num_period
                Components_value_CHPS.append(y_sum_th_CHPS)
                Components_value_thermal_machinery.append(y_sum_th_CHPS)
            for valore in tree.findall('.//Node_1/CHPS/istanza/Pts/VAL'):
                Pot = float(valore.text)
                sum_all_th_CHPS=sum_all_th_CHPS+Pot
            sum_all_th_CHPS=sum_all_th_CHPS*num_mese/num_period




            for valore in tree.findall('.//Node_1/CHPS/istanza/Ptvs/VAL'):
                Pot = float(valore.text)
                y_Pot_st_CHPS.append(Pot)
            for x in range(0,len(y_Pot_st_CHPS),168):
                y_pot_st_CHPS=(y_Pot_st_CHPS[x:x+168])
                y_sum_st_CHPS=sum(float(x) for x in y_pot_st_CHPS)
```

```
                y_sum_st_CHPS=y_sum_st_CHPS*num_mese/num_period
                Components_value_CHPS.append(y_sum_st_CHPS)
                Components_value_steam_machinery.append(y_sum_st_CHPS)
            for valore in tree.findall('.//Node_1/CHPS/istanza/Ptvs/VAL'):
                Pot = float(valore.text)
                sum_all_st_CHPS=sum_all_st_CHPS+Pot
            sum_all_st_CHPS=sum_all_st_CHPS*num_mese/num_period



            for valore in tree.findall('.//Node_1/CHPS/istanza/Pcs/VAL'):
                Pot = float(valore.text)
                y_Pot_fu_CHPS.append(Pot)
            for x in range(0,len(y_Pot_fu_CHPS),168):
                y_pot_fu_CHPS=(y_Pot_fu_CHPS[x:x+168])
                y_sum_fu_CHPS=sum(float(x) for x in y_pot_fu_CHPS)
                y_sum_fu_CHPS=y_sum_fu_CHPS*num_mese/num_period
                Components_value_CHPS.append(y_sum_fu_CHPS)
                Components_value_fuel_machinery.append(y_sum_fu_CHPS)
            for valore in tree.findall('.//Node_1/CHPS/istanza/Pcs/VAL'):
                Pot = float(valore.text)
                sum_all_fu_CHPS=sum_all_fu_CHPS+Pot
            sum_all_fu_CHPS=sum_all_fu_CHPS*num_mese/num_period



        else:
            y_sum_el_CHPS=0
            Components_value_CHPS.append(y_sum_el_CHPS)
            y_sum_th_CHPS=0
            Components_value_CHPS.append(y_sum_th_CHPS)
            y_sum_st_CHPS=0
            Components_value_CHPS.append(y_sum_st_CHPS)
            y_sum_fu_CHPS=0
            Components_value_CHPS.append(y_sum_fu_CHPS)
        with open(name_post_processing_CHPS, "a", newline="") as risultati:           # update csv file
                    writer = csv.writer(risultati, delimiter=";")
                    writer.writerow(Components_value_CHPS)

if(l_CHPS/2)>0:
    df = pd.read_csv(name + "_post_processing_CHPS.csv",header=0,delimiter=';')
    a=df.iloc[3:5,:].sum()
    a.iloc[0]=a.iloc[0]/2
```

```
    a_row=pd.Series(a)
    row_df = pd.DataFrame([a_row],index=[4.5])
    df = df.append(row_df, ignore_index=False)
    df = df.sort_index().reset_index(drop=True)
    df=df.drop(index=3)
    df=df.drop(index=4)
    a=df.iloc[7:9,:].sum()
    a.iloc[0]=a.iloc[0]/2
    a_row=pd.Series(a)
    row_df = pd.DataFrame([a_row],index=[9.5])
    df = df.append(row_df, ignore_index=False)
    df = df.sort_index().reset_index(drop=True)
    df=df.drop(index=7)
    df=df.drop(index=8)
    a=df.iloc[9:11,:].sum()
    a.iloc[0]=a.iloc[0]/2
    a_row=pd.Series(a)
    row_df = pd.DataFrame([a_row],index=[12.5])
    df = df.append(row_df, ignore_index=False)
    df = df.sort_index().reset_index(drop=True)
    df=df.drop(index=9)
    df=df.drop(index=10)
    df.to_csv(name + "_post_processing_CHPS.csv",index=False)
```

## A.2 Result_CB_final

```
    import os
import os.path
import xml.etree.ElementTree as ET
import numpy as np
import pandas as pd
import csv
import statistics
from Eta_el_rif import eta_el_rif
from Eta_th_rif import eta_th_rif
from K_calculation import k_calculation


def results(main_path, Old_maintenance, netlist_only_names,CHP_tag):

        features=["Electricity from cogeneration","Thermal energy
    from cogeneration",\
                "Steam from cogeneration","Fuel from cogeneration","
    Useful thermal energy",\
```

```
            "Thermal dissipation","Useful steam","Steam dissipation","Useful heat",\
             "Electric efficiency","Heat efficiency","Overall efficiency","Beta",\
              "Heat from CAR","Electricity from CAR","Fuel from CAR","PES","RISP",\
                  "White certificates","€ from White Certificates",\
                      "€/kWh from White Certificates","Maintenance cost"]

    Emissions = []
    E_thermal = []
    E_electrical = []
    E_steam=[]
    E_fuel=[]
    Dissipation_thermal = []
    Dissipation_steam=[]
    E_thermal_ut=[]
    E_steam_ut=[]
    E_st_ut_a=[]
    E_heat_ut=[]
    Beta=[]
    eta_ele=[]
    eta_heat=[]
    eta_glo=[]
    El_CAR=[]
    Heat_CAR=[]
    Fu_CAR=[]
    Rend_el_CAR=[]
    Rend_heat_CAR=[]
    PES=[]
    RISP=[]
    CB=[]
    Euro_CB=[]
    Euro_CB_sp=[]
    rendimento_E_rif = float(0.46)
    rendimento_T_rif = float(0.9)
    E_elettrica = 0
    E_termica = 0
    E_vapore=0
    E_combustibile = 0
    E_storage_in = 0
    Dissipazione_termica = 0
    Dissipazione_vapore = 0
    Emissioni = 0
    E_ter_boiler = 0
    Utenza_ter = 0
    Month = 0
    Costo = 0
```

```
        Utenza_ele = 0
        E_p = 0
        E_s = 0


        E_storage_in = 0
        EmissioniGlobali = "undefined"
        E_th = 0
        E_el = 0
        E_st = 0
        Dissipazione_termica = 0
        Dissipazione_vapore = 0
        E_fu = 0
        E_storage_in = 0
        EmissioniGlobali = "undefined"
        y_sum_diss_st=0
        y_sum_el_CHPS=0
        y_sum_th_CHPS=0
        y_sum_st_CHPS=0
        y_sum_fu_CHPS=0
        y_Pot_el_CHP=[]
        y_Pot_th_CHP=[]
        y_Pot_st_CHP=[]
        y_Pot_fu_CHP=[]
        y_Pot_el_CHPS=[]
        y_Pot_th_CHPS=[]
        y_Pot_st_CHPS=[]
        y_Pot_fu_CHPS=[]
        y_Pot_el_CHPS=[]
        y_Pot_th_CHPS=[]
        y_Pot_st_CHPS=[]
        y_Pot_fu_CHPS=[]
        y_Diss_th=[]
        y_Diss_st=[]
        y_Elc_sold=[]
        y_Elc_pur=[]


        Components_value_st_diss=[]
        Components_value_Elc_sold=[]
        Components_value_Elc_pur=[]
        Th_ut=[]
        St_ut=[]
        TH_diss=[]
        ST_diss=[]
        Heat_ut=[]
        Rend_ele=[]
        Rend_heat=[]
        Rend_glo=[]
```

```
        Beta=[]
        Eta_el_CHPS=[]
        El_CAR=[]
        El_NON_CAR=[]
        Heat_CAR=[]
        Fu_CAR=[]
        Fu_NON_CAR=[]
        Eta_el_CAR=[]
        Eta_heat_CAR=[]
        Eta_rif_el=[]
        Eta_rif_th=[]
        Eta_rif_st=[]
        Eta_rif_dg=[]
        Eta_std_el=[]
        Eta_rif_heat=[]
        PES=[]
        RISP=[]
        Cb_obt=[]
        Euro_obt=[]
        Ccb=[]
        New_maintenance=[]
        Overall_values=[]
        Comp=[]
        comp_features=[]
        N_rate=[]
        Max_P=[]
        N_line=[]

        a_th=[]
        a_st=[]
        Eta_std_th = [0.9,0.9]
        a = float(0.086)
        const = float(0.086)
        eta_std_el = float(0.46)
        Eta_std_th = float(0.9)
        Eta_std_st = float(0.9)
        CB_val = float(264.08)
        # euro per CB
        os.chdir(main_path)

        with open("Useful_parameter.txt") as f:
            for line in f:
                if line.startswith('eta_lim='):
                    eta_lim=line.split('eta_lim=',1)[1]
                    eta_lim=eta_lim.replace('\n',"")
                    eta_lim=(eta_lim.split())
                    eta_lim=[float(i) for i in eta_lim]
                elif line.startswith('h_sat='):
                    h_sat=line.split('h_sat=',1)[1]
```

```
            h_sat=h_sat.replace('\n',"")
            h_sat=(h_sat.split())
            print(h_sat)
            h_sat=[float(i) for i in h_sat]
            print(h_sat)
        elif line.startswith('h_cond='):
            h_cond=line.split('h_cond=',1)[1]
            h_cond=h_cond.replace('\n',"")
            h_cond=(h_cond.split())
            h_cond=[float(i) for i in h_cond]
        elif line.startswith('Year_of_construction='):
            year_construction=line.split('Year_of_construction=',1)[1]
            year_construction=year_construction.replace('\n',"")
            year_construction=list(year_construction.split())
            year_construction=[float(i) for i in year_construction]
        elif line.startswith('Fuel_typology='):
            fuel_type=line.split('Fuel_typology=',1)[1]
            fuel_type=fuel_type.replace("\n","")
            fuel_type=list(fuel_type.split())
        elif line.startswith('Average_temperature='):
            T_avg=line.split('Average_temperature=',1)[1]
            T_avg=T_avg.replace("\n","")
            T_avg=list(T_avg.split())
            T_avg=[float(i) for i in T_avg]
        elif line.startswith('Voltage='):
            V_avg=line.split('Voltage=',1)[1]
            V_avg=V_avg.replace("\n","")
            V_avg=list(V_avg.split())
            V_avg=[float(i) for i in V_avg]
        elif line.startswith('Eta_el_RISP='):
            Eta_el_RISP=line.split('Eta_el_RISP=',1)[1]
            Eta_el_RISP=Eta_el_RISP.replace('\n',"")
            Eta_el_RISP=(Eta_el_RISP.split())
            Eta_el_RISP=[float(i) for i in Eta_el_RISP]
        elif line.startswith('Eta_heat_RISP='):
            Eta_heat_RISP=line.split('Eta_heat_RISP=',1)[1]
            Eta_heat_RISP=Eta_heat_RISP.replace('\n',"")
            Eta_heat_RISP=(Eta_heat_RISP.split())
            Eta_heat_RISP=[float(i) for i in Eta_heat_RISP]
        elif line.startswith('Condensation='):
            cond=line.split('Condensation=',1)[1]
            cond=cond.replace("\n","")
            cond=list(cond.split())
        elif line.startswith('ans='):
            ans=line.split('ans=',1)[1]
            ans=ans.replace("\n","")
```

```
                ans=list(ans.split())
            elif line.startswith('n_reg='):
                n_reg=line.split('n_reg=',1)[1]
                n_reg=n_reg.replace("\n","")
                n_reg=list(n_reg.split())

    print((Eta_heat_RISP))

    Beta_all=[]
    Beta_all_week=[]
    RISP_all=[]
    RISP_all_week=[]
    # features=["Electricity from cogeneration","Thermal energy from cogeneration",\
    #        "Steam from cogeneration","Fuel from cogeneration","Useful thermal energy",\
    #       "Thermal dissipation","Useful steam","Steam dissipation","Useful heat",\
    #        "Electric efficiency","Heat efficiency","Overall efficiency","Beta",\
    #         "Electricty from CAR","Heat from CAR","Fuel from CAR","PES","RISP",\
    #            "White certificates","€ from White Certificates",\
    #                "€/kWh from White Certificates","Maintenance cost"]
    os.chdir(main_path)

    with open("defaultDIR.txt", "r", encoding='utf8') as directories:
        Paths = directories.readlines()
        # Paths[2] contains the path of the components directory
        # Paths[0] contains the path of the work directory with the results
        # Paths[3] contains name of the netlist .txt
        netlist_path = str(Paths[0].strip("\n"))  # il percorso della cartella netlist
        AllResults = [0] * len(netlist_only_names)

    os.chdir(netlist_path)  # va nella cartella delle netlist e legge l'xml
    for week in range(int(len(netlist_only_names))):
        AllResults = netlist_only_names[week] + ".xml"
        tree = ET.parse(AllResults)
        print(AllResults)

        Emissions = []
        E_thermal = []
        E_electrical = []
```

```
E_steam=[]
E_fuel=[]
Dissipation_thermal = []
Dissipation_steam=[]
E_thermal_ut=[]
E_steam_ut=[]
E_st_ut_a=[]
E_heat_ut=[]
Beta=[]
eta_ele=[]
eta_heat=[]
eta_glo=[]
El_CAR=[]
Heat_CAR=[]
Fu_CAR=[]
Rend_el_CAR=[]
Rend_heat_CAR=[]
PES=[]
RISP=[]
CB=[]
Euro_CB=[]
Euro_CB_sp=[]
rendimento_E_rif = float(0.46)
rendimento_T_rif = float(0.9)
E_el= 0
E_th= 0
E_st=0
E_fu= 0
E_storage_in = 0
Dissipazione_termica = 0
Dissipazione_vapore = 0
Emissioni = 0
E_ter_boiler = 0
Utenza_ter = 0
Month = 0
Costo = 0
Utenza_ele = 0
E_p = 0
E_s = 0
y_sum_el_CHPS=0
y_sum_th_CHPS=0
y_sum_st_CHPS=0
y_sum_fu_CHPS=0

E_storage_in = 0
EmissioniGlobali = "undefined"
E_th = 0
E_el = 0
E_st = 0
```

```
        Dissipazione_termica = 0
        Dissipazione_vapore = 0
        E_fu = 0
        E_storage_in = 0
        EmissioniGlobali = "undefined"

        y_Pot_el_CHP=[]
        y_Pot_th_CHP=[]
        y_Pot_st_CHP=[]
        y_Pot_fu_CHP=[]
        y_Pot_el_CHPS=[]
        y_Pot_th_CHPS=[]
        y_Pot_st_CHPS=[]
        y_Pot_fu_CHPS=[]
        y_Pot_el_CHPS=[]
        y_Pot_th_CHPS=[]
        y_Pot_st_CHPS=[]
        y_Pot_fu_CHPS=[]
        y_Diss_th=[]
        y_Diss_st=[]
        y_Elc_sold=[]
        y_Elc_pur=[]
        Components_value_el_CHPS=[]
        Components_value_th_CHPS=[]
        Components_value_st_CHPS=[]
        Components_value_fu_CHPS=[]
        Components_value_el_CHPLE=[]
        Components_value_th_CHPLE=[]
        Components_value_fu_CHPLE=[]
        Components_value_th_diss=[]
        Components_value_st_diss=[]
        Components_value_Elc_sold=[]
        Components_value_Elc_pur=[]
        Comp=[]

        New_maintenance=[]
        Overall_values=[]
        Comp=[]
        comp_features=[]
        N_rate=[]
        Max_P=[]
        N_line=[]

        a_th=[]
        a_st=[]

        for valore in tree.findall('.//Node_1/CHPS/istanza/Pes/
    VAL'):
            Pot = float(valore.text)
```

```
            E_el = E_el + Pot
            y_Pot_el_CHPS.append(Pot)
        if E_el==0:
            y_Pot_el_CHPS=[0]*168*int(len(CHP_tag))
        for x in range(0,len(y_Pot_el_CHPS),168):
            y_pot_el_CHPS=(y_Pot_el_CHPS[x:x+168])
            y_sum_el_CHPS=sum(float(x) for x in y_pot_el_CHPS)
            Components_value_el_CHPS.append(y_sum_el_CHPS)
            Overall_values.append(y_sum_el_CHPS)

        for valore in tree.findall('.//Node_1/CHPS/istanza/Pts/VAL'):
            Pot = float(valore.text)
            E_th = E_th + Pot
            y_Pot_th_CHPS.append(Pot)
        if E_th==0:
            y_Pot_th_CHPS=[0]*168*int(len(CHP_tag))
        for x in range(0,len(y_Pot_th_CHPS),168):
            y_pot_th_CHPS=(y_Pot_th_CHPS[x:x+168])
            a_th.append(y_pot_th_CHPS)
            df_th=pd.DataFrame(a_th)
            y_sum_th_CHPS=sum(float(x) for x in y_pot_th_CHPS)
            Components_value_th_CHPS.append(y_sum_th_CHPS)
            Overall_values.append(y_sum_th_CHPS)

        for valore in tree.findall('.//Node_1/CHPS/istanza/Ptvs/VAL'):
            Pot = float(valore.text)
            E_st = E_st + Pot
            y_Pot_st_CHPS.append(Pot)
        if E_st==0:
            y_Pot_st_CHPS=[0]*168*int(len(CHP_tag))
        for x in range(0,len(y_Pot_st_CHPS),168):
            y_pot_st_CHPS=(y_Pot_st_CHPS[x:x+168])
            a_st.append(y_pot_st_CHPS)
            df_st=pd.DataFrame(a_st)
            y_sum_st_CHPS=sum(float(x) for x in y_pot_st_CHPS)
            Components_value_st_CHPS.append(y_sum_st_CHPS)
            Overall_values.append(y_sum_st_CHPS)


            # reads electrical powers produced by CHP
        for valore in tree.findall('.//Node_1/CHPS/istanza/Pcs/VAL'):
            Pot = float(valore.text)
            E_fu = E_fu + Pot
            y_Pot_fu_CHPS.append(Pot)
        if E_fu==0:
            y_Pot_fu_CHPS=[0]*168*int(len(CHP_tag))
```

```
            Counter=[]
            for x in range(0,len(y_Pot_fu_CHPS),168):
                y_pot_fu_CHPS=(y_Pot_fu_CHPS[x:x+168])
                counter=0
                y_sum_fu_CHPS=sum(float(x) for x in y_pot_fu_CHPS)
                Components_value_fu_CHPS.append(y_sum_fu_CHPS)
                Overall_values.append(y_sum_fu_CHPS)
                for x in range(int(len(y_pot_fu_CHPS))):
                    if y_pot_fu_CHPS[x]!=0:
                        counter=counter+1
                Counter.append(counter)
            print(Counter)

                # reads powers entering CHP

            #      # CHPLE
            # for valore in tree.findall('.//Node_1/CHPLE/istanza/
    Ptle/VAL'):
            #      Pot = float(valore.text)
            #      E_termica = E_termica + Pot
            #      # reads thermal powers produced by CHPLE
            # for valore in tree.findall('.//Node_1/CHPLE/istanza/
    Pele/VAL'):
            #      Pot = float(valore.text)
            #      E_elettrica = E_elettrica + Pot
            #      # reads electrical powers produced by CHPLE
            # for valore in tree.findall('.//Node_1/CHPLE/istanza/
    Pcle/VAL'):
            #      Pot = float(valore.text)
            #      E_in = E_in + Pot
                # reads powers entering CHPLE

                # CHPS




            # print(Components_value_st_CHPS)
                # reads thermal powers produced by CHPS


                # reads electrical powers produced by CHPS

            #      # reads powers entering CHPS

            for valore in tree.findall('.//Node_1/Stt/istanza/PSttin/
    VAL'):
                Pot = float(valore.text)
                E_storage_in = E_storage_in + Pot
```

```
                # reads powers enetering the storage (if present)

            for valore in tree.findall('.//Node_1/Dt/Dt/VAL'):
                Pot = float(valore.text)
                Dissipazione_termica = Dissipazione_termica + Pot
                y_Diss_th.append(Pot)
            for x in range(0,len(y_Diss_th),168):
                y_diss_th=(y_Diss_th[x:x+168])
                a_th.append(y_diss_th)
                df_th=pd.DataFrame(a_th)
                y_sum_diss_th=sum(float(x) for x in y_diss_th)
                Components_value_th_diss.append(y_sum_diss_th)


                # reads thermal dissipation

            for valore in tree.findall('.//Node_1/Dtv/Dtv/VAL'):
                Pot = float(valore.text)
                Dissipazione_vapore = Dissipazione_vapore + Pot
                y_Diss_st.append(Pot)
            for x in range(0,len(y_Diss_st),168):
                y_diss_st=(y_Diss_st[x:x+168])
                a_st.append(y_diss_st)
                df_st=pd.DataFrame(a_st)
                y_sum_diss_st=sum(float(x) for x in y_diss_st)
                Components_value_st_diss.append(y_sum_diss_st)

            for valore in tree.findall('.//Node_1/Grid/istanza/Ps/VAL'):
                Pot = float(valore.text)
                y_Elc_sold.append(Pot)
            for x in range(0,len(y_Elc_sold),168):
                y_elc_sold=(y_Elc_sold[x:x+168])
                y_sum_elc_sold=sum(float(x) for x in y_elc_sold)
                Components_value_Elc_sold.append(y_sum_elc_sold)
            print(Components_value_Elc_sold)
            for valore in tree.findall('.//Node_1/Grid/istanza/Pp/VAL'):
                Pot = float(valore.text)
                y_Elc_pur.append(Pot)
            for x in range(0,len(y_Elc_pur),168):
                y_elc_pur=(y_Elc_pur[x:x+168])
                y_elc_pur=sum(float(x) for x in y_elc_pur)
                Components_value_Elc_pur.append(y_elc_pur)
            print(Components_value_Elc_pur)

            for i in range(len(CHP_tag)):
                if CHP_tag[0]=='ReteNew':
                  th_ut=0
```

```
                        th_diss=0
                        st_ut=0
                        st_diss=0
                        heat_ut=0
                        rend_ele=0
                        rend_heat=0
                        rend_glo=0
                        beta=0
                        el_CAR=0
                        heat_CAR=0
                        fu_CAR=0
                        Pes=0
                        Risp=0
                        cb_obt=0
                        euro_obt=0
                        ccb=0
                        new_maintenance=0

                        Beta.append(beta)
                        RISP.append(Risp)
                        New_maintenance.append(new_maintenance)
                        Overall_values.append(y_sum_el_CHPS)
                        Overall_values.append(y_sum_th_CHPS)
                        Overall_values.append(y_sum_st_CHPS)
                        Overall_values.append(y_sum_fu_CHPS)
                        Overall_values.append(th_ut)
                        Overall_values.append(th_diss)
                        Overall_values.append(st_ut)
                        Overall_values.append(st_diss)
                        Overall_values.append(heat_ut)
                        Overall_values.append(rend_ele)
                        Overall_values.append(rend_heat)
                        Overall_values.append(rend_glo)
                        Overall_values.append(beta)
                        Overall_values.append(el_CAR)
                        Overall_values.append(heat_CAR)
                        Overall_values.append(fu_CAR)
                        Overall_values.append(Pes)
                        Overall_values.append(Risp)
                        Overall_values.append(cb_obt)
                        Overall_values.append(euro_obt)
                        Overall_values.append(ccb)
                        Overall_values.append(new_maintenance)



                df_th=df_th.transpose()
                    # print(df_th)
                df_st=df_st.transpose()
```

```
n_row=int(len(df_th.index))
n_col=int(len(CHP_tag))



th_ut=[]
for i in range(0,n_row):
    j=int(len(df_th.columns))-2
    Th_diss_tot=df_th.iloc[i,int(len(df_th.columns))-1]
    Th_diss_rim=df_th.iloc[i,int(len(df_th.columns))-1]
    Th_diss_sum=0


    while j>=0:
        Th_diss=0
        if df_th.iloc[i,j]!=0:
            if Th_diss_sum<Th_diss_tot:
              Th_Ut=df_th.iloc[i,j]-Th_diss_rim
              if Th_Ut<=0:
                Th_Ut=0
                Th_diss=Th_diss+df_th.iloc[i,j] #15
                Th_diss_sum=Th_diss_sum+Th_diss #15
                Th_diss_rim=Th_diss_rim-Th_diss #10
                j=j-1
                # print(Th_Ut)
                # print(Th_diss_sum)
                # print(Th_diss_rim)
                th_ut.append(Th_Ut)
              else:
                Th_Ut=df_th.iloc[i,j]-Th_diss_rim
                Th_diss=Th_diss+Th_diss_rim
                Th_diss_sum=Th_diss_sum+Th_diss
                Th_diss_rim=Th_diss_rim-Th_diss
                # print(Th_Ut)
                # print(Th_diss_sum)
                # print(Th_diss_rim)
                th_ut.append(Th_Ut)
                j=j-1
            else:
                Th_Ut=df_th.iloc[i,j]
                # print(Th_Ut)
```

```
                        # print(Th_diss_sum)
                        # print(Th_diss_rim)
                        j=j-1
                        th_ut.append(Th_Ut)

                else:
                    Th_Ut=0
                    # print(Th_Ut)
                    # print(Th_diss_sum)
                    # print(Th_diss_rim)
                    j=j-1
                    th_ut.append(Th_Ut)
        # print(th_ut)
        # print(len(th_ut))
        th_ut_rev=[]
        for i in reversed(th_ut):
            th_ut_rev.append(i)

        # print(th_ut_rev)

        Th_ut=[]
        for i in range(int(len(CHP_tag))):
          Th_ut.append(sum(th_ut_rev[i::n_col]))
          Overall_values.append(sum(th_ut_rev[i::n_col]))

        # print(th_ut)


        Th_diss=[]
        for i in range(int(len(CHP_tag))):
            if Components_value_th_CHPS[i]==0:
                th_diss=0
                Th_diss.append(th_diss)
                Overall_values.append(th_diss)
            else:
                th_diss=Components_value_th_CHPS[i]-Th_ut[i]
                Th_diss.append(th_diss)
                Overall_values.append(th_diss)



        st_ut=[]
        for i in range(0,n_row):
            j=int(len(df_st.columns))-2
            St_diss_tot=df_st.iloc[i,int(len(df_st.columns))-1]
            St_diss_rim=df_st.iloc[i,int(len(df_st.columns))-1]
            St_diss_sum=0

            St_diss=0
```

```
                while j>=0:
                    if df_st.iloc[i,j]!=0:
                        if St_diss_sum<St_diss_tot:
                          St_Ut=df_st.iloc[i,j]-St_diss_rim
                          if St_Ut<=0:
                            St_Ut=0
                            St_diss=St_diss+df_st.iloc[i,j] #15
                            St_diss_sum=St_diss_sum+St_diss #15
                            St_diss_rim=St_diss_rim-St_diss_sum #10
                            j=j-1
                            # print(St_Ut)
                            # print(Th_diss_sum)
                            # print(Th_diss_rim)
                            st_ut.append(St_Ut)
                          else:
                            St_Ut=df_st.iloc[i,j]-St_diss_rim
                            St_diss=St_diss+min(St_Ut,St_diss_rim)
                            St_diss_sum=St_diss_sum+St_diss #15
                            St_diss_rim=St_diss_rim-St_diss_sum
                            # print(St_diss)
                            # print(Th_diss_sum)
                            # print(Th_diss_rim)
                            st_ut.append(St_Ut)
                            j=j-1
                        else:
                            St_Ut=df_st.iloc[i,j]
                            # print(Th_Ut)
                            # print(St_diss_sum)
                            # print(Th_diss_rim)
                            j=j-1
                            st_ut.append(St_Ut)

                    else:
                        St_Ut=0
                        # print(Th_Ut)
                        # print(St_diss_sum)
                        # print(Th_diss_rim)
                        j=j-1
                        st_ut.append(St_Ut)






            st_ut_rev=[]
            for i in reversed(st_ut):
                 st_ut_rev.append(i)

```

```
        St_us=[]
        for i in range(int(len(CHP_tag))):
            St_us.append(sum(st_ut_rev[i::n_col]))
        ## print(St_us)



        St_ut=[]
        for i in range(int(len(CHP_tag))):
            if St_us[i]==0:
                st_ut=0
                St_ut.append(st_ut)
                Overall_values.append(st_ut)
            else:
                m_vap=St_us[i]/(h_sat[i])
                e_cond=m_vap*h_cond[i]/3600
                st_ut=St_us[i]-e_cond
                St_ut.append(st_ut)
                Overall_values.append(st_ut)




        for i in range(int(len(CHP_tag))):
            if Components_value_st_CHPS[i]==0:
                st_diss=0
                ST_diss.append(st_diss)
                Overall_values.append(st_diss)
            else:
                st_diss=Components_value_st_CHPS[i]-St_ut[i]
                ST_diss.append(st_diss)
                Overall_values.append(st_diss)


        # for i in range(int(len(CHP_tag))):
            # st_ut=0
            # st_diss=0
            # St_ut.append(st_ut)
            # ST_diss.append(st_diss)
            # Overall_values.append(st_ut)
            # Overall_values.append(st_diss)


        for i in range(int(len(CHP_tag))):
            if Th_ut[i]==0 and St_ut[i]==0:
                heat_ut=0
                Heat_ut.append(heat_ut)
```

```
                    Overall_values.append(heat_ut)
                else:
                    heat_ut=Th_ut[i]+St_ut[i]
                    Heat_ut.append(heat_ut)
                    Overall_values.append(heat_ut)
            # print(Heat_ut)


            for i in range(int(len(CHP_tag))):
                if Components_value_fu_CHPS[i]==0:
                    rend_ele=0
                    Rend_ele.append(rend_ele)
                    Overall_values.append(rend_ele)
                else:
                    rend_ele=Components_value_el_CHPS[i]/Components_value_fu_CHPS[i]
                    Rend_ele.append(rend_ele)
                    Overall_values.append(rend_ele)


            for i in range(int(len(CHP_tag))):
                 if Components_value_fu_CHPS[i]==0:
                     rend_heat=0
                     Rend_heat.append(rend_heat)
                     Overall_values.append(rend_heat)
                 else:
                     rend_heat=Heat_ut[i]/Components_value_fu_CHPS[i]
                     Rend_heat.append(rend_heat)
                     Overall_values.append(rend_heat)

            for i in range(int(len(CHP_tag))):
                rend_glo=Rend_ele[i]+Rend_heat[i]
                Rend_glo.append(rend_glo)
                Overall_values.append(rend_glo)

            for i in range(int(len(CHP_tag))):
                if Components_value_th_CHPS[i]==0:
                    beta=0
                    Beta.append(beta)
                    Beta_all.append(beta)
                    Overall_values.append(beta)
                else:
                    beta=(Th_diss[i]+ST_diss[i])/(Components_value_th_CHPS[i]+Components_value_st_CHPS[i])
                    Beta.append(beta)
                    Beta_all.append(beta)
                    Overall_values.append(beta)
            beta_avg=statistics.mean(Beta_all)
            Beta_all_week.append(beta_avg)
```

```
            print(Beta)



            for i in range(int(len(CHP_tag))):
                eta_rif_el=eta_el_rif(year_construction,fuel_type,CHP_tag)
                eta_rif_th=eta_th_rif(year_construction,fuel_type,CHP_tag)
                eta_rif_st=eta_th_rif(year_construction,fuel_type,CHP_tag)
                eta_rif_dg=eta_th_rif(year_construction,fuel_type,CHP_tag)
                Eta_rif_el.append(eta_rif_el)
                Eta_rif_th.append(eta_rif_th)
                Eta_rif_st.append(eta_rif_st)
                Eta_rif_dg.append(eta_rif_dg)
            print(Eta_rif_el)

            if E_el==0:
                Eta_rif_el=[eta_rif_el]*len(CHP_tag)
            if E_th==0:
                Eta_rif_th=[eta_rif_th]*len(CHP_tag)
            if E_st==0:
                Eta_rif_st=[eta_rif_st]*len(CHP_tag)

            Eta_rif_el_T=[]
            for i in range(int(len(year_construction))):
                # if fuel_type[i]=="G10" or fuel_type[i]=="G11" or fuel_type[i]=="G12":
                    # T_avg=input("Insert the yearly average temperature: ")
                    # if (T_avg[i])>15:
                        eta_rif_el_T=Eta_rif_el[i]+0.00369
                        Eta_rif_el_T.append(eta_rif_el_T)
                    # else:
                    #     eta_rif_el=eta_rif_el+0.001*(15-T_avg[i])
                    #     Eta_rif_el.append(eta_el_rif)

            print(Eta_rif_el_T)

            # V_avg=input("Insert the electric voltage: ")

            Eta_rif_el_V=[]
            for i in range(int(len(CHP_tag))):

                if V_avg[i]>=345000:
                    F_corr_ext=1
                    F_corr_int=0.976
```

```
                elif V_avg[i]<345000 and V_avg[i]>=200000:
                    F_corr_ext=0.972
                    F_corr_int=0.963
                elif V_avg[i]<200000 and V_avg[i]>=100000:
                    F_corr_ext=0.963
                    F_corr_int=0.951
                elif V_avg[i]<100000 and V_avg[i]>=50000:
                    F_corr_ext=0.952
                    F_corr_int=0.936
                elif V_avg[i]<50000 and V_avg[i]>=12000:
                    F_corr_ext=0.935
                    F_corr_int=0.914
                elif V_avg[i]<12000 and V_avg[i]>=450:
                    F_corr_ext=0.918
                    F_corr_int=0.891
                else:
                    F_corr_ext=0.888
                    F_corr_int=0.851
                     #chiedere a Luca
            Perc_aut=[]
            # min(E,prodotta dalla macchina),% elettrico immesso / elettrico prodotto, dove l'energia immessa e uguale al minimo valore fra energia elettrica prodotta dalla macchina e quella immessa (misurata da ENEL, contributo di tutte le macchine) rapporto fra minimo valore dell' energia immessa e prodotta, %=
            for i in range(int(len(CHP_tag))):
                if Components_value_el_CHPS[i]==0:
                    perc_aut=0
                    Perc_aut.append(perc_aut)
                else:
                    el_prod=float(Components_value_el_CHPS[i])
                    perc_aut=(min(el_prod,y_sum_elc_sold)/el_prod)
                    Perc_aut.append(perc_aut)

            Eta_rif_el_pes=[]
            Eta_std_el_risp=[]
            for i in range(int(len(CHP_tag))):
                eta_rif_el=eta_el_rif(year_construction,fuel_type,CHP_tag)
                eta_rif_th=eta_th_rif(year_construction,fuel_type,CHP_tag)
                eta_rif_st=eta_th_rif(year_construction,fuel_type,CHP_tag)
                eta_rif_dg=eta_th_rif(year_construction,fuel_type,CHP_tag)
                Eta_rif_el.append(eta_rif_el)
                Eta_rif_th.append(eta_rif_th)
                Eta_rif_st.append(eta_rif_st)
                Eta_rif_dg.append(eta_rif_dg)
```

```
        print(Eta_rif_el)

        if E_el==0:
            Eta_rif_el=[eta_rif_el]*len(CHP_tag)
        if E_th==0:
            Eta_rif_th=[eta_rif_th]*len(CHP_tag)
        if E_st==0:
            Eta_rif_st=[eta_rif_st]*len(CHP_tag)

        Eta_rif_el_T=[]
        for i in range(int(len(year_construction))):
            # if fuel_type[i]=="G10" or fuel_type[i]=="G11" or fuel_type[i]=="G12":
                # T_avg=input("Insert the yearly average temperature: ")
                # if (T_avg[i])>15:
                    eta_rif_el_T=Eta_rif_el[i]+0.00369
                    Eta_rif_el_T.append(eta_rif_el_T)
                # else:
                #     eta_rif_el=eta_rif_el+0.001*(15-T_avg[i])
                #     Eta_rif_el.append(eta_el_rif)

        print(Eta_rif_el_T)

        # V_avg=input("Insert the electric voltage: ")

        Eta_rif_el_V=[]
        for i in range(int(len(CHP_tag))):

            if V_avg[i]>=345000:
                F_corr_ext=1
                F_corr_int=0.976
            elif V_avg[i]<345000 and V_avg[i]>=200000:
                F_corr_ext=0.972
                F_corr_int=0.963
            elif V_avg[i]<200000 and V_avg[i]>=100000:
                F_corr_ext=0.963
                F_corr_int=0.951
            elif V_avg[i]<100000 and V_avg[i]>=50000:
                F_corr_ext=0.952
                F_corr_int=0.936
            elif V_avg[i]<50000 and V_avg[i]>=12000:
                F_corr_ext=0.935
                F_corr_int=0.914
            elif V_avg[i]<12000 and V_avg[i]>=450:
                F_corr_ext=0.918
                F_corr_int=0.891
            else:
                F_corr_ext=0.888
```

```
                    F_corr_int=0.851
                     #chiedere a Luca
            Perc_aut=[]
            # min(E,prodotta dalla macchina),% elettrico immesso / elettrico prodotto, dove l'energia immessa e uguale al minimo valore fra energia elettrica prodotta dalla macchina e quella immessa (misurata da ENEL, contributo di tutte le macchine) rapporto fra minimo valore dell' energia immessa e prodotta, %=
            for i in range(int(len(CHP_tag))):
                if Components_value_el_CHPS[i]==0:
                    perc_aut=0
                    Perc_aut.append(perc_aut)
                else:
                    el_prod=float(Components_value_el_CHPS[i])
                    perc_aut=(min(el_prod,y_sum_elc_sold)/el_prod)
                    Perc_aut.append(perc_aut)

            Eta_rif_el_pes=[]
            Eta_std_el_risp=[]
            for i in range(int(len(CHP_tag))):
                eta_rif_el_pes=Eta_rif_el_T[i]*((1-Perc_aut[i])*F_corr_ext+Perc_aut[i]*F_corr_int)
                eta_rif_el_risp=Eta_el_RISP[i]*((1-Perc_aut[i])*F_corr_ext+Perc_aut[i]*F_corr_int)#(minimo fra immessa e prodotta)/prodotta*F_ext+(1-minimo(minimo)
                Eta_rif_el_pes.append(eta_rif_el_pes)
                Eta_std_el_risp.append(eta_rif_el_risp)
                Overall_values.append(eta_rif_el_pes)
                Overall_values.append(eta_rif_el_risp)
            # print(Eta_rif_el_pes)
            # print(Eta_std_el_risp)

            for i in range(int(len(CHP_tag))):
                eta_rif_th=eta_rif_th
                Eta_rif_th.append(eta_rif_th)
            for i in range(int(len(CHP_tag))):
                if cond[i]=="Yes":
                  eta_rif_st=eta_rif_st+0.05
                  Eta_rif_st.append(eta_rif_st)
                else:
                  eta_rif_st=eta_rif_st+0.05
                  Eta_rif_st.append(eta_rif_st)

            Eta_rif_th_ref=[]
            for i in range(int(len(CHP_tag))):
                eta_rif_th=Eta_rif_th[i]*Components_value_th_CHPS[i]+Eta_rif_st[i]*Components_value_st_CHPS[i]
                Eta_rif_th_ref.append(eta_rif_th)
```

```
        Eta_rif_st_ref=[]
        for i in range(int(len(CHP_tag))):
            eta_rif_st=Components_value_th_CHPS[i]+Components_value_st_CHPS[i]
            Eta_rif_st_ref.append(eta_rif_st)


        Eta_rif_heat=[]

        for i in range(int(len(CHP_tag))):
             if Components_value_th_CHPS[i]==0 and Components_value_st_CHPS[i]==0:
                    eta_rif_heat=0
                    Eta_rif_heat.append(eta_rif_heat)
                    Overall_values.append(eta_rif_heat)
             else:
                    eta_rif_heat=Eta_rif_th_ref[i]/Eta_rif_st_ref[i]
                    Eta_rif_heat.append(eta_rif_heat)
                    Overall_values.append(eta_rif_heat)

        # print(Eta_rif_heat)






        for i in range(int(len(CHP_tag))):
            if Rend_glo[i]<eta_lim[i]:
                heat_CAR=Heat_ut[i]
                Heat_CAR.append(heat_CAR)
                Overall_values.append(heat_CAR)
            else:
                heat_CAR=Heat_ut[i]
                Heat_CAR.append(heat_CAR)
                Overall_values.append(heat_CAR)

        # print(Heat_CAR)

        # Components_value_el_CHPS=np.array(Components_value_el_CHPS)
        # Components_value_fu_CHPS=np.array(Components_value_fu_CHPS)



        for i in range(int(len(CHP_tag))):
            if Rend_glo[i]<eta_lim[i]:
                if Components_value_fu_CHPS[i]==0:
```

```
                el_CAR=0
                El_CAR.append(el_CAR)
                eta_el_CAR=0
                Eta_el_CAR.append(eta_el_CAR)
                Overall_values.append(el_CAR)
            else:
                eta_el_CHPS=Components_value_el_CHPS[i]/Components_value_fu_CHPS[i]
                Eta_el_CHPS.append(eta_el_CHPS)
                C_eff=Rend_ele[i]/(eta_lim[i]-Rend_ele[i])
                el_CAR=Heat_ut[i]*C_eff
                El_CAR.append(el_CAR)
                el_NON_CAR=Components_value_el_CHPS[i]-el_CAR
                El_NON_CAR.append(el_NON_CAR)
                eta_el_CAR=el_CAR/Components_value_fu_CHPS[i]
                Eta_el_CAR.append(eta_el_CAR)
                Overall_values.append(el_CAR)
        else:
            eta_el_CHPS=Components_value_el_CHPS[i]/Components_value_fu_CHPS[i]
            Eta_el_CHPS.append(eta_el_CHPS)
            el_CAR=Components_value_el_CHPS[i]
            El_CAR.append(el_CAR)
            el_NON_CAR=0
            El_NON_CAR.append(el_NON_CAR)
            Overall_values.append(el_CAR)
#   print(El_CAR)




for i in range(int(len(CHP_tag))):
    if Rend_glo[i]<eta_lim[i]:
        if Components_value_fu_CHPS[i]==0:
            fu_CAR=0
            Fu_CAR.append(fu_CAR)
            Overall_values.append(fu_CAR)
        else:
            fu_NON_CAR=El_NON_CAR[i]/Eta_el_CHPS[i]
            Fu_NON_CAR.append(fu_NON_CAR)
            fu_CAR=Components_value_fu_CHPS[i]-fu_NON_CAR
            Fu_CAR.append(fu_CAR)
            Overall_values.append(fu_CAR)
    else:
        fu_CAR=Components_value_fu_CHPS[i]
        Fu_CAR.append(fu_CAR)
        Overall_values.append(fu_CAR)

print(Fu_CAR)
```

```
        for i in range(int(len(CHP_tag))):
            if Fu_CAR[i]==0:
                eta_el_CAR=0
                eta_heat_CAR=0
                Eta_el_CAR.append(eta_el_CAR)
                Eta_heat_CAR.append(eta_heat_CAR)
            else:
                eta_el_CAR=El_CAR[i]/Fu_CAR[i]
                eta_heat_CAR=Heat_CAR[i]/Fu_CAR[i]
                Eta_el_CAR.append(eta_el_CAR)
                Eta_heat_CAR.append(eta_heat_CAR)
        print(Eta_el_CAR)
        print(Eta_heat_CAR)

        for i in range(int(len(CHP_tag))):
            if Components_value_el_CHPS[i]==0:
                eta_el_pes=0
                Eta_el_pes.append(eta_el_pes)
            else:
                eta_el_pes=Eta_el_CAR[i]/Eta_rif_el_pes[i]
                Eta_el_pes.append(eta_el_pes)
        print(Eta_el_pes)

        for i in range(int(len(CHP_tag))):
            if Components_value_el_CHPS[i]==0:
                eta_heat_pes=0
                Eta_heat_pes.append(eta_heat_pes)
            else:
                eta_heat_pes=Eta_heat_CAR[i]/Eta_rif_heat[i]
                Eta_heat_pes.append(eta_heat_pes)
        print(Eta_heat_pes)


        for i in range(int(len(CHP_tag))):
            if Eta_el_pes[i]==0 and Eta_heat_pes[i]==0:
                Pes=0
                PES.append(Pes)
                Overall_values.append(Pes)
            else:
                Pes=1-1/(Eta_el_pes[i]+Eta_heat_pes[i])
                print(Pes)
                PES.append(Pes)
                Overall_values.append(Pes)

        RISP_all=[]
        for i in range(int(len(CHP_tag))):
             if Components_value_fu_CHPS[i]==0:
```

```
                 Risp=0
                 RISP.append(Risp)
                 RISP_all.append(Risp)
                 Overall_values.append(Risp)
             else:
                 Risp=El_CAR[i]/Eta_std_el_risp[i]+Heat_CAR[i]/Eta_heat_RISP[i]-Fu_CAR[i]
                 RISP.append(Risp)
                 RISP_all.append(Risp)
                 Overall_values.append(Risp)
        RISP_avg=statistics.mean(RISP_all)
        RISP_all_week.append(RISP_avg)


        P_eq=[]
        for i in range(int(len(CHP_tag))):
            if PES[i]<0.1:
                print("No access to White Certificates")
                K=0
                cb_obt=const*RISP[i]*K
                Cb_obt.append(cb_obt)
            else:
                print("Access to White Certificates")
                if ans[i]=="No": #c'è già impianto, anche se le macchine sono diverse, k=1, se spostato, dopo 12 anni cambiano macchinari, rifacimento k=1, se si pacca motore ammordamento
                    K=1
                else: #euqivalente prato verde
                    h_eq=Components_value_el_CHPS[i]/Counter[i] # cogenerazione totale, ore cal
                    p_eq=El_CAR[i]/h_eq #P_ #energia elettrica cogenerazione CAR, p car el
                    P_eq.append(p_eq)
                    K=k_calculation(P_eq,n_col)
                cb_obt=const*RISP[i]*K/1000
                Cb_obt.append(cb_obt)
            Overall_values.append(cb_obt)
        # print(Cb_obt)

        for i in range(int(len(CHP_tag))):
            euro_obt=Cb_obt[i]*CB_val
            Euro_obt.append(euro_obt)
            Overall_values.append(euro_obt)
        # print(Euro_obt)

        for i in range(int(len(CHP_tag))):
            if Components_value_el_CHPS[i]==0:
                ccb=0
                Ccb.append(ccb)
```

```
                        Overall_values.append(ccb)
                    else:
                        ccb=Euro_obt[i]/Components_value_el_CHPS[i]
                        Ccb.append(ccb)
                        Overall_values.append(ccb)#sostituire con valore energia elettrica prodotta
                print(Ccb)
                # for i in range(int(len(CHP_tag))):
                #     new_maintenance=Old_maintenance[i]-Ccb[i]
                #     New_maintenance.append(new_maintenance)
                #     Overall_values.append(new_maintenance)
                # print(New_maintenance)
                    # print(Ccb)
                    # for i in range(int(len(CHP_tag))):
                    #     new_maint=old_maintenance[i]-Ccb[i]
                    #     Overall_values.append(new_maint)
                for i in range(int(len(CHP_tag))):
                    Comp.append(Overall_values[i::int(len(CHP_tag))])


                for k in range(int(len(CHP_tag))):
                  file_name= str(netlist_only_names[week])+'_'+str(CHP_tag[k])+'_'+str(k+1)+"_risultati_iterazioni.csv"
                  with open(file_name,"a") as f:
                        writer = csv.writer(f, delimiter=";", lineterminator='\n')
                        writer.writerow(Comp[k])

        Total_el_CHPS=sum(Components_value_el_CHPS)
        Total_th_CHPS=sum(Components_value_th_CHPS)
        Total_st_CHPS=sum(Components_value_st_CHPS)
        Total_fu_CHPS=sum(Components_value_fu_CHPS)
        Total_heat_ut=sum(Heat_ut)
        Total_beta=sum(Beta)

        if Total_fu_CHPS!=0:
            Total_rend_ele=Total_el_CHPS/Total_fu_CHPS
            Total_rend_heat=(Total_th_CHPS+Total_st_CHPS)/(Total_fu_CHPS)
        else:
            Total_rend_ele=0
            Total_rend_heat=0

        if Total_rend_ele + Total_rend_heat <=0.75:
            if Total_fu_CHPS==0:
                Total_heat_CAR=0
                Total_el_CAR=0
                Total_fu_CAR=0
                Total_eta_el_CAR=0
```

```
                Total_heat_CAR=0
            else:
                Total_heat_CAR=Total_heat_ut
                Total_C_eff=(Total_rend_ele/(0.75-Total_rend_ele))
                Total_el_CAR=Total_el_CHPS*Total_C_eff
                Total_el_non_CAR=Total_el_CHPS-Total_el_CAR
                Total_fu_non_CAR=Total_el_non_CAR/Total_rend_ele
                Total_fu_CAR=Total_fu_CHPS-Total_fu_non_CAR
                Total_eta_el_CAR=Total_el_CAR/Total_fu_CAR
                Total_heat_CAR=Total_heat_ut/Total_fu_CAR
        else:
            Total_heat_CAR=Total_heat_ut
            Total_el_CAR=Total_el_CHPS
            Total_fu_CAR=Total_fu_CHPS
            Total_eta_el_CAR=Total_el_CAR/Total_fu_CAR
            Total_heat_CAR=Total_heat_ut/Total_fu_CAR

        Total_eta_el_RISP=statistics.mean(Eta_std_el_risp)
        Total_eta_heat_RISP=statistics.mean(Eta_heat_RISP)
        Total_eta_el_PES=statistics.mean(Eta_rif_el_pes)
        Total_eta_heat_PES=statistics.mean(Eta_rif_heat)

        Total_PES=1-1/(Total_eta_el_CAR/Total_eta_el_PES+Total_heat_CAR/Total_eta_heat_PES)
        Total_RISP=Total_el_CAR/Total_eta_el_RISP+Total_heat_CAR/Total_eta_heat_RISP-Total_fu_CAR

        if Total_PES==0:
            Total_CB=0
            Total_Euro_CB=0
            Total_Euro_CB_sp=0
        else:
            Total_CB=Total_RISP*K*const/1000
            Total_Euro_CB=Total_CB*CB_val
            Total_Euro_CB_sp=Total_Euro_CB/Total_el_CHPS
        print(Total_Euro_CB_sp)


        for i in range(int(len(CHP_tag))):
            new_maintenance=Old_maintenance[i]-Total_Euro_CB_sp
            New_maintenance.append(new_maintenance)
        print(New_maintenance)

        os.chdir(main_path)

        return (New_maintenance,Overall_values,Total_beta,Total_RISP)
```

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