UCLouvain

École polytechnique de Louvain

An economic and primary energy savings analysis of 2-spool humidified mGTs for domestic applications

Author: **Alexandre WINAND**
Supervisor: **Francesco CONTINO**
Readers: **Yann BARTOSIEWICZ, Angelos GAITANIS**
Academic year 2022–2023
Master [120] in Electro-mechanical Engineering

Acknowledgements

This work brings to an end my five years as an Electro-mechanical Engineering student at UCLouvain. First, I would like to thank my thesis supervisor, Professor Francesco Contino, for his availability and guidance throughout the year. His invaluable insights and thoughtful advice have been crucial in shaping the trajectory of my research. His in-depth questions and profound reflections have consistently motivated me to delve deeper into my work, enabling me to acquire a more complete understanding of the subject.

I would like to extend my thanks to Professor Yann Bartosiewicz for his attentive consideration of my work and for his inspiring course of Thermal cycles, which led me to choose a thesis in this field.

I would like to express my deepest gratitude to Aggelos Gaitanis for his ongoing help and support throughout this year. I am very grateful for our discussions and meetings, for his valuable comments, suggestions and expertise, and for his patience in answering my many questions.

Finally, I would like to acknowledge my parents and family for their moral support and interest in my work, as well as their continuous encouragement during all these years at UCLouvain.

Table of Contents

List of Tables

List of Figures

Acronyms

AHAT	Advanced Humid Air Turbine
CHP	Combined Heat and Power
DES	Decentralized Energy System
EU	European Union
GC	Green Certificate
HRSG	Heat Recovery Steam Generator
ICE	Internal Combustion Engine
IRR	Internal Rate of Return
mGT	Micro Gas Turbine
mHAT	Micro Humid Gas Turbine
NPV	Net Present Value
PBT	PayBack Time
PES	Primary Energy Savings
REVAP	REgenerative EVAPoration
STIG	STeam-Injected Gas turbine
TIT	Turbine Inlet Temperature
WAC	Water Atomizing Inlet Air Cooling

Chapter 1

Introduction

Europe has entered a new era defined by growing global concerns over the environmental impact of conventional energy practices and an urgent need towards sustainable development. The world needs innovative and efficient energy solutions. The effects of traditional fossil fuel consumption and the challenges posed by climate change and finite resource depletion lead to a shift towards cleaner and more diverisified energy resources. This shift is imperative for mitigating environmental degradation and ensuring a secure energy future for humanity.

The aim of sustainable development requires to rethink how energy is produced and distributed. For a long time, the usual way to create energy was in big power plants and this energy was sent and distributed to the final consumers over long distances and several electricity networks (transmission and distribution). This solution is not the most efficient, it implies big power losses through the transport and distribution networks. These reasons coupled with the constant growing number of renewable energy systems have led to a shift towards making energy in smaller, local systems. These new systems, called Distributed or Decentralized Energy Systems (DES), are great because they use different types of energy sources and reduce the dependence on big power plants that use fossil fuels. The difference between the two systems are depicted in Fig. 1.1. In addition to reducing losses, these systems offer the following advantages: the risk of blackouts is reduced and the energy system is more flexible. In short, decentralized energy systems, including renewable energy setups and combined heat and power (CHP) systems, are a smart move towards a more sustainable energy future.

The traditional CHP system used in decentralized energy systems is the Internal Combustion Engine (ICE). For a long time, it has been preferred to the micro gas turbine (mGT) because of its higer electrical efficiency. But recently, mGTs have attracted increasing attention for their potential role in distributed energy systems. These compact gas turbines operate on the fundamental principles of open-cycle gas turbines. This involves a process wherein air is compressed, heated

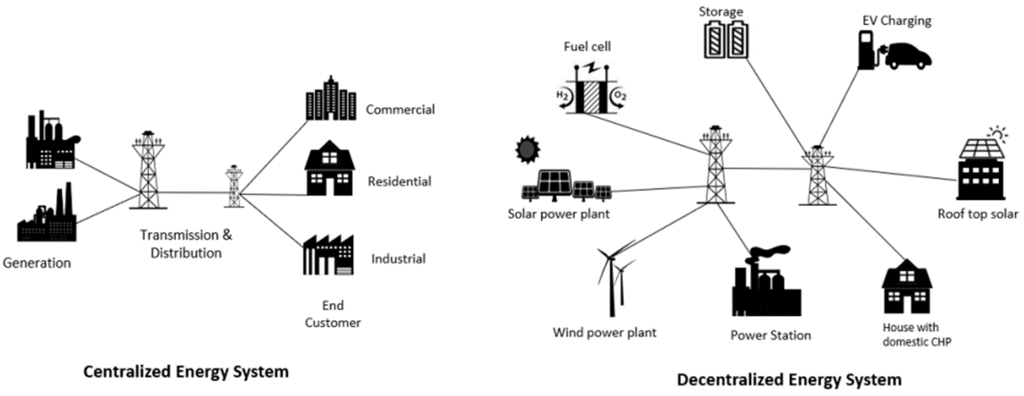

Figure 1.1: Centralized and Decentralized Energy Systems

through combustion with added fuel, and then expanded in a turbine to generate power. The electrical efficiency of mGTs has been for a long time worse than the one of ICEs but new technologies have been developed and mGTs can now compete with traditional ICEs. mGTs promise also great adaptability to diverse fuels, lower maintenance costs, suitability for various applications, which include standby power, mobile sources, energy generation, and microgrid integration.

One solution to increase the electrical efficiency of mGTs is water injection in the cycle of the gas turbine. Most CHP units are heat-driven engines which means that they run following the heat demand of the consumer. The produced electricity is used on site and the excess electricity is sold to the grid. If the electricity demand is too high compared to the production, electricity is bought from the grid. To avoid big losses and to keep good efficiencies and the system profitable, if the heat demand is too low, the engine is shut down and electricity is bought from the grid. This can be avoided thanks to water injection. If the heat demand is low, water is injected into the cycle of the gas turbine. This water is heated thanks to the exhaust gases and this helps to increase the electrical efficiency. This allows to decouple the heat and electricity demands.

The remarkable flexibility of mGTs, demonstrated by their capacity to operate on a range of fuels such as natural gas, hydrogen, and biomass, underscores their potential in addressing the pressing challenges associated with climate change and resource depletion. Their application in microgrids and combined heat and power systems further shows that they could play a crucial role in the transition towards sustainable energy solutions.

This master thesis aims to assess the profitability of humidified gas turbines aswell as their primary energy savings in domestic applications. The objective is to determine the economic performance of a humidified mGT, by taking the Aurelia A400 as a reference, and compare it to dry mGTs and ICEs. Such a study has already been performed by Marina Montero Carrero on a smaller and less efficient humidified mGT, a modified Turbec T100 with a saturation tower [1]. Since her work proves the economic infeasibility of this technology, I wanted to compete the ICE technologies more effectively by using the most efficient mGT in the market.

The chapter 2 provides a review of literature that aims to show the current state of the art of mGTs aswell as the different types of water injection and their limits. The next chapter explains the methodology used to produce the results. In the chapter 4, the economic analysis is performed in a generic point of view. Several heat and electricity demands from grouped private households in Brussels, Madrid and Riga are studied with a wide variety of gas and electricity prices in order to show the conditions that give advantage to these cogeneration technologies. A sensitivity analysis is also performed in order to see the impact of important parameters in the model. In the last chapter, the specific cases of two countries, Spain and Belgium, are studied. These countries have different types of cogeneration policies and subsidies. The goal of this part is to see how these subsidies can help the cogeneration units to perform and to achieve economic feasibility.

Chapter 2

Literature review

The aim of this chapter is to explain the previous work done about mGTs and humidified mGTs. First, the current state of mGTs is described with their role and applications as well as the challenges and opportunities they face. Then, the advantages of humidify the gas cycle is explained in more details before the different types of water injection are depicted with their limitations. Ultimately, a description of 2-spools mGTs is given.

2.1 Micro gas turbines

Micro gas turbines have a power output range up to 500 kW [2] and operate on the same principle as open-cycle gas turbines. The setup includes a compressor, a combustion chamber, and a turbine which form a basic Brayton cycle [3]. The air is compressed by the compressor, then mixed with fuel in the combustion chamber, and ultimately expanded in the turbine to generate power. The optimum rotational speed is between 60,000 to 120,000 rpm for typical power ratings. mGTs have a low pressure ratio between 2 to 5, and the turbine inlet temperature can go up to 1000°C [4].

Permanent magnet generators are used to compensate for the high varying rotational speed of mGTs. They generate high-frequency alternating current which must be first rectified and then converted into alternating current at the supply frequency [5].

The net electrical efficiency of basic Brayton cycle micro gas turbines is usually low due to the small cycle pressure ratio. Thus, a recuperator is added to the turbine in order to improve the overall efficiency. This recuperator is an air-to-air heat exchanger that preheats the compressed air using exhaust gases, increasing efficiency [2]. In cogeneration mode, the remaining heat in the exhaust gases is transferred through another heat exchanger for heating or cooling applications.

The complete cycle is showed in Fig. 2.1 with the recuperator and an economizer which is used in cogeneration mode.

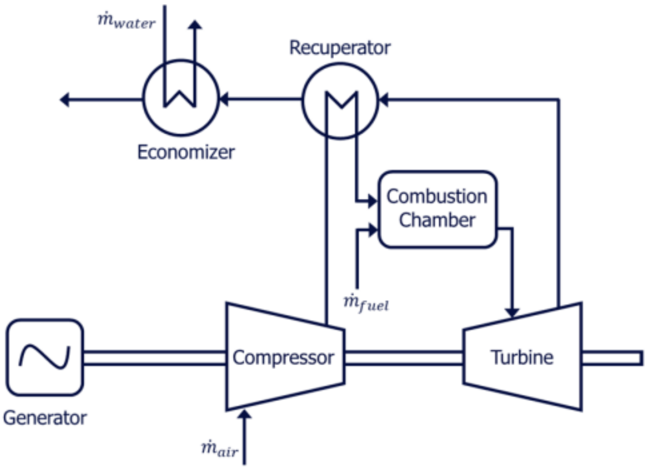

Figure 2.1: Micro gas turbine's cycle : the recuperator is used to preheat the air with the heat from the exhaust gases and the economizer is used for cogeneration applications

2.1.1 Historical developments and technological advancements

The development of mGTs starts in the early 20th century, where the concept of gas turbines first emerged [2]. However, it was only in the late 1950s that the development of mGTs gained momentum, driven by the automotive industry's interest in utilizing them as alternatives to reciprocating piston engines [4]. Early mGTs were primarily designed for automotive engines and auxiliary power supply devices for military products [2]. During this period, significant efforts were made to improve the overall structure and performance of mGTs.

In the 1980s, the integration of permanent magnets as high-speed generators marked a crucial advancement in mGT technology [4]. This innovation eliminated the need for a gearbox and coupling, resulting in an increased efficiency, a reduced size, and weight. As a result, mGTs became more suitable for commercial applications, offering advantages such as small size, light weight, high reliability, and low maintenance.

The introduction of recuperators at the end of the 20th century has revolutionized the efficiency of mGTs [2]. They allowed the recovery of waste heat, significantly increasing the overall thermal efficiency of mGTs by approximately 5 to 10% [2]. This development made mGTs more attractive for distributed energy systems, where cogeneration has become vital for using waste heat to produce energy more efficiently.

The latest mGTs have achieved higher thermal efficiency, ranging from approximately 25 to 35% [2]. These advances in efficiency have been made possible through the utilization of high-temperature materials and improved combustion technologies. Companies such as Capstone, Elliott Energy Systems, Aurelia, Turbec, AlliedSignal, Browman Power, and ABB Distributed Generation have played major roles in introducing commercial mGT products with varying power outputs for microgrid installations and hybrid vehicles [4].

Elliott's TA series mGTs, for example, utilize oil-lubricated bearings and offer power ratings ranging from 45 kW to 200 kW [6]. Turbec's T100 mGT has achieved a higher turbine inlet temperature of around 950 °C and an electrical efficiency of approximately 30% [7]. Other mGTs, like PowerWorks PW70 and FlexTurbine GT333s, have demonstrated high efficiencies through proper overall design and component arrangements such as double-shaft [2].

Despite the significant progress in mGT technology, challenges remain in terms of increasing operational flexibility, reducing operating costs, and improving reliability and availability while mitigating environmental impact. The ongoing research and development in mGTs aim to simplify their structure, increase turbine inlet temperature, and employ lightweight materials to enhance their compactness and flexibility for diverse applications [5].

2.1.2 Role and applications of micro gas turbines

Micro gas turbines have found a diverse range of applications in modern energy systems, making them a versatile and valuable component of distributed energy generation. Their power output typically ranges now up to 500 kW, making them suitable for various small-scale and decentralized energy applications [2].

One of the main roles of mGTs is in decentralized energy systems, where they are considered key elements for efficient and on-demand power supply. DES allows customers to choose and install different energy sources to meet their specific power needs. Within DES, mGTs play an essential role in CHP systems, commonly employed in distributed generation settings [8]. These systems simultaneously generate electricity and capture waste heat for local use which improves overall energy efficiency when compared to traditional centralized power generation.

mGTs can operate on different fuels, including natural gas, liquefied petroleum gas (LPG), hydrogen, and biomass-derived fuels [5], making them an attractive choice for decentralized energy systems with varying fuel availability.

Beyond CHP applications, mGTs are used for many other roles. They serve as standby power sources, ensuring reliable power supply during grid outages or emergency situations. mGTs are also employed as mobile power sources, providing energy for off-grid and remote locations, and as range extenders for electric vehicles, enhancing the vehicles' mileage and operational flexibility [2, 5].

The integration of mGTs with renewable energy sources has opened new possibilities for sustainable power generation. In solar power generation, mGTs are used as a backup system when no or few electricity is produced from solar, allowing for more stable and reliable power supply regardless of weather conditions [4]. Gas turbine-fuel cell systems represent another application, where mGTs can be combined with high-temperature fuel cells to enhance system efficiency [9].

Concentrated solar power systems have also adopted mGTs in order to provide extended operations after sunset. This technology has been implemented in various facilities worldwide, showcasing the maturity and potential of mGTs in the renewable energy landscape [10].

Furthermore, mGTs are being explored for various industrial processes, where their compact size, low noise levels, and low emissions make them well-suited for distributed energy applications within factories and manufacturing facilities [2].

2.1.3 Challenges and opportunities

While mGTs offer lots of advantages and promise to be a key player in the transition to sustainable energy systems, they also face several challenges.

One challenge for mGTs lies in increasing their operational flexibility. Compared to larger gas turbines, mGTs have lower cycle pressure ratios, higher shaft speeds, and smaller compressor and turbine stages, requiring different optimization approaches. Achieving high efficiency at part-load conditions remains a significant challenge. A poor matching between heat and power demands can also lead to reduced overall performance. To overcome this, further research is needed to develop innovative control strategies and operational schemes that can optimize mGT performance under varying load conditions [4].

Improving the overall efficiency of mGT cycles is another crucial area of focus. Improving the different components, such as enhancing the performance of compressors, recuperators, and combustion chambers, can significantly contribute to increasing mGT efficiency [2].

In terms of opportunities, continuous development in mGT technology provides a pathway to overcoming these challenges. Incorporating lightweight materials and improving the Turbine Inlet Temperature (TIT) can enhance overall efficiency and reduce component loss [2]. The exploration of hydrogen-driven mGTs holds the promise of achieving zero carbon dioxide emissions, aligning with the global efforts towards decarbonization [2].

2.1.4 mGTs in the energy transition

The increasing focus across the world on reducing greenhouse gas emissions and achieving ambitious energy targets has led to more sustainable energy systems. Centralized power generation is no longer favored due to its environmental impact. Instead, DES is becoming more popular, offering a more flexible and eco-friendly alternative. Within DES, mGTs play a crucial role in providing decentralized energy solutions that align with the energy target goals [4].

DES allows customers to choose and install different energy sources, enabling a mix of gas turbines, fuel cells, diesel/gas engines, solar panels, and wind turbines, among others. The advantages of DES include reduced CO_2 emissions, long-term cost savings, and decreased energy losses during transmission [11]. By improving voltage profiles and power quality, DES also reduces power losses and unnecessary flows in the distribution network [12].

As the European Union (EU) shifts towards a more decentralized power and heat generation structure, renewable energy sources become more accessible and are better integrated into the energy mix. The availability of renewable resources and the need to reduce carbon footprints are very favorable for achieving this transition. mGTs are a key component of DES and they offer a stable, efficient energy production system near consumption points. They provide a reliable, cost-effective, and decentralized solution for electricity and heat production which makes them a favorable option for powering private households and public buildings. Those decentralized solutions, including mGTs and renewable energy sources, create networks called micro grids [4].

As the EU and other regions strive to achieve ambitious energy targets, mGTs are considered a transitional technology that can facilitate the transition towards a greener and more sustainable energy future. Their high efficiency, low emissions, and adaptability to various fuel sources make them an attractive option for decentralized power generation, leading towards a low-carbon energy scheme.

2.2 Advantages of humid air injection into mGTs

The advantages of injecting water into a micro gas turbine are multiple [13]. First, it will increase the power output. If the water is injected after the compressor, the humidification increases the mass flow rate through the turbine, resulting in a higher specific power output. The turbine power rises while the compressor work remains constant, leading to an increased overall efficiency. The efficiency is also increased because the heat capacity of the working fluid is increased. When water is injected after the compressor and before the recuperator, the working fluid recover more heat from the exhaust gases. The humidification lowers the cold inlet temperature of the recuperator, increasing the temperature difference and enabling higher heat recovery. This, in turn, improves the overall efficiency. Finally, humidifying the gas cycle facilitates the recovery of waste heat. By utilizing a part of the remaining heat in the exhaust gases to preheat water or produce steam, the waste heat can be harnessed, leading to further efficiency improvements.

The injection of water into gas turbines has other advantages than an increase power output and a higher efficiency. It also helps to reduce NOx emissions in a significant way. The addition of water during combustion lowers the flame temperature, reducing the formation of thermal NOx. This happens because the water in the air increases the heat capacity of the combustion air. The presence of water also affects the concentrations of certain species involved in NOx formation. As a result, humidified cycles contribute to significantly reducing NOx emissions. But, for mGTs, this is more a side effect because mGTs have already smaller NOx emissions.

2.3 Different types of water injection

Three main possibilities exist to inject water into gas turbines [13], they are all represented in Fig. 2.2 :

- water can be injected in a liquid state that will fully evaporate
- water can be injected in a steam state
- water can be injected thanks to liquid water in a saturation tower with a water recovery loop

2.3.1 Liquid water injection

Liquid water can be injected at different moments in the gas cycle :

- Before the compressor
- Between the compressor and the recuperator
- In the combustion chamber

Liquid water injection before the compressor

This option for liquid water injection focuses on reducing the work done by the compressor by injecting water before the compressor. This option differs from the main idea of humidified gas turbine which is increasing the mass flow rate in the turbine in order to increase the power output [13].

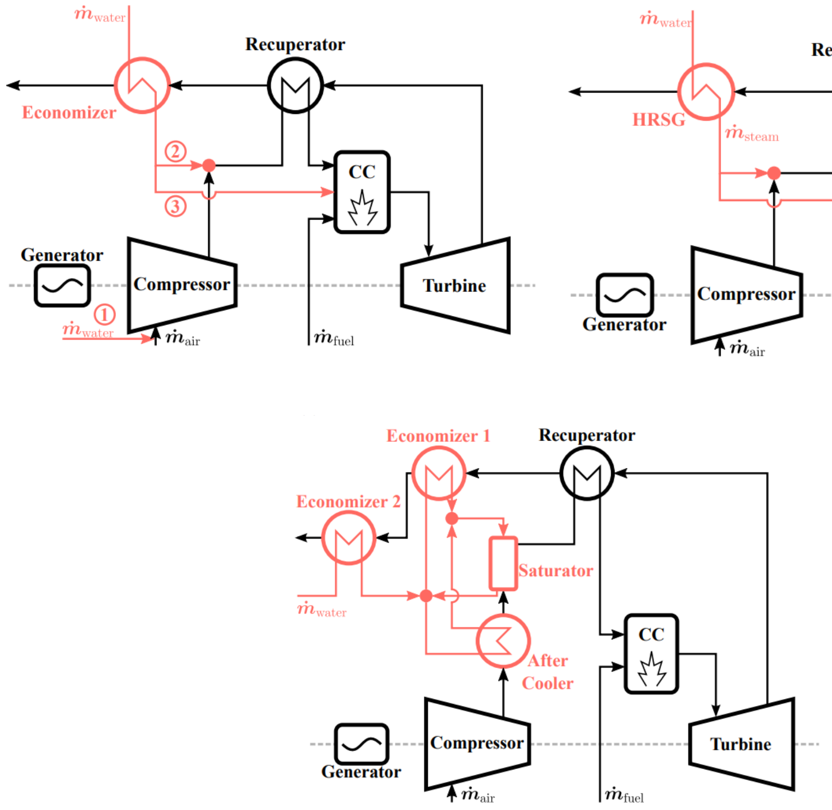

Figure 2.2: Different humidification cycles : on the top left, liquid water that can be injected either before the compressor, between the compressor and the recuperator and in the combustion chamber. On the top right : steam injection either between the compressor and the recuperator or in the combustion chamber. On the bottom : water is injected from a saturation tower with a water recovery loop

Water introduction can be realize in two ways, each with a different purpose : inlet air cooling and wet compression. Inlet air cooling aims to lower the compressor inlet temperature, reducing its work. Water Atomizing Inlet Air Cooling (WAC) and inlet air fogging are two methods used for inlet air cooling. These techniques are effective in hot and dry climates, augmenting mGT power output on hot days. In the other hand, wet compression provides higher efficiency improvement compared to simple inlet air cooling. Wet compression involves introducing liquid droplets into the compressor to cool the air during compression and reduce the work done by the compressor. However, the use of liquid droplets can lead to the erosion of the blades of the compressor over time [13].

These two techniques increase efficiency and specific power production of mGTs. Unfortunately, these alternative methods do not facilitate waste heat recovery from the exhaust gases. But, they can offer flexibility to optimize gas turbine performance based on specific requirements and constraints, particularly in hot and dry regions [13].

Different teams of searchers have designed and tested those techniques such as Williamson et al. who used C60 Capstone mGTs equipped with an evaporative cooler [14], Renzi et al. who tested the inlet air fogging method on T100 mGT [15]. However, none of these solutions are developed commercially [13].

Liquid water injection between the compressor and the recuperator

The second option is to inject liquid water between the compressor and the recuperator [13]. This water can be preheated and it aims to cool down the air after the compressor thanks to the evaporation of injected water. The evaporation process extracts heat from the compressed air resulting in lowering its temperature. This method allows for higher heat recovery from the recuperator and is considered the optimal approach for waste heat recovery and electrical efficiency increase for a Turbec T100 through humidification [16].

To fully exploit the potential of evaporative aftercooling, a larger amount of water needs to be injected than what actually evaporates in the hot compressed air. In this case, liquid water droplets would enter the recuperator [17]. This has for effect to increase the heat capacity of the working fluid and, thus, it increases significantly the heat exchange in the system. But this heat exchange is limited by the area of the heat exchanger, a new, larger recuperator is, thus needed to deal with this increased heat exchange.

Restricting the injected water amount to match a relative humidity of 100% after the compressor still leads to efficiency and power output increases. However, injecting steam into the recuperator inlet yields a higher increase in efficiency and power output compared to restricting the water injection amount [18].

Liquid water injection in the combustion chamber

The third option is to inject water directly in the combustion chamber. This is used in large-scale gas turbines in order to reduce peak temperatures and NOx production. However, this latter is not of significant interest for mGT applications, as mGT combustors already have low NOx exhaust emissions [13].

When water is introduced in the combustion chamber instead of between the compressor and the recuperator, the electrical power output of the mGT is enhanced. However, the effect of increasing the heat recovery is lost and the electrical efficiency is reduced. This goes with an increase in fuel consumption because water needs to evaporate [18].

Injecting water into the combustion chamber offers a significant advantage, as it maintains or even increases the available heat for thermal power production when compared to the dry cycle. This advantage is not observed when water is injected before the recuperator [18].

2.3.2 Steam injection

Water can also be injected in the state of steam. When steam is injected, it is always done behind the compressor in mGT cycles, either in front of the recuperator or in the combustion chamber. Steam is not injected in front of the compressor as it is ineffective because the work done by the compressor would increase due to a higher inlet air temperature resulting of the steam state of the water [13].

For the humidification through steam, a Heat Recovery Steam Generator (HRSG) uses heat from the exhaust gases leaving the recuperator to auto-raise steam. Steam injection before the recuperator leads to the highest increase in electrical efficiency compared to liquid water injection [13].

Experimental studies have demonstrated that steam injection leads to stable operation, to an increase of the efficiency, and to reduced NOx emissions. Economic analyses indicate that steam injection in mGTs can be profitable, with minimum operating hours required for profitability (at least 5,000 hours at dry operation and minimum 1,500 hours at wet operation as Delattin et al. showed for a T100 converted into a STeam-Injected Gas turbine (STIG) [19]). It was also proved that steam injection should be combined with dry CHP operation mode when there is a heat demand to be profitable [13].

2.3.3 mGTs with a saturation tower

The third way of humidifying the mGT cycle is by using a saturation tower. This tower is placed between the compressor outlet and the recuperator inlet in order to achieve a higher efficiency thanks to extra heat recovery from the exhaust gases. By adding a saturation tower, the mGT is converted into a micro Humid Air Turbine (mHAT) [13].

The water is injected into the saturation tower to humidify the air, and a small fraction of this water evaporates in the compressed air. Then, the excess water is heated in a heat recovery loop using exhaust gases. By humidifiying gas turbines cycle with a saturation tower, less exergy is destructed than with steam injection and it is, thus, more favorable [13].

The concept of humidification with a saturation tower was first introduced by Rao in the 80s on large gas turbines, leading to the development of the humid air turbine cycle [20]. The mHAT cycle shows remarkable increases in efficiency and specific work. Experimental tests on mHAT systems have shown increased power output and electrical efficiency [17].

The mHAT cycle has the highest potential for humidified mGT cycles as it offers an operational flexibility and it reduces the capital costs compared to traditional mGTs. From economic analysis, it is suggested that the mHAT can be financially attractive for distributed CHP generation [21]. Exotic humidified cycles with saturation tower, such as AHAT (Advanced Humid Air Turbine : expansion happens below the atmospheric pressure) and REVAP (REgenerative EVAPoration), exist but are less likely to be further developed due to their complexity and their higher costs [22].

2.3.4 Limitations of the humidified mGT

The first limitation that can appear is the turbo-machinery behaviour. When water is injected after the compressor, the mass flow rates in the compressor and in the tubrine are different which means that the shaft mechanical stress is increased [13]. But experiments have shown that this is not a big deal [23, 24]. This mass flow rate difference leads to a shift of the compressor operating point to the surge limit. The gas turbine is choked and the maximal flow rate through the turbine is limited by the choking constant.

Another limitation of humidifying the gas turbine cycle is the cycle layout limitations [13]. Additional pressure drops can happen and since the pressure ratio is already small, even small pressure drops have a significant impact on the performances of the mGTs. The additional volume is also an important factor. During shutdown and load shift, if the volume added exceeds the critical volume for the compressor, it will lead to surge. With the new components added to the cycle, the control system and the procedures will become more complex and the mGT will lose its main advantage of being easy and simple.

The injection of water has also an impact on the combustion stability. The presence of water can affect the flame stability which can lead to an incomplete combustion and more CO emissions [13].

The water injected has a big impact on the material and the recuperator. It can cause corrosion problems, especially on the recuperator. This can lead to a decrease of the lifetime of the mGT [13].

Finally, feedwater requirements can be mandatory, water should be very clean, especially when water is injected in liquid state or in steam state. It is less important in the case of a saturation tower since only a portion of the water evaporates [13].

2.4 2-spool mGTs

2-spool mGTs are mGTs with two levels of compression and two levels of expansion. Malkämaki et al. designed a prototype of a 400 $\mathrm{kW_e}$ 2-spool recuperated and intercooled gas turbine [25].

The design of this mGT includes two main shafts : one with the first compression and the final expansion and the other one with the final compression and the first expansion. Those two spools have identical nominal speeds and the two generators are identical as well. The low pressure and the high pressure spools have been designed to produce the same nominal power. The two spools have an independent speed control in order to simplify the start-up and the control of the shafts. The identical generators implies a cost reduction. The maximum TIT is set to 1,350 K. The pressure ratio has to be kept below five. The degree of recuperation of the turbine is around 0.9.

A performance analysis has been performed by Malkämaki et al. [26]. The optimum ratio pressure for this turbine is below five because the temperature at the inlet of the turbine is moderate and a higher pressure ratio would decrease the useful amount of heat available after the turbine. The performance analysis shows that a higher pressure ratio would be impossible as the rotational speed would be too high. A higher efficiency is obtained with a higher TIT. Also, if the degree of recuperation decreases, then the optimum pressure ratio depends on the TIT.

The degree of recuperation plays an important role. With the highest possible degree of recuperation, the best efficiency is obtained with the highest TIT and the lowest pressure ratio. But with the lowest possible degree of recuperation, the best efficiency is obtained with the highest TIT and the highest pressure ratio. Eventually, the optimum operating point is the one with the highest TIT and the highest degree of recuperation.

2.5 Conclusion

In conclusion, this literature review highlights the significant progress in micro gas turbine technology, driven by companies like Capstone, Elliott Energy Systems, and others. These mGTs have found applications in distributed energy systems, CHP systems. Humidification of mGTs through water or steam injection offers advantages such as increased power output, improved efficiency, and reduced NOx emissions. However, challenges remain, including operational flexibility and optimizing efficiency at part load conditions. The integration of mGTs with renewable energy sources presents new opportunities for sustainable power generation. Additionally, 2-spool mGTs have been explored as a promising option for improved performance. Despite certain limitations, mGTs are seen as a transitional technology that can contribute to a greener and more sustainable energy future.

Chapter 3

Methodology

This chapter describes the methodology used in this work as well as the different metrics used to measure the performances of all technologies. First, the three technologies under study are presented and the humidification cyle of the Aurelia A400 is described. Then, the method for sizing the heat and electricity demands for each European city studied in the thesis is explained. Subsequently, the different working principles for each technology are characterized. Ultimately, the various metrics are depicted : the Primary Energy Savings (PES), the Net Present Value (NPV), the Internal Rate of Return (IRR) and the PayBack Time (PBT).

3.1 The three studied technologies

In this master thesis, three technologies are studied and compared : the 2-spool humidified micro gas turbine (Aurelia A400), a 2-spool micro gas turbine and an internal combustion engine. All technologies are CHP which means they all produce heat and electricity at the same time.

The ICE units under study are the 2G Agenitor 406 [27] which uses natural gas and the 2G Agenitor 408 [28] which uses biogas. Since these two units have a nominal electrical power output of $250\,\mathrm{kW_e}$ and $360\,\mathrm{kW_e}$ respectively, the electrical and thermal efficiencies and the thermal and electrical power outputs of these two ICEs have been rescaled to reach a nominal electrical power output of $400\,\mathrm{kW_e}$ in order to have a consistent comparison and analysis with the dry mGT and the humidified mGT under study.

The nominal thermal power of the 2G Agenitor 406 is $422.4\,\mathrm{kW_{th}}$, its nominal electrical efficiency is 42.5% and its nominal thermal efficiency is 44.9%. The nominal thermal power of the 2G Agenitor 408 is $393\,\mathrm{kW_{th}}$, its nominal electrical efficiency is 42.5% and its nominal thermal efficiency is 41.8%.

The mGT used in this thesis is a 2-spool micro gas turbine, it is the Aurelia

A400 without the wet part load mode. For both fuels, the part load efficiency is better than the full load efficiency which is a design choice from the manufacturer and at part load, the effectiveness of the recuperator increases which also assists in the increase of the electrical efficiency. The curves of efficiencies and power outputs of both mGTs come from a model developed by the Thermodynamics and Fluid Mechanics division of UCLouvain using the methodologies described by Aggelos Gaitanis et al. [29].

The nominal thermal power of the mGT using natural gas is 543.5 $\mathrm{kW_{th}}$, its nominal electrical efficiency is 39.64% and its nominal thermal efficiency is 53.84%. The nominal thermal power of the mGT using biogas is 543.5 $\mathrm{kW_{th}}$, its nominal electrical efficiency is 39.73% and its nominal thermal efficiency is 53.55%.

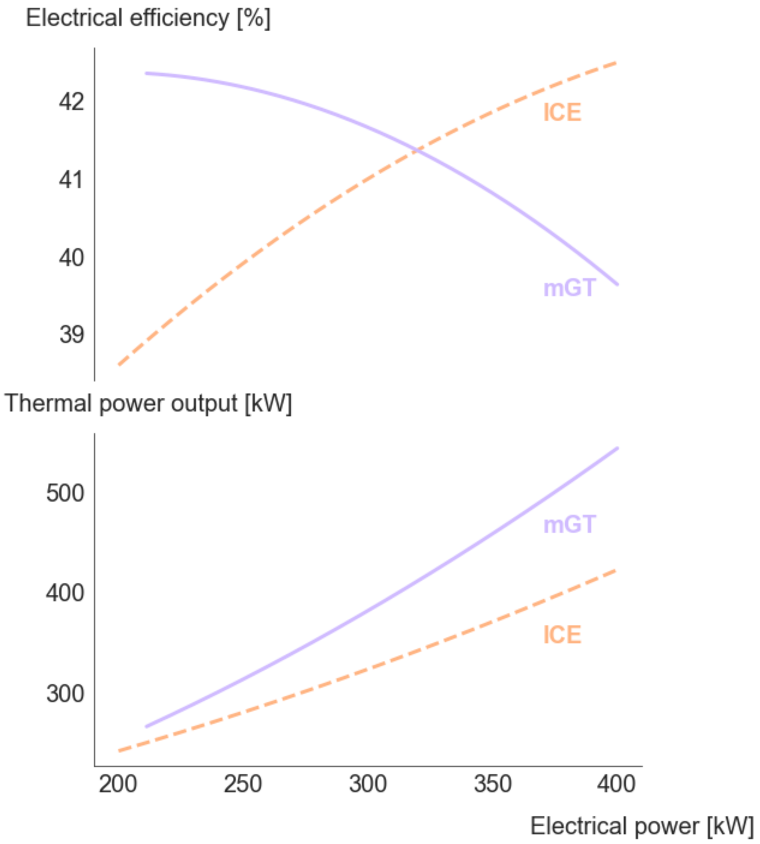

Figure 3.1: Electrical efficiencies and thermal power outputs of ICE and mGT operating with natural gas : the electrical efficiency of the ICE is better at full load but below 320 $\mathrm{kW_e}$ the part load efficiency is higher for the mGT and the thermal power output of the mGT is higher than the one of the ICE.

The electrical efficiencies and the thermal power outputs of both the ICE and the mGT units are depicted in Fig. 3.1 for the engines using natural gas and in

Fig. 3.2 for the engines running with biogas. The ICE with biogas has a better efficiency than the ICE with natural gas but the mGT with biogas has lower electrical efficiencies than the mGT with natural gas.

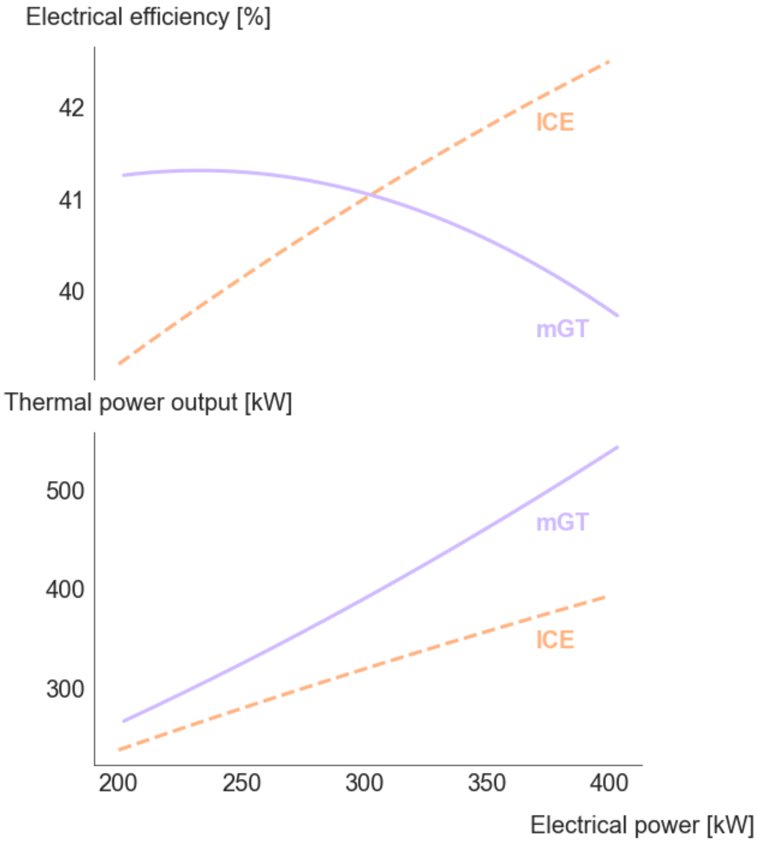

Figure 3.2: Electrical efficiencies and thermal power outputs of ICE and mGT operating with biogas : the electrical efficiency of the ICE is better at full load but below around 300 $\mathrm{kW_e}$ the part load efficiency is higher for the mGT and the thermal power output of the mGT is higher than the one of the ICE.

The humidified mGT unit under study is the Aurelia A400. For the dry part, it behaves just as the dry mGT described previously but below the 50% part load, the engine runs on wet mode. It means that liquid water is injected into the turbine in order to have a higher electrical efficiency. At this mode, the turbine generates full electrical power (400 $\mathrm{kW_e}$).

The two humidified mGTs, the one running thanks to biogas and the one with natural gas, have similar dry electrical efficiency (39.73% and 39.64% respectively) but have slightly different wet electrical efficiency. The natural gas turbine has a higher wet electrical efficiency (43.75%) compared to the biogas turbine (43.18%). The electrical efficiencies of both turbines are depicted in Fig. 3.3 and 3.4.

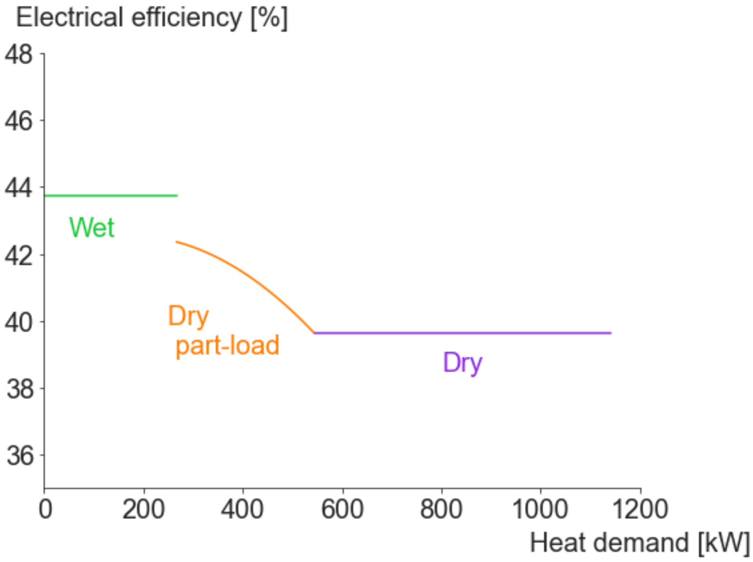

Figure 3.3: Electrical efficiency of the natural gas humidified mGT : below 50% part load, the turbine runs in wet mode with a constant electrical efficiency and above 50% part load, the turbine runs in dry mode just as the dry mGT

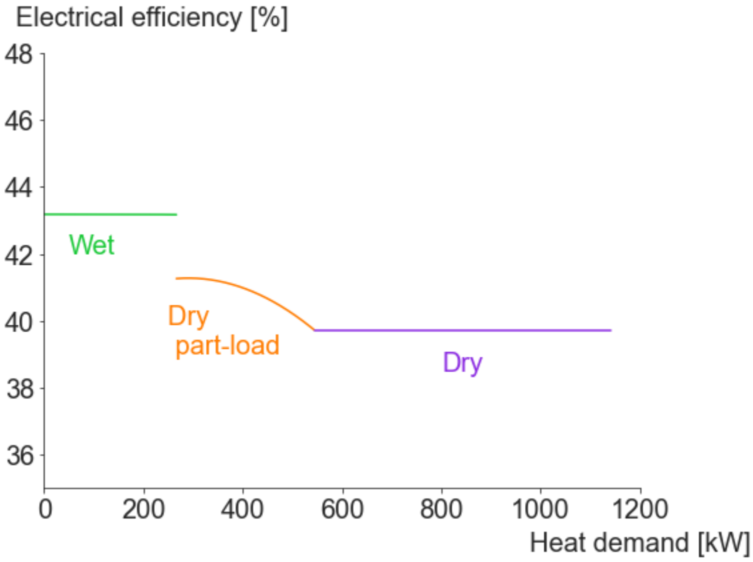

Figure 3.4: Electrical efficiency of the biogas humidified mGT : below 50% part load, the turbine runs in wet mode with a constant electrical efficiency and above 50% part load, the turbine runs in dry mode just as the dry mGT

These engines have different lifetimes. The ICE has a shorter lifetime than the mGTs. Its lifetime is around 60,000 hours [1] but the lifetime of the mGTs is around

80,000 hours [4]. Also the ICE needs more maintenance but since it does not run all year long, it is assumed that the maintenance happens when the unit is shut down. mGTs need between 4,000 and 8,000 hours of maintenance during their all lifetime [4]. The dry mGT does not run all year long and thus, the maintenance is assumed to happen when the unit is shut down. The humidified mGT run all year long which means that it can run for nine years before being decommissioned. It is thus assumed that the humidified mGT needs around one month of maintenance per year. This period is chosen when the demand is the lowest.

3.2 Humidification cycle

When the humidified mGT is in wet mode, liquid water is injected through the turbine with the combustion air. This is done in order to increase the electrical efficiency of the turbine when the external heat demand is low. In this mode, the electrical power output is the nominal power output ($400\,\mathrm{kW_e}$). With liquid water injection, the amount of water injected is fixed, the electrical efficiency and the electrical power output are also fixed. The counter effect is that the thermal efficiency is very low and so is the total efficiency. With water injection at very low heat demand, the engine can run all year round.

The water injection cycle is divided into two different cycles that join together before water is injected into the gas cycle. The goal of these two cycles is to heat the water before injecting it to the gas cycle and to give the remaining heat for the external demand. The water in the first cycle passes through the intercooler between the two compressors which works as a heat exchanger between the compressed air and the water. The heat passes into the water from the compressed air which needs to be cooled down so that the second compressor needs less work to compress the air. The water in the second cycle passes through an economizer which is a heat exchanger. This economizer is placed after the recuperator at the end of the gas cycle. The economizer works as a heat exchanger between the exhaust gases and the water. After the intercooler and the economizer, the two cycles join each other. Then, the water is injected into the turbine in a liquid state and the remaining heat in the water is used to fufil the external heat demand. At the end of the cycle, the two sub-cycles separate each other and the cycles start again.

3.3 Demand sizing

Traditionnaly, the engines are sized and designed to meet a certain demand in heat or in electricity in order to fulfil it. In this master thesis, the specifications of the Aurelia A400 are given to us. So, the demand is sized with respect to the engines. The method for sizing the demand is illustrated in Fig. 3.6.

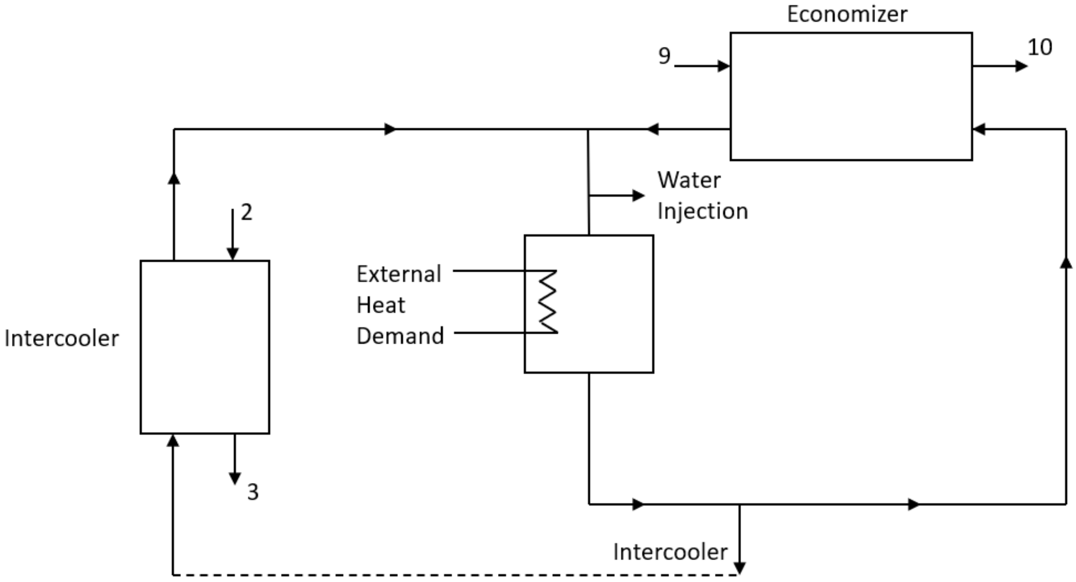

Figure 3.5: Humidification cycle : water is heated in two different cycles : one that passes through the intercooler between the two compressors and one that passes through the economizer at the end of the gas cycle. Both circuits join each other, then liquid water is injected with the combustion air, the rest of the water is used to fulfil the external heat demand

The technologies are heat-driven which means that they run following the heat demand curve. In this approach, the heat demand from an user through an entire year is used. This curve represents the heat needed by the user each hour of the year. The first step of the method is to arrange and sort this heat demand curve in a descending order. The area under this heat load curve represents the total thermal energy that the user need. The second step of the method is to find the maximum rectangle area below the heat load curve. From here, the height of the maximum rectangle area and the nominal heat power of the engine are known. The demand can be sized from those two parameters. The ratio between the nominal heat power and the height of the rectangle corresponds to the number of dwellings that are grouped to size the demand. Those grouped dwellings represent together a new heat demand that fit with the studied technology. The curve of the heat demand is multiplied by the ratio between the nominal thermal power and the height of the maximum rectangle to obtain the demand corresponding to the size of the engine.

The nominal heat power for the internal combustion engine is different from the two others technologies (ICE : $422\,\mathrm{kW_{th}}$ and mGTs : $543\,\mathrm{kW_{th}}$) which means that the number of dwellings are different for the ICE technology and that the demand curve is different too.

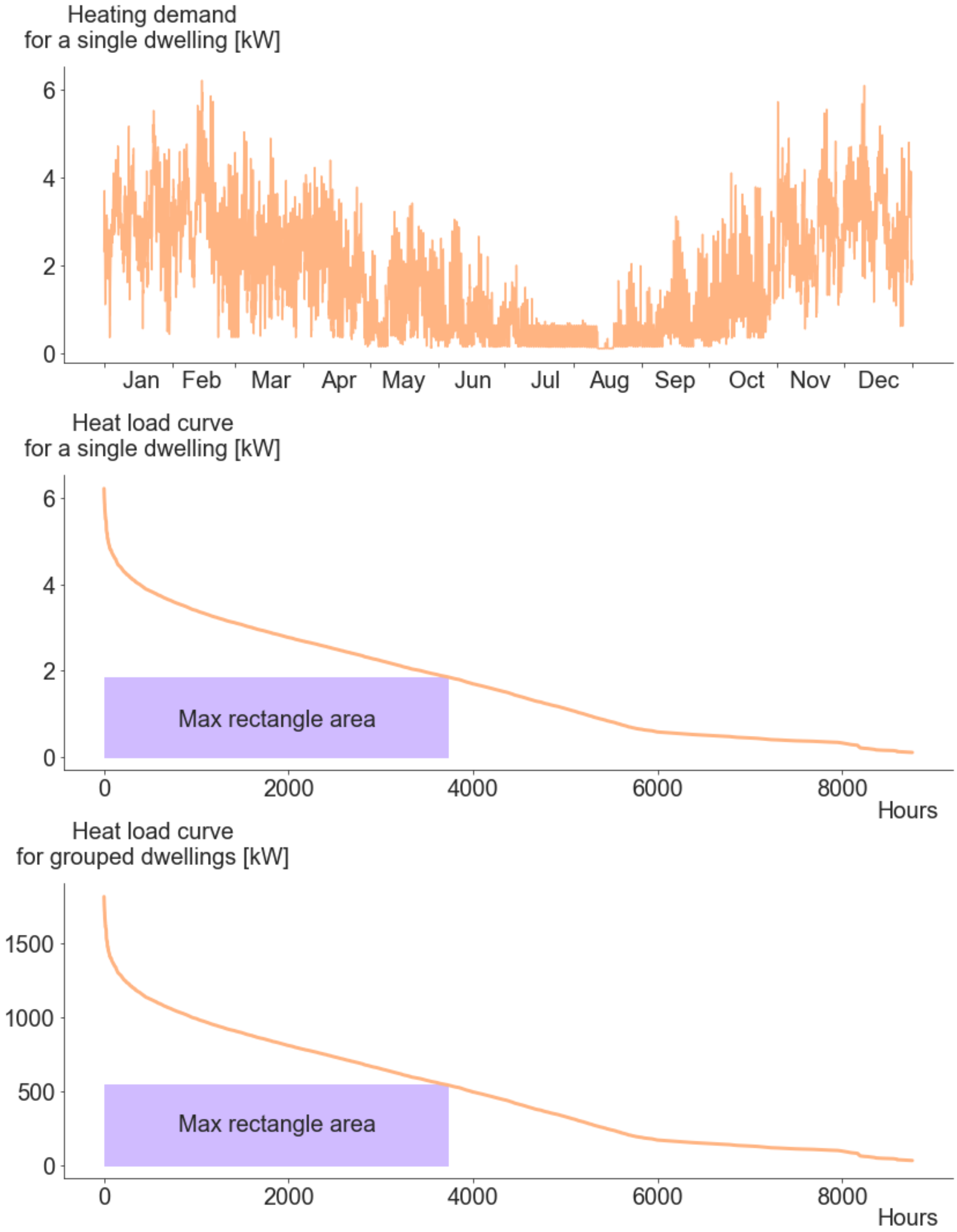

Figure 3.6: Methodology for sizing the demand : from the heat demand of a single dwelling, the curve is arranged in a descending order and the height of the maximum rectangle area is found. The ratio between the nominal thermal power of the engine and the height of the rectangle corresponds to the number of dwellings that are grouped to form the new demand.

Thus, from the heat demand of a certain dwelling, we group the dwellings to build a demand compatible with the technologies studied.

This entire approach aims to reduce the primary energy needed to fulfil the heat demand from the users.

3.4 Working principles of the different CHP units

Each hour, the model evaluates the heat demand curve. From this evaluation, there are three different cases that can appear. Those three cases are different following the technology involved. The ICE and the dry mGT behave in the same way but the humidified mGT has a different behaviour.

For the ICE and the dry mGT, the three different cases are full load, part load and when the engine doesn't run. If the heat demand is higher than the nominal thermal power output of the engine, the engine is in full load mode. It means that the engine will produce its nominal thermal power and its nominal electrical power. The excess heat demand is fulfilled with a boiler. If the heat demand is between 50% part load (electrical load) and full load, the engine runs in part load mode. The heat demand is entirely fulfilled with the engine. For both cases, if the electricity demand is higher than the electrical production, electricity is bought from the grid. And if the electricity demand is lower than the electrical production, the excess produced electricity is sold to the grid. When the heat demand is below 50% part load, the engine does not run anymore because the efficiency is not good enough and it is not profitable to run the engine. The heat demand is fulfilled with a boiler and the electricity is bought from the grid. This method is illustrated in Fig. 3.7.

For the humidified mGT, the two first cases are the same as for the ICE and dry mGT. When the heat demand is higher than the nominal thermal power output, the humidified mGT runs at full load and the excess heat demand is fulfilled with a boiler. If the heat demand is between 50% part load and full load, the heat demand is fulfilled thanks to the engine and the engine is in dry part load mode. As for the ICE and dry mGT, the excess produced electricity is sold to the grid and if there is an excess in the electricity demand, the electricity is bought from the grid. When the heat demand is below 50% part load, the humidified mGT runs in wet mode. In this mode, the mGT produces thermal power corresponding to the heat demand, and electricity with a high electrical efficiency thanks to the injection of liquid water in the turbine. In this mode, the engine produces the nominal electrical power ($400\,\mathrm{kW_e}$). Again, if the electricity demand is not completely fulfilled, electricity is bought from the grid and if there is an excess of produced electricity, it is sold to the grid. This method is illustrated in Fig. 3.8.

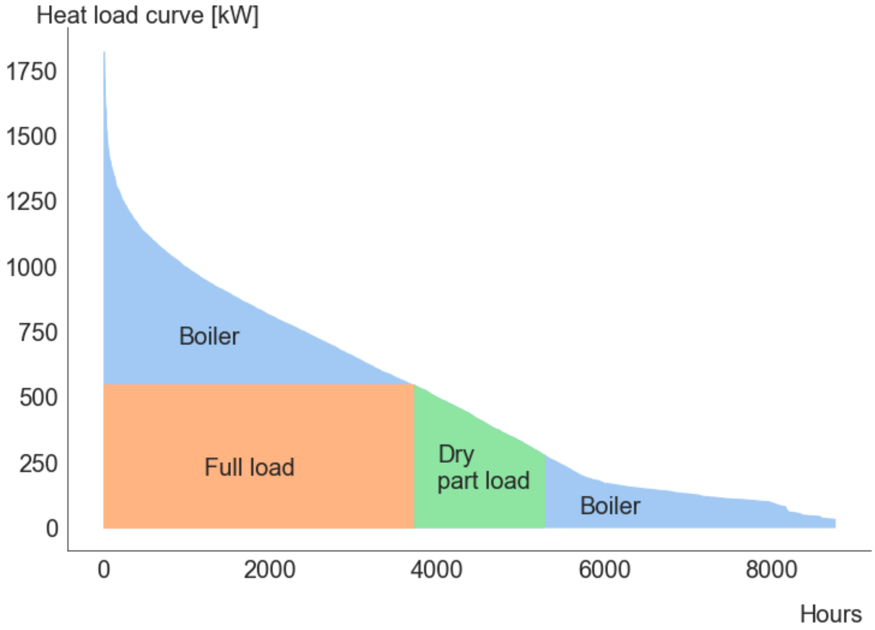

Figure 3.7: Working principle of the ICE and dry mGT : the ICE and dry mGT run following the heat demand curve. The excess heat demand is produced thanks to a boiler and the excess electricity is either bought from the grid or sold to the grid.

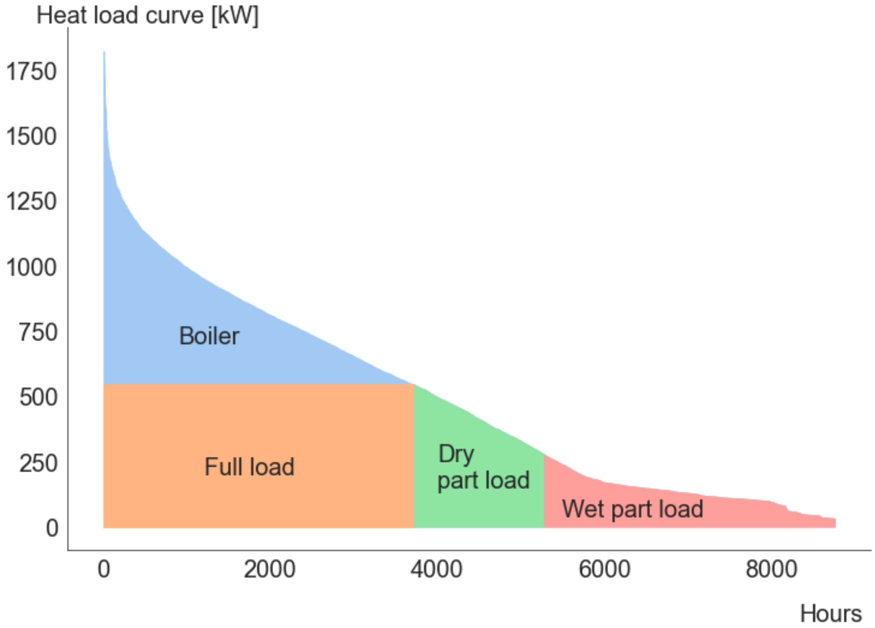

Figure 3.8: Working principle of the humidified mGT : it runs following the heat demand curve. When the heat demand is too low, the mGT runs following the wet part load mode. The excess electricity is either bought from the grid or sold to the grid.

3.5 Primary energy savings

The PES is a way of measuring the energy saved in comparison with a reference scenario. In this thesis, the PES is computed through the following formula with respect to the European directives on energy efficiency [30] :

$$\text{PES} = 1 - \frac{1}{\dfrac{\eta_{\text{E,CHP}}}{\eta_{\text{E,ref}}} + \dfrac{\eta_{\text{Q,CHP}}}{\eta_{\text{Q,ref}}}} \tag{3.1}$$

The electrical efficiency of the CHP, $\eta_{\text{E,CHP}}$, is the ratio between the total electrical energy produced by the engine and the total energy of the fuel used to produce both the thermal and electrical energy outputs. In a same way, the thermal efficiency of the CHP, $\eta_{\text{Q,CHP}}$, is the ratio between the total thermal energy produced by the engine and the total energy of the fuel used to produce both the thermal and electrical energy outputs.

For the reference efficiencies, the European Union has published a regulation in which the efficiency reference values are reharmonised [31]. The reference value for the electrical efficiency with natural gas is 53% and with biogas is 42% and the reference value for the thermal efficiency with natural gas is 92% and with biogas is 80%.

The European directives take also into account the grid connections by including a correction factor for grid losses. In the context of this thesis which is about domestic applications, it is assumed that the engine is connected on low voltage grid. Thus, the correction factor off-site is 0.888 and the correction factor on-site is 0.851. These corrections factors modify the electrical efficiency reference value thanks to the following formula (here for a CHP unit running with natural gas) :

$$\eta_{\text{E,ref}} = 53\% \cdot (0.851 \cdot P_{onsite} + 0.888 \cdot P_{offsite}) \tag{3.2}$$

where
P_{onsite} is the proportion of produced electricity consumed on the site and
$P_{offsite}$ is the proportion of produced electricity sold to the grid.

3.6 Net present value, internal rate of return and payback time

The NPV is an economical concept that applies for all projects with different cashflows at different times. The NPV can asset the profitability of a project and compare it to other financial projects. If the NPV is higher than zero, then the project is valuable, if the NPV is equal to zero, the project is neither profitable or unprofitable and when the NPV is lower than zero, the project is not profitable.

The NPV is the sum of the different cashflows, benefits and depenses, for each year by taking into account the discount rate.

The NPV is calculated with the following formula :

$$\mathrm{NPV} = -C_0 + \sum_{n=1}^{L} \frac{B_n - C_n}{(1+r)^n} \tag{3.3}$$

where
C_0 represents the initial investment of the project,
L represents the lifetime of the project in years,
B_n represents the benefits made each year,
C_n represents the depenses made each year,
r represents the discount rate

When computing the NPV, a value for the discount rate has to be assumed. This discount rate takes into account the inflation but also the risk of the project. In this work, the discount rate is assumed to be equal to 10%.

More important than the NPV is the IRR, the internal rate of return. It is a metric that can assess if a project is financially profitable. The IRR indicates how fast a project is growing. It is the discount rate needed for the NPV to be equal to zero at the end of the project's lifetime. The IRR is found by equaling the NPV to zero :

$$\mathrm{NPV} = -C_0 + \sum_{n=1}^{L} \frac{B_n - C_n}{(1+r)^n} = 0 \tag{3.4}$$

and the IRR is given by r in this equation.

For some projects, it is possible to find negative IRR or no IRR at all, those projects are not valuable and not profitable.

The payback time is the time you have to wait before the NPV goes on above zero. It is the time after which your project is profitable. From this time, you are earning money from the project.

Chapter 4

Results

In this part, the methodology defined in the previous chapter is used to assess the conditions in which the humidified mGT is profitable and outperforms the other CHP technologies.

First, the different economic costs and benefits are defined. Then, the users demands are built for each country. Subsequently, results are showed in Brussels for engines operating with natural gas and biogas and in Madrid and in Riga only for natural gas engines. Despite the good results of the biogas mGTs thanks to low biogas prices compared to the natural gas price, the rest of the thesis focuses on the present and so, only on natural gas units. Afterwards, a gas and electricity prices analysis is produced in order to determine the best market conditions in which the CHP engines can operate. At last, a sensitivity analysis is performed to show the influence of several major parameters.

4.1 Definitions of the costs and benefits

The costs are divided into the annual costs and the capital costs. The capital costs are the costs of the different investments that have to be done before launching the project :

- The capital cost of the CHP unit is 1,000 €/kW$_e$ for the dry mGT [26] which leads to 400,000 € and for the ICE unit, the cost is assumed to be 20% lower which leads to 320,000 € and the cost of the humidified mGT is assumed to be 10% higher than the one of the dry mGT which means 400,000 €.
- The capital cost of the boiler is estimated to be 30,000 € for a boiler of this output capacity [1]

The annual costs represent all the depenses that are made each year during the lifetime of the project. Later in this thesis, the impact of the variation of those costs is assessed. These costs are :

- The maintenance costs of the CHP units. They are the costs to maintain the unit and to prevent it from falling down. This cost for the dry mGT is assumed to be 12.5 €/MWh$_e$ [26]. The humidified mGT is basically the same engine as the dry mGT plus the water injection, its maintenance cost is thus assumed to be 10% higher. The maintenance cost of the ICE unit is higher than the one of the mGTs because of the lubrification needs and it requires more maintenance. Its cost is 16 €/MWh$_e$ [26]

- The costs of the fuel. It is the cost of the natural gas or the biogas used by both the CHP unit and the boiler

- The cost of the purchased electricity. It is the cost of the electricity needed if the CHP engine is not able to fulfil the electricity demand of the users. This electricity is bought from the grid

The main costs for the different CHP units are resumed in the table 4.1.

Table 4.1: Main costs of the different CHP units

	ICE	Dry mGT	Hum. mGT
Initial cost [€]	320,000	400,000	440,000
Maintenance costs [€/MWh$_e$]	16	12.5	13.75

The annual benefits of the projects represent all the positive cashflows that come from the project. They depend all either on the fuel price or the electricity price which means that a sensitivity analysis on those benefits is made later in the thesis. These benefits are :

- The sold electricity to the grid. If the CHP engine produces more electricity than needed by the users, the excess produced electricity is sold to the grid and it generates an influx of cash

- The avoided electricity cost. It is the cost of electricity that would have been bought from the grid if there was no CHP

- The avoided fuel cost. It is the cost of fuel that would have been consumed by a boiler if the CHP was not installed

4.2 The users and their demands

The demand curves are obtained thanks to data of heating and electricity consumptions [32]. These data are the ones for different cities in the United States. The weathers of the studied cities have been matched with the weathers in american cities [33]. Brussels matches with Cascadia, Oregon at 99% which is a city near Eugene, Oregon and thus the data of Eugene have been used for Brussels. Madrid weather matches with Rocklin, California at 98% which is a city near Sacramento, California and thus its data have been used for Madrid. Riga weather matches at 98% with the one in Livingston, Montana and so its data have been used. By doing this, the shape of the demand is good but needs to be rescaled in order to have the right amount of energy really consumed by the user. With the total yearly amount of heat and electricity consumptions, the scale factor can be computed and then the demand can be rescaled.

Table 4.2: Annual heat and electricity consumption per dwelling for the three different users [34]

	Brussels	Madrid	Riga
Heat [kWh]	19,655	9,350	18,259
Electricity [kWh]	3,758	3,918	2,063

From the data in the USA, the annual heat consumption and the annual electrical consumption are computed. The heat scale factor is the ratio between the real heat consumption and the one from the american data. Then all the heat demand dataset is multiplied by this factor in order to have the heat demand for the specific studied country. The same thing is done with the electricity demand dataset by using the electricity scale factor which is computed in the same way as the heat scale factor. The different demands for the three studied countries are depicted in Fig. 4.1.

In Brussels, the total yearly heat consumption per dwelling is 19,655 kWh [34] and the one for electricity consumption is 3,758 kWh [34]. The summer season is marked with a low heat demand and during the winter, the heat demand is obviously higher. The electricity demand is more constant over the year. Since the heating demand is way higher than the electricity demand for almsot all the year and since the CHP engines are heat driven, one can deduce that there is an excess of produced electricity when the CHP engines are running.

In Madrid, the total yearly heat consumption per dwelling is 9,350 kWh [34] and the one for electricity consumption is 3,918 kWh [34]. The summer season is marked with a low heat demand but a high electrical demand due to the use of

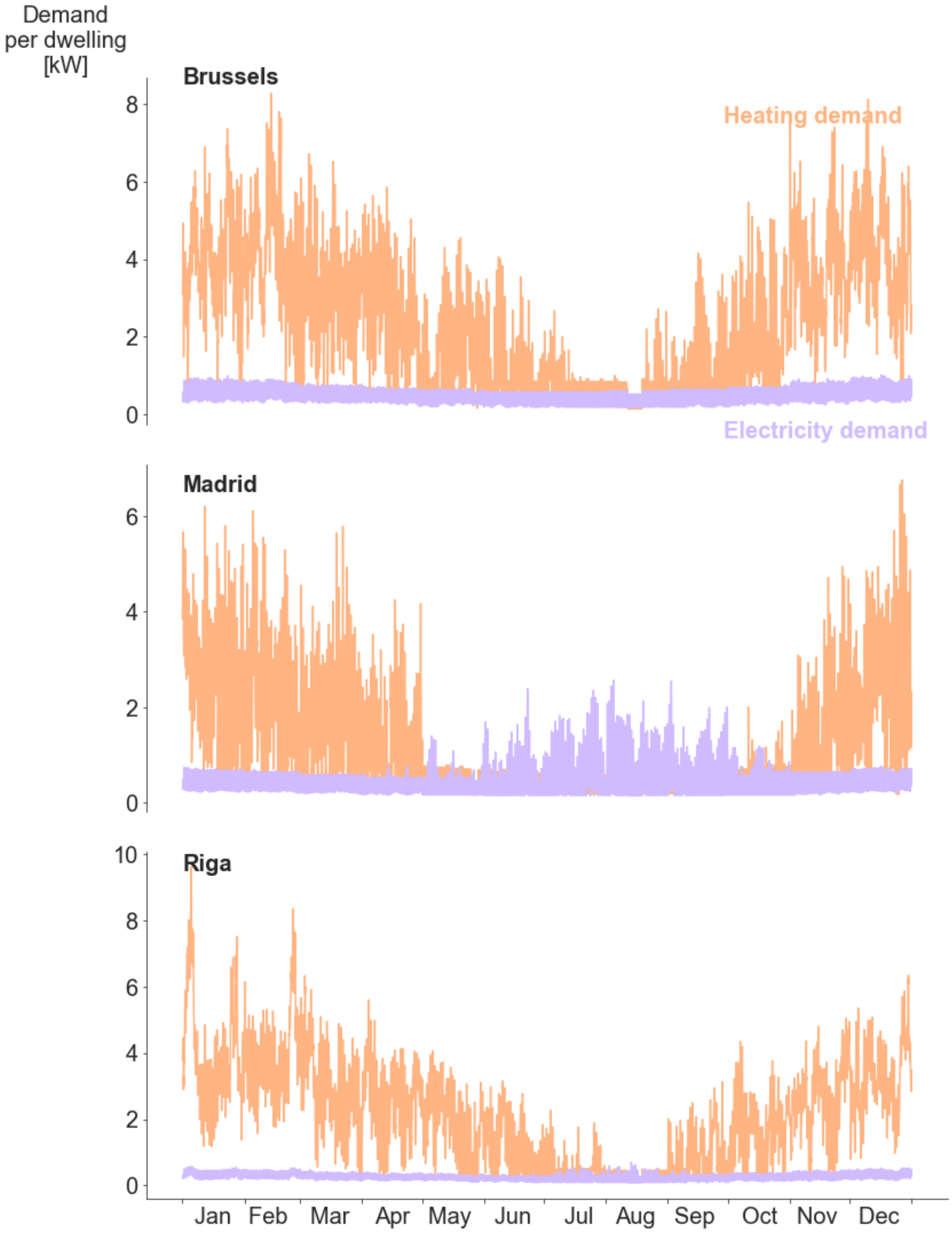

Figure 4.1: Heat and electricity demands per dwelling in Brussels, Madrid and Riga

air conditioning. This high electrical demand combined with a low heat demand fits well with the design of the humidified mGT. When it runs in wet mode, it produces low heat output and a constant electrical output of 400 kW with a high electrical efficiency. And this electricity is very useful for the users who do not need to sell this electricity at low prices.

In Riga, the total yearly heat consumption per dwelling is 18,259 kWh [34] and the one for electricity consumption is 2,063 kWh [34]. The main difference with Brussels is that the electricity demand is lower.

4.3 Results in Brussels

4.3.1 Natural gas

The results of the sizing methodology applied here show that the humidified mGT can be used for 220 dwellings as for the dry mGT but the ICE can supply only 171 dwellings since its nominal thermal power is lower. All engines run at full load for 3,719 hours. The ICE runs for 5,262 hours each year and the dry mGT for 5,279 hours which means their lifetime is 12 years. The humidified mGT runs 2,761 hours in wet mode. As already said in the chapter 3, the maintenance happens when the engines don't run except that the humidified mGT runs all year and it has to be shut down during 30 days each year, during the lowest demand, which represents 720 hours.

Table 4.3: Results of the sizing methodology for the natural gas engines in Brussels

	Hum. mGT	Dry mGT	ICE
Number of dwellings	220	220	171
Number of hours at full load	3,719	3,719	3,719
Number of hours at part load	1,560	1,560	1,543
Number of hours at wet mode	2,761	-	-
Number of hours in maintenance	720	-	-

The Fig. 4.2 shows the net electricity production of the CHP engines. When the production is positive, the electricity is sold to the grid at the electricity price multiplied by the electricity price factor. This latter is the ratio between the price of sold electricity and the price of bought electricity. For example, if it is equal to 0.5 and that one kilowatthour of electricity is bought from the grid at 0.30 €, then one kilowatthour of electricity is sold to the grid for 0.15 €. When the net production is negative, there is a deficit of electricity and the electricity is bought from the grid at the electricity price. One can clearly see that when the engines are running, they produce more electricity than needed and this excess electricity is sold to the grid. For the ICE and the dry mGT, the user has to buy electricity from the grid almost only when the the engines are turned down because the heat demand is below 50% part load. And the user of the humidified mGT needs to buy electricity only when the engine is in maintenance.

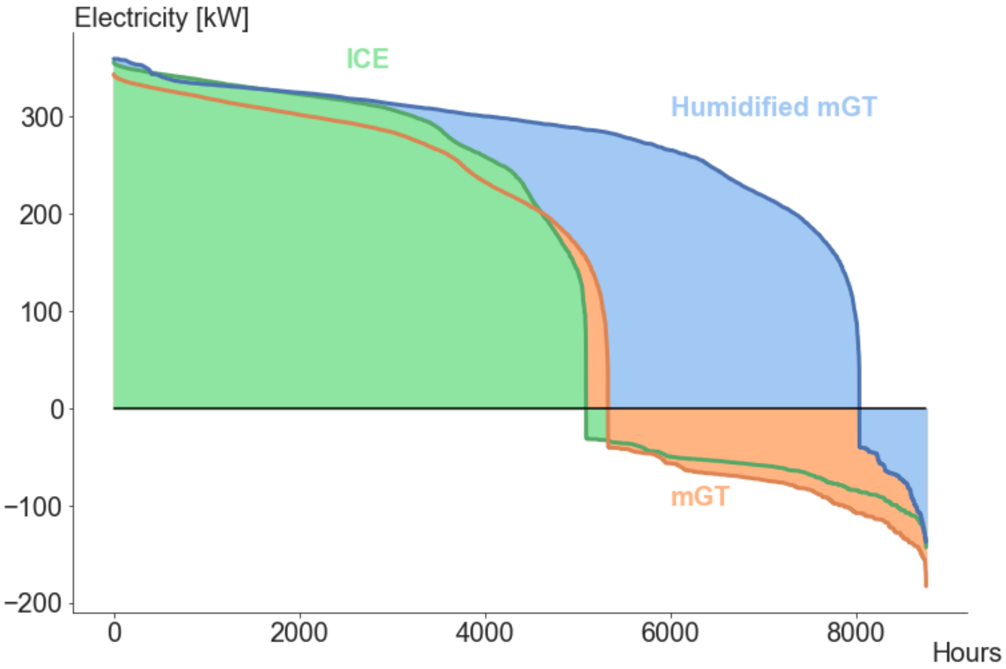

Figure 4.2: Net electricity production in Brussels for natural gas : the negative production corresponds to the electrity bought from the grid and the postive production to the electricity sold to the grid

The table 4.4 shows the principal quantities that are involved in the costs and benefits. The upper part of this table shows the quantities that are involved in the annual costs of the engines. And the lower part of the table shows the quantities involved in the annual benefits of the engines. These quantities are assumed to be constant each year since the demands are assumed constant each year. When they are coupled with their associate prices, this can lead to different cashflows in function of the prices. These prices are the gas and electricity prices aswell as the electricity price factor and the maintenance costs. Since the quantities do not change for this case in Brussels with the natural gas engines, the different prices play an important role in the profitability of the different technologies.

Table 4.4: The different annual quantities influencing the cashflows in Brussels for the three engines running with natural gas : in the first part, the quantities generating costs and in the second part, the quantities generating benefits.

	Hum. mGT	Dry mGT	ICE
Fuel consumption [kWh]	8,743,047	6,698,184	5,961,347
Electricity bought [kWh]	50,682	278,537	232,842
Produced electricity by the CHP [kWh]	3,077,663	1,993,263	1,909,492
Electricity sold [kWh]	2,302,150	1,445,605	1,500,228
Fuel avoided [kWh]	4,666,465	4,666,465	3,626,706
Electricity avoided [kWh]	826,195	826,195	642,106

To better illustrate this, let's take some values for these prices and see how these affect the cashflows. The prices of electricity and natural gas are chosen from the first semester of 2022. The electricity price was 0.3377 €/kWh [35] and the natural gas price was 0.0939 €/kWh [36]. The electricity price factor chosen here is 0.5. The real value of the electricity price factor is generally lower than this but this value allows to see in a better way the effects of the other parameters and the overall trends. But this low value leads to better results than for real situations which will be discussed later in the thesis. The discount rate applied in this situation is equal to 10%.

In this situation, the humidified mGT generates each year 225,500 €, the dry mGT 213,340 € and the ICE 141,747 €. This situation ends with positive NPVs for all technologies. Both mGTs have similar cashflows while the ICE has a lower one. Indeed, even if the humidified mGT produces a lot of excess electricity compared to the dry mGT, especially when it operates in wet mode, and that less electricity has to be bought from the grid but the fuel costs are so big and the price at which the electricity is sold is too low in order to create a difference in the cashflows. Plus, the humidified mGT needs more maintenance and its costs are higher. The cashflows are only slightly better for the humidified mGT. The ICE has a lower cashflow because it needs lot of fuel, lot of electricity from the market, has higher maintenance costs and it does not avoid much electricity and fuel.

But no conclusion can be made from this example. Indeed, if the electricity price factor goes down to 0.15 which is closer from the reality, cashflows become very different. In this case, the humidified mGT and the ICE produce negative cashflows because with this lower electricity price factor, the electricity sold to the grid brings in less money and the benefits become smaller than the costs. This is why subsidies for cogeneration systems are important and studied in the next chapter. A sensitivity analysis must also be performed in order to assess when the technologies are profitable.

Currently, we live in an era where energy saving is very important. This is why the PES has to be measured for each technology. In Brussels, the humidified mGT is the engine with the lowest PES but it is due to the fact that it runs all year long. In wet mode, the total efficiency is almost equal to the electrical efficiency which is pretty low and so the PES is lowered because of its lower total thermal efficiency. The mGT has a better PES than the ICE because it produces more heat for the same electrical power output and so its thermal efficiency is way better than the one of the ICE. And even if the electrical efficiency of the ICE is better than the one of the dry mGT, it does not compensate the better thermal efficiency. The table 4.5 shows the different PES for each technology as well as their global efficiencies.

Table 4.5: PES and global efficiencies in Brussels for each technology running with natural gas

	Hum. mGT	Dry mGT	ICE
η_e [%]	41.75	40.49	42.20
η_{th} [%]	41.40	54.39	44.82
η_{tot} [%]	83.14	94.87	87.02
PES [%]	25.73	31.57	28.16

4.3.2 Biogas

The results of the sizing methodology applied here show the same results for the mGTs as the situation with natural gas in Brussels since the engines are the same. These results are depicted in the table 4.6. The only things that change are the electrical efficiencies and the thermal power outputs. The obtained results are not the same for the ICE since it is not the same engine anymore. It can supply less dwellings, 159 instead of 170. The number of working hours at part load changes slightly for the ICE, 1,536 instead of 1,543. The lifetimes of the engines do not change either.

Table 4.6: Results of the sizing methodology for the biogas engines in Brussels

	Hum. mGT	Dry mGT	ICE
Number of dwellings	220	220	159
Number of hours at full load	3,719	3,719	3,719
Number of hours at part load	1,560	1,560	1,536
Number of hours at wet mode	2,761	-	-
Number of hours in maintenance	720	-	-

The Fig. 4.3 shows the net electricity production of the CHP engines. As for the case with natural gas, when the engines are running, they produce almost every time an excess of electricity that needs to be sold to the grid. And when the engines are not running, the users need to buy electricity from the grid.

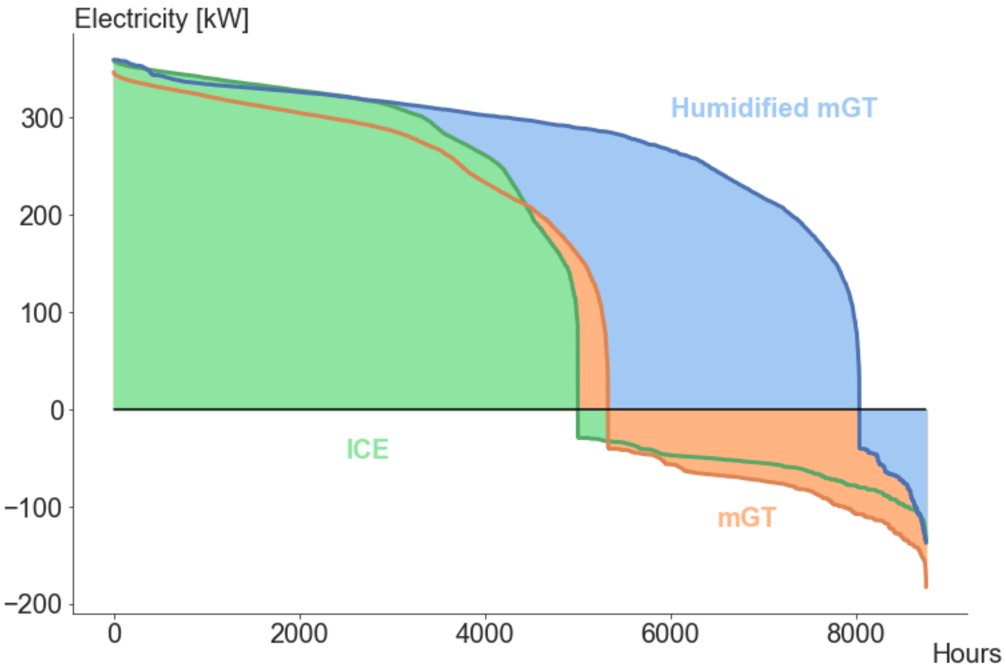

Figure 4.3: Net electricity production in Brussels for biogas : the negative production corresponds to the electrity bought from the grid and the postive production to the electricity sold to the grid

The table 4.7 shows the different quantities that influence the cashflows. Although the electricity graph is the same as in the natural gas case except for the ICE, the biogas engines are less efficient and require more fuel to produce the same results. But the biogas price is lower which helps to reduce the fuel costs. An average price for the production of biogas in Europe is 0.0546 €/kWh [37]. If we take the same example as for the natural gas case, higher cashflows are obtained: 365,362 € for the humidified mGT, 280,807 € for the dry mGT and 217,237 € for the ICE. Despite the lower efficiencies for the mGTs and thus higher fuel consumption, the fuel costs are lower because of the low biogas price compared to the natural gas price (the biogas production price was taken in this example).

Table 4.7: The different annual quantities influencing the cashflows in Brussels for the three engines running with biogas : in the first part, the quantities generating costs and in the second part, the quantities generating benefits

	Hum. mGT	Dry mGT	ICE
Fuel consumption [kWh]	9,130,383	6,939,716	5,787,226
Electricity bought [kWh]	50,683	278,537	222,242
Produced electricity by the CHP [kWh]	3,082,830	1,998,430	1,868,738
Electricity sold [kWh]	2,307,317	1,450,772	1,493,566
Fuel avoided [kWh]	4,666,465	4,666,465	3,374,279
Electricity avoided [kWh]	826,195	826,195	597,414

The table 4.8 shows the results of the PES and the global efficiencies for each engine. For all technologies, the PES are higher than with natural gas because the reference values for the electrical and thermal efficiencies are lower for biogas engines but the technologies have similar performance curves. The humidified mGT has still the lowest PES for the same reasons as before (long time in wet mode with low total and thermal efficiency despite the slightly higher electrical efficiency). And the dry mGT has a higher PES than the ICE because of its higher thermal output for the same electric output which means that less fuel is used to reach the same heat output.

Table 4.8: PES and global efficiencies in Brussels for each technology running with biogas

	Hum. mGT	Dry mGT	ICE
η_e [%]	39.73	38.69	42.20
η_{th} [%]	39.33	51.84	42.14
η_{tot} [%]	79.06	90.54	84.34
PES [%]	36.23	41.09	40.04

4.4 Results in Madrid

The results of the sizing methodology applied here show that the mGTs can be used for 320 dwellings but the ICE can supply only 249 dwellings. All engines run 1,967 hours at full load which is lower than for the case in Brussels. This is due to the shape of the heat load curve which is steeper. The ICE runs for 2,914 hours each year and the dry mGT 2,923 hours which means the ICE can run for 20 years and the dry mGT for 27 years. The humidified mGT runs 5,117 hours in wet mode which is almost the double as in Brussels.

Table 4.9: Results of the sizing methodology for the natural gas engines in Madrid

	Hum. mGT	Dry mGT	ICE
Number of dwellings	320	320	249
Number of hours at full load	1,967	1,967	1,967
Number of hours at part load	956	956	947
Number of hours at wet mode	5,117	-	-
Number of hours in maintenance	720	-	-

The Fig. 4.4 shows the net electricity production of the CHP engines and the table 4.10 shows the quantities that influence the cashflows. The ICE and the dry mGT run for less hours than in Belgium, this leads to lower quantities of produced electricity and thus higher quantities of bought electricity particularly as the electricity demand is higher in summer when the engines are out of service. But on the other hand, this requires to buy less fuel. The user of the humidified mGT in Madrid needs to buy more electricity from the grid than the user in Brussels because the engine is shut down in summer for maintenance when the heat demand is low but the electricity demand increases in this period. This can lead to lower cashflows in Spain compared to Belgium. But this can also prove that the humidified mGT is well suited to Spain because, with the two other technologies, way more electricity needs to be bought from the grid which can cost a lot of money.

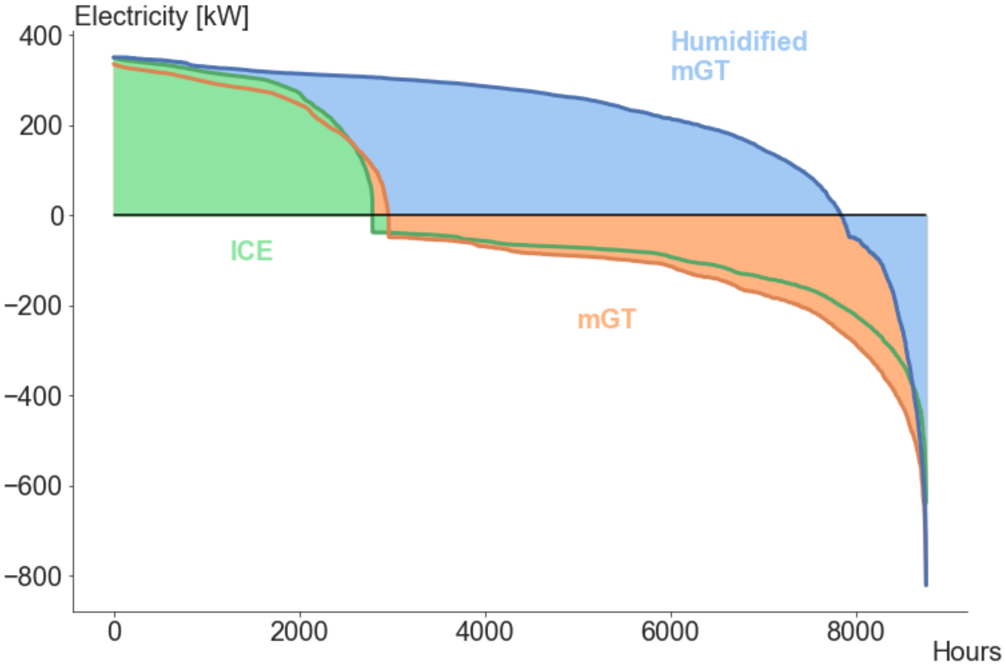

Figure 4.4: Net electricity production in Madrid : the negative production corresponds to the electrity bought from the grid and the postive production to the electricity sold to the grid

The results for the PES and global efficiencies in Spain are presented in the table 4.14. The PES of the ICE and the dry mGT are almost the same as the case in Brussels with natural gas. This is quite normal as the engines run only at full load or above 50% part load and so their thermal and electrical efficiencies are always very good just as in Brussels. The PES of the humidified mGT is lower than in Brussels. This happens because it runs more often in wet mode. Thus its total efficiency is lower because, in wet mode, the total efficiency is close to the electrical efficiency which is low.

Table 4.10: The different annual quantities influencing the cashflows in Madrid for the three engines running with natural gas : in the first part, the quantities generating costs and in the second part, the quantities generating benefits

	Hum. mGT	Dry mGT	ICE
Fuel consumption [kWh]	8,114,563	4,347,548	3,782,174
Electricity bought [kWh]	173,572	909,007	723,444
Produced electricity by the CHP [kWh]	3,126,476	1,096,475	1,038,467
Electricity sold [kWh]	2,046,303	751,738	787,520
Fuel avoided [kWh]	3,231,061	3,231,061	2,511,132
Electricity avoided [kWh]	1,253,744	1,253,744	974,391

Table 4.11: PES and global efficiencies in Madrid for each technology running with natural gas

	Hum. mGT	Dry mGT	ICE
η_e [%]	42.89	40.54	42.17
η_{th} [%]	30.56	54.37	44.81
η_{tot} [%]	73.45	94.92	86.98
PES [%]	20.44	31.69	28.17

4.5 Results in Riga

The results of the sizing methodology applied here show that the mGTs can supply 245 dwellings and the ICE 190 dwellings. All engines run at full load for 4,006 hours which is a little bit more than in Brussels. The dry mGT runs for 5,663 hours each year and the ICE for 5,650 which means they can run during 12 years. The humidified mGT runs 2,377 hours in wet mode which is a little bit less than in Brussels.

Table 4.12: Results of the sizing methodology for the natural gas engines in Riga

	Hum. mGT	Dry mGT	ICE
Number of dwellings	245	245	190
Number of hours at full load	4,006	4,006	4,006
Number of hours at part load	1,657	1,657	1,644
Number of hours at wet mode	2,377	-	-
Number of hours in maintenance	720	-	-

The Fig. 4.5 shows the net electricity production of the engines in Riga. The graph has the same shape as the one for Brussels except that in Riga, the excess production of electricity is higher which means more electricity is sold to the grid and there is slightly less need of electricity from the grid because of its lower electricity demand. Compared to Brussels, the ICE and the dry mGT produce a bit more of electricity and so use a bit more fuel.

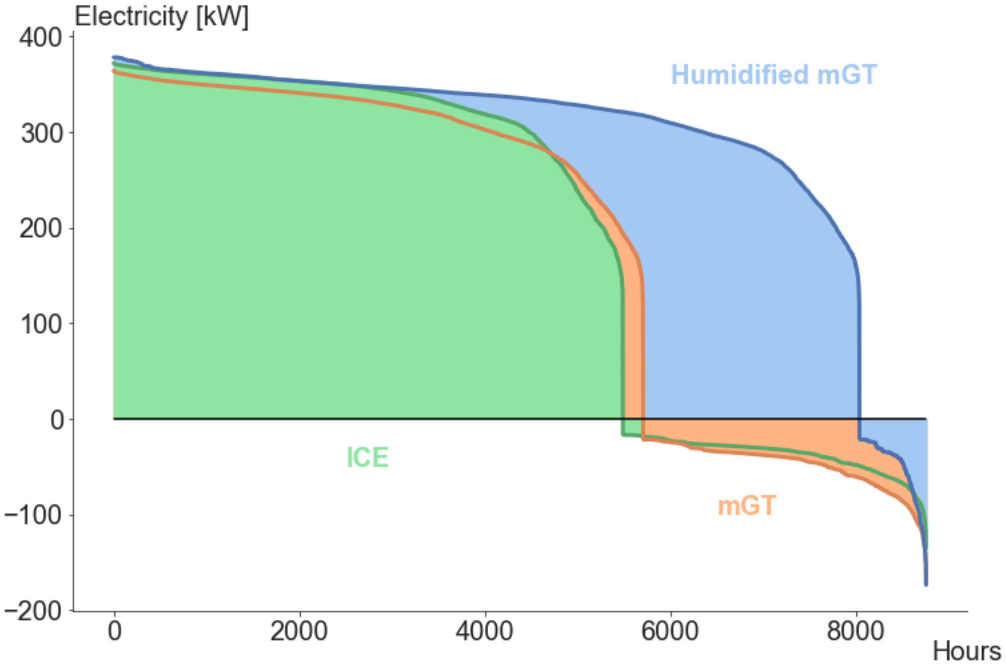

Figure 4.5: Net electricity production in Riga : the negative production corresponds to the electrity bought from the grid and the postive production to the electricity sold to the grid

Table 4.13: The different annual quantities influencing the cashflows in Riga for the three engines running with natural gas : in the first part, the quantities generating costs and in the second part, the quantities generating benefits

	Hum. mGT	Dry mGT	ICE
Fuel consumption [kWh]	8,832,733	7,014,704	6,274,716
Electricity bought [kWh]	36,177	148,812	124,194
Produced electricity by the CHP [kWh]	3,076,692	2,143,492	2,062,462
Electricity sold [kWh]	2,607,609	1,787,043	1,793,974
Fuel avoided [kWh]	4,829,283	4,829,283	3,753,247
Electricity avoided [kWh]	505,261	505,261	392,681

The PES of the technologies in Riga are almost the same as in Brussels because the heat demands are very close frome each other. The fact that the electricity demand is lower in Riga does not change anything because the engines are heat-driven and the PES takes into account all the electricity produced by the CHP unit no matter if it is used on-site or off-site.

Table 4.14: PES and global efficiencies in Riga for each technology running with natural gas

	Hum. mGT	Dry mGT	ICE
η_e [%]	41.56	40.47	42.21
η_{th} [%]	42.53	54.39	44.81
η_{tot} [%]	84.08	94.86	87.02
PES [%]	25.97	31.37	28.00

4.6 Gas and electricity prices analysis

An analysis of the gas and electricity prices has to be perform in order to show the market conditions when the different technologies become profitable. This analysis will be performed only for the cases with natural gas.

In this analysis, the discount rate is equal to 10% and the electricity price factor to 0.5.

The results are depicted in the table 4.15 for the ICE, in the table 4.16 for the dry mGT and in the table 4.17 for the humidified mGT. The tables show the IRR for different pairs of gas and electricity prices. A dash in the table indicates that no result was found when equalising the NPV to zero and the project is not feasible economically. A negative result also shows that the project is not feasible. The higher the IRR, the more profitable the project will be.

It can be seen that a low gas price and a high electricity price are suitable for the CHP engines as it was predicted. Indeed, the CHP engines produce both electricity and heat from gas. So, if the gas is cheap and the electricity from the grid is expensive, it is cost effective to produce our own electricity from gas.

One can also witness that the IRR for the humidified mGT is more sensitive to the different prices changes. It is less stable and more volatile following the gas and electricity prices. When the price of electricity increases, the IRR for the humidified mGT gets bigger and bigger at a higher rate than the one of the two other engines. And when the gas price increases, the IRR of the humidified mGT decreases at a faster rate than the one of the two other engines.

Madrid is the best place among the three studied cities for the humidified mGT as its IRRs are almost always bigger than the ones in Brussels and Riga. But for the two other engines, the IRRs are greater in Brussels and Riga than in Madrid. This is also due to the fact that the lifetime of the ICE and the dry mGT is higher in Madrid since the engines run less hours during the year and so last longer.

Table 4.15: Prices analysis for the ICE unit : in the 1st table, the results for Brussels, in the 2nd table, the results for Madrid and in the 3rd table, the results for Riga. This table shows the resulting IRRs following the different combinations of gas and electricity prices, they are expressed in [%]

Gas prices	**Electricity prices**				**Electricity prices**				**Electricity prices**			
	0.15	**0.25**	**0.35**	**0.45**	**0.15**	**0.25**	**0.35**	**0.45**	**0.15**	**0.25**	**0.35**	**0.45**
0.02	24.93	60.07	93.47	126.65	14.60	33.94	52.45	70.88	23.57	59.05	92.64	126
0.05	-4.59	38.83	72.85	106.12	-0.53	22.76	41.53	59.98	-10.21	36.57	70.90	104.4
0.07	-	23.71	59.00	92.42	-	14.89	34.21	52.71	-	20.34	56.27	89.91
0.1	-	-7.00	37.70	71.79	-	-0.02	23.04	41.79	-	-20.55	33.63	68.15
0.15	-	-	-9.71	36.58	-	-	0.47	23.31	-	-	-	30.65

Table 4.16: Prices analysis for the mGT unit : in the 1st table, the results for Brussels, in the 2nd table, the results for Madrid and in the 3rd table, the results for Riga. This table shows the resulting IRRs following the different combinations of gas and electricity prices, they are expressed in [%]

Gas prices	**Electricity prices**				**Electricity prices**				**Electricity prices**			
	0.15	**0.25**	**0.35**	**0.45**	**0.15**	**0.25**	**0.35**	**0.45**	**0.15**	**0.25**	**0.35**	**0.45**
0.02	28.17	58.53	88.15	117.71	16.48	33.50	50.27	67.03	26.16	56.17	85.33	114.41
0.05	11.76	44.18	73.96	103.53	7.78	25.67	42.48	59.24	7.76	40.68	70.06	99.16
0.07	-3.42	34.44	64.48	94.08	0.14	20.40	37.28	54.05	-	30.09	59.85	90.00
0.1	-	19.00	50.20	79.89	-	12.17	29.47	46.26	-	12.68	44.43	73.72
0.15	-	-	25.65	56.18	-	-	16.24	33.26	-	-	17.18	48.15

Table 4.17: Prices analysis for the humidified mGT unit : in the 1st table, the results for Brussels, in the 2nd table, the results for Madrid and in the 3rd table, the results for Riga. This table shows the resulting IRRs following the different combinations of gas and electricity prices, they are expressed in [%]

Gas prices	**Electricity prices**				**Electricity prices**				**Electricity prices**			
	0.15	**0.25**	**0.35**	**0.45**	**0.15**	**0.25**	**0.35**	**0.45**	**0.15**	**0.25**	**0.35**	**0.45**
0.02	32.3	75.65	117.1	158.1	34.64	81.57	126.6	171.4	26.99	67.61	105.8	143.7
0.05	-3.79	48.7	90.83	132.1	-10.75	49.41	95.3	140.2	-13.59	40.74	80.03	118.1
0.07	-	29.58	73.23	114.6	-	26.34	74.25	119.4	-	21.09	62.6	100.9
0.1	-	-8.99	46.16	88.42	-	-	41.69	88.03	-	-48.61	35.36	75.07
0.15	-	-	-15.5	43.61	-	-	-	33.72	-	-	-	29.83

The NPVs for different gas and electricity prices are depicted in Fig. 4.6. As already mentioned, a high electricity price implies a higher NPV and a high gas prices implies a lower NPV. The trend is also not always the same following the gas price. If the gas price is low, the humidified mGT has a higher NPV for every electricity price studied (except very low electricity prices). But if the gas price is higher, the NPV for the humidified mGT is below the other NPVs except for quite high electricity prices. It also should be in mind that the lifetime of the humidified mGT is shorter than the other's. The NPV would have been higher if the humidified mGT had ran the same amount of years as the other engines.

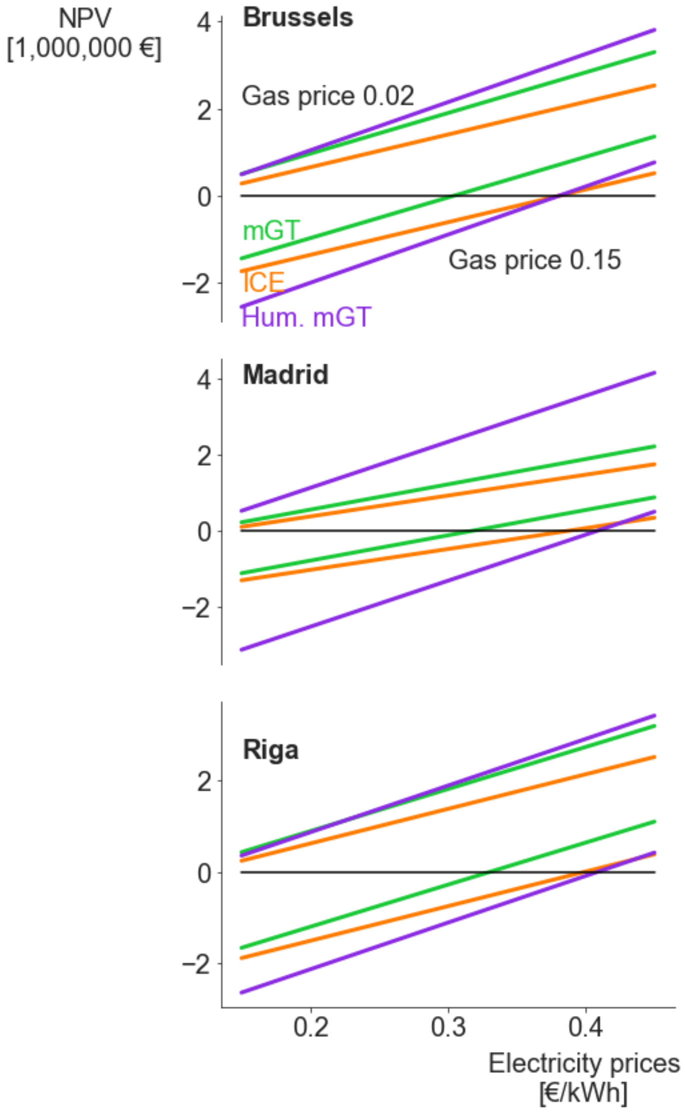

Figure 4.6: NPVs following the electricity and gas prices : the higher the electricity price the higher the NPV and the lower the gas price, the higher the NPV. When the NPV is above 0, the projects are profitable. The NPVs are the ones at the end of the lifetime of the respective technology. The gas prices are expressed in [€/kWh]

4.7 Sensitivity analysis

In this section, the goal is to analyze the effect of different parameters on the results. The parameters under study are the maintenance costs, the electricity price factor and the discount rate. For this part, the reference electricity price factor is equal to 0.5, the reference discount rate to 10% and the reference costs of maintenance are described in the section 4.1. In Brussels, the prices are the ones used in the example at the section 4.3.1. In Madrid, the prices of electricity and natural gas are the ones from the first semester of 2022. The electricity price is 0.3071 €/kWh [35] and the natural gas price is 0.0897 €/kWh [36]. In Riga, the prices of electricity and natural gas are the ones from the first semester of 2022. The electricity price is 0.2236 €/kWh [35] and the natural gas price is 0.0462 €/kWh [36].

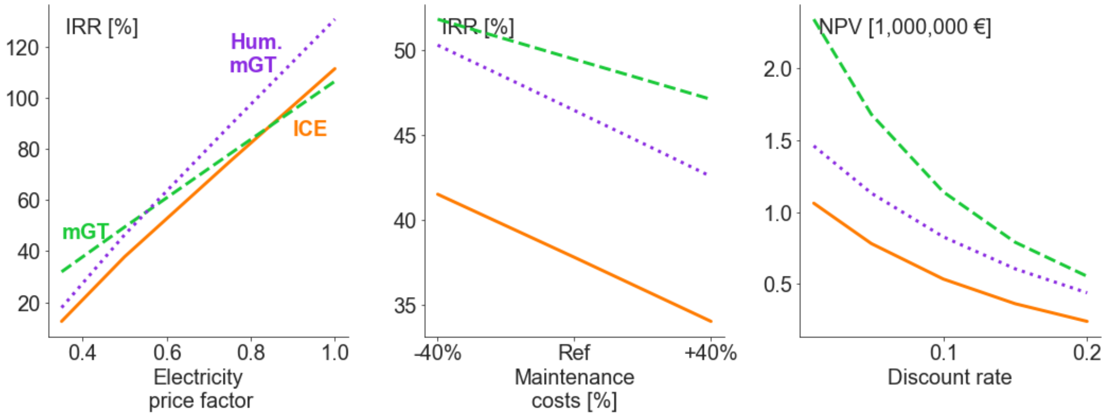

Figure 4.7: Sensitivity results in Brussels : the influence of the electricity price factor is strong, the variations of the maintenance costs influence but not as much as the electricity factor and the discount rate has a very strong influence on the resulting NPVs

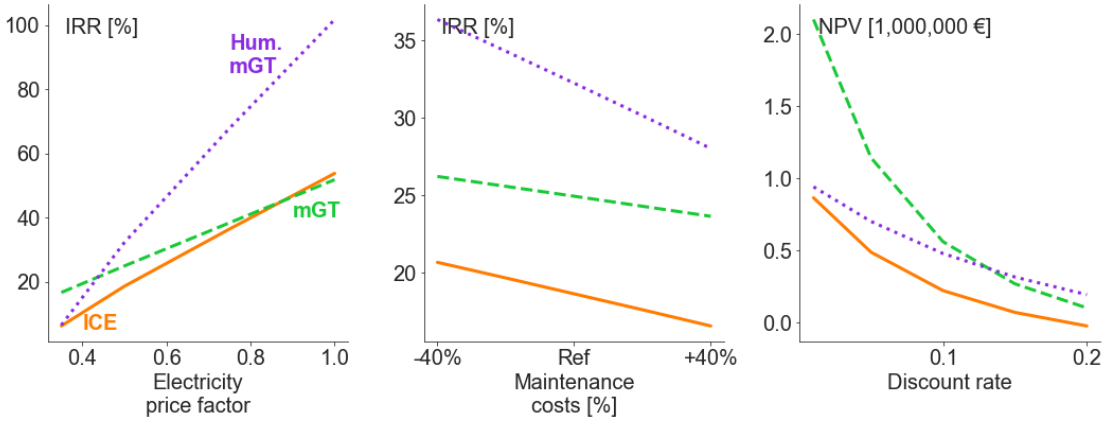

Figure 4.8: Sensitivity results in Madrid : the influence of the electricity factor is strong especially on the humidified engine, the variations of the maintenance costs influence but not as much as the electricity price factor and the discount rate has a very strong influence on the resulting NPVs but is less influent on the humidified turbine

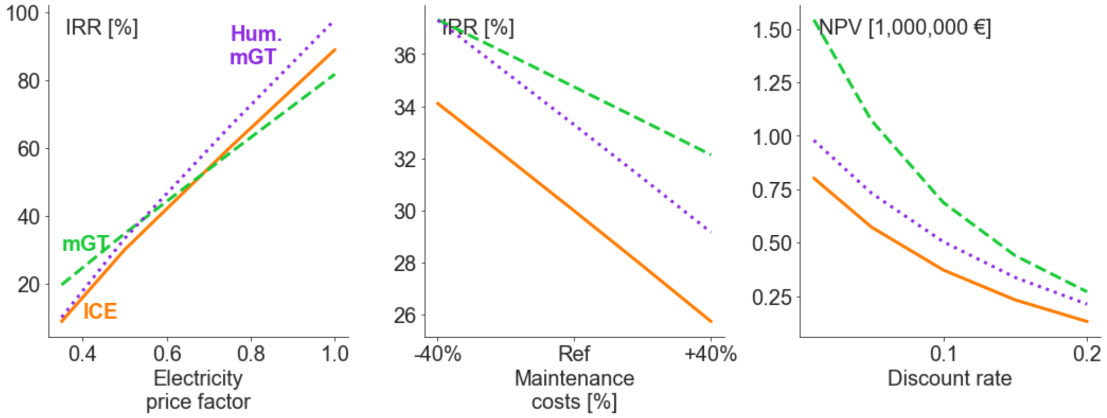

Figure 4.9: Sensitivity results in Riga : the influence of the electricity price factor is strong, the variations of the maintenance costs influence but not as much as the electricity factor and the discount rate has a very strong influence on the resulting NPVs

The variation of the maintenance costs do not have a strong influence. Of course, as the maintenance costs increase, the IRR decreases as the NPV. This variation is linear and the gradient is small thus it has not a big impact compared to the other parameters.

The variation of the discount rate has a high impact. As the discount rate increases, the IRR decreases. Here, the variation is not linear and as the discount rate increases, the gradient decreases. The variation is thus higher for changes of small values of discount rate. This happens because, with a higher discount rate, the cashflows after several years, even if they stay the same, have a smaller present value compared to the cashflows that suffer smaller discount rate.

The variation of the electricity price factor is more interesting because one can see that the curves of the variation of IRR cross each other at certain point. When the electricity price factor is small, the dry mGT and the ICE behave better than the humidified mGT. The humidified mGT produces a lot of excess electricity which is sold to the grid. To produce this electricity, it uses a lot of fuel. This big quantity of fuel can cost a lot of money and if the electricity price factor is not big enough, the benefits from the sold electricity are not enough to compensate the costs of fuel and to create higher cashflows than the ones generated by the dry mGT and the ICE. At a certain point, the electricity price factor becomes sufficiently high so that it is best to run in wet mode than buying electricity from the grid. This factor at which the humidified mGT becomes more interesting than the dry mGT is smaller for Madrid because the electricity demand is high in summer when the heat demand is low which means that the Spanish user does not need to sell a lot of electricity at low prices. This makes save him money compared to users from other region who sell big quantities of electricity at these low prices.

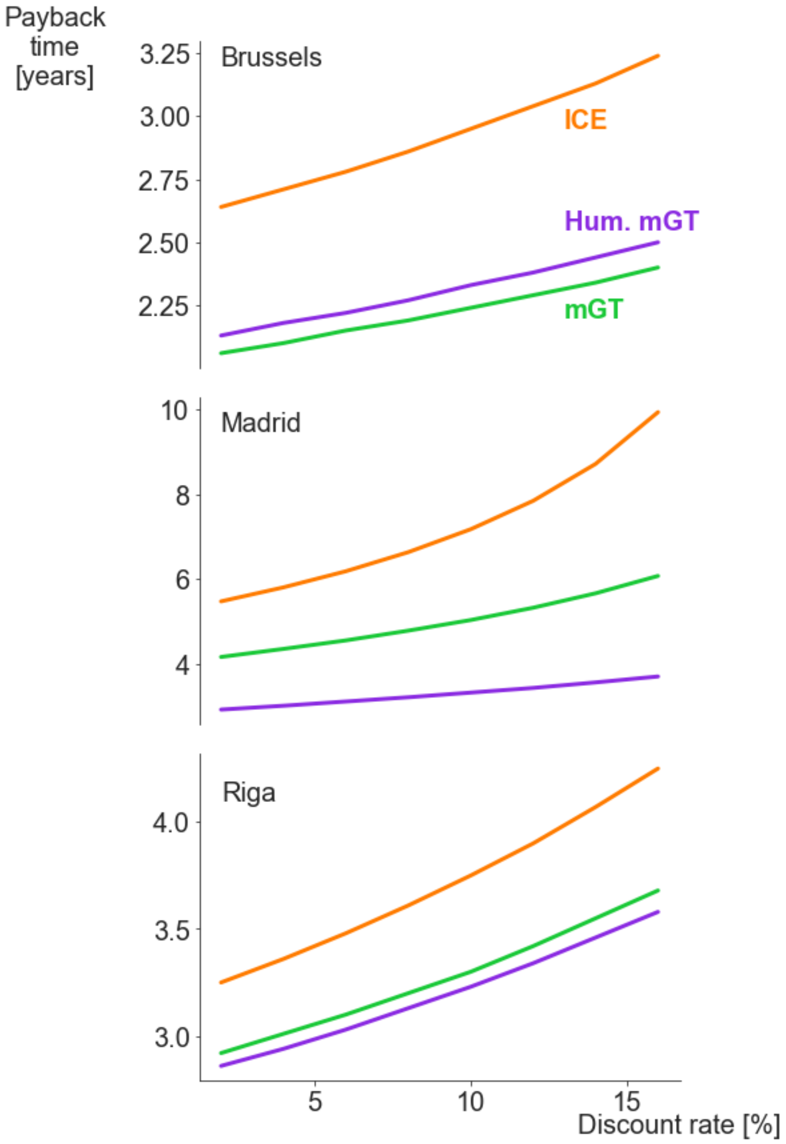

Figure 4.10: Payback time in function of the discount rate : the ICEs have the highest PBTs, humidified mGTs have the smallest PBTs except in Brussels, and Madrid is the place where the PBTs are the highest because the lifetime is higher and the cashflows are lower

The different PBTs following the engines, the places and the discount rates are depicted in Fig. 4.10. In every place, the ICE has the longest PBT. This is due to the lower cashflows that it generates because it feeds less dwellings but needs more fuel to produce the same amount of heat which increases the costs and reduces the cashflows. In Brussels, the humidified mGT has a longer PBT than the dry mGT. This is because their cashflows are really close and even if the cashflows of the humidified mGT are a little bit bigger, this does not compensate the initial cost of the engines which is lower for the dry mGT. With so close cashflows and that difference of initial costs, the NPV curves cross each other after the PBT point. The PBT in Brussels are the smallest because the cashflows are bigger. Also the PBTs in Madrid are longer because the cashflows are smaller and the lifetime of the ICE and the dry mGT is higher. And as the discount rate increases, the PBTs increase aswell. This happens because with higher discount rates, the cashflows over the years even if they stay the same do not represent the same present values. This present value of cashflows decrease with the years and thus more time is needed to recoup the investment.

4.8 Conclusion

In the present chapter, we have analyzed three different heat and electricity demands, one in Brussels, one in Madrid and one in Riga. Although the demand curves in Brussels and Riga were pretty similar with a constant electricity demand all over the year (this demand was smaller in Riga) and a distinction between summer and winter for the heat demand, the curves in Madrid were pretty different with a summer season charaterized by a higher electrical demand due to the use of air conditioning and a low heat demand. This low heat demand leads to a longer time in wet mode for the humidified mGT which offers better perspective compared to the other technologies. Instead of buying high quantities of electricity from the grid, the humidified mGT produces even more than needed and can sell the excess to the grid. And if the market conditions are met (with a higher electricity price and a lower gas price), the humidified mGT outperforms certainly the other technologies. In Brussels and Riga, this latter is more uncertain and the market conditions need to be really favorable for the humdified mGT to compete the dry mGT. The biogas engines were also under study in Brussels and thanks to a lower gas price, it can show great performances despite their lower efficiencies.

At the same time, the PES has been computed for every technology in the different cities. All technologies present positive PES. Brussels and Riga have very similar results but they differ a little for the humdified mGT in Madrid. The dry mGT has the best PES because it has slightly the same global electrical efficiency as the two other engines but its thermal efficiency is higher. ICE has a lower thermal efficiency because, for the same electrical output, it produces less thermal output. The humidified mGT has a low PES because of its low total efficiency in wet mode. Indeed, when it runs in wet mode, the total efficiency is almost equal to the electrical efficiency which is a bit higher but not enough to compensate the tiny thermal efficiency. This happens because a big part of the heat is used to heat water in order to inject it into the gas cycle to increase the electrical efficiency.

The biogas technologies have a similar behavior but their PES are higher thanks to the lower reference efficiencies and the good efficiencies of the engines.

Then, a price analysis has been performed. Results show that the higher the electricity price and the lower the gas price, the more profitable the project. If the gas price is low, the best technology is the humidified mGT but if it is high, the best solution is the dry mGT. On the opposite, if the electricity price is low, the best engine is the dry mGT and if it is high, the best unit is the humidified mGT. Thus, the humdified mGT outperforms the dry mGT and the ICE when the gas price is low and the electricity price is high. With a low gas price, the turbine produces lot of electricity, especially in wet mode, for a low fuel cost and then the electricity can be used on-site at very little cost or can be sold to the grid at a good price in comparison with its little production cost, and that even if the electricity price factor is small. On the contrary, the dry mGT outperforms the humdified mGT when the gas price is high because it is certainly more cost-effective to directly buy electricity from the grid than produce its own electricity from expensive gas. With a high electricity price, the humidified mGT is the best technology because instead of buying expensive electricity, it can be produced from gas no matter the heat demand. In contrast, the dry mGT is a better solution when the electricity price is low because the user needs to buy more electricity from the grid with this engine and this is profitable because the electricity is cheap. And the user of the humdified mGT produces more electricity from expensive gas compared to the cheap electricity and this electricity is sold to the grid at a very low price.

Ultimately, the sensitivity analysis showed the parameters that play a crucial role in the viability of the projects. The most important parameter is the electricity price factor. A low electricity price factor does not advantage the humidified mGT. Indeed, this engine produces way more electricity than the two others but also way more than the electrical demand which means that the excess electricity needs to be sold to the grid. And the lower the electricity price factor, the less profitable is the project. In comparison with the ICE and the dry mGT, the electricity price factor has the biggest influence in Spain. The maintenance costs have a minor impact on the economic performances. As they increase, the viability of the projects decreases but slowly. The discount rate has a real influence, especially for small values of discount rate. As it increases, the NPV decreases and the PBT increases which is normal because the present values of the cashflows decrease at a higher rate with the years.

Chapter 5

Results including subsidies

After having assessed the profitability of humidified mGTs and CHP units from a generic point of view, this chapter aims to study the feasibility of humidified mGTs in two specific countries by taking into account their different policies about cogeneration systems and the subsidies they attribute to these systems. The two countries are Spain and Belgium. They both offer subsidies but their conditions to attribute them differ. In Belgium, they are three regions with different policies and they distribute certificates following some conditions on CHP savings and CO_2 savings. These certificates can be sold to energy companies. In Spain, subsidies are divided into a capital subsidy and operational helps.

A review of the different cogeneration policies in each region has been performed. Then the economic feasibility of these units in the market conditions of the specific countries has been evaluated. The results show that Spain is the most favorable region to implement humidified mGTs. And in Belgium, Brussels is the most generous region but it advantages most the dry mGT.

5.1 Policies

5.1.1 Spain

The policies and the subsidies attributed in Spain for electricity production from renewable energy and from cogeneration systems are described in the Royal Decree 413/2014 [38] and in the Order IET/1045/2014 [39]. According to the directives, a specific remuneration is given to the cogeneration and the renewable energy systems in order to be able to compete economically against other energy sources. This sepcific remuneration is divided into two different components for small-scale CHP units :

- The investment remuneration (R_{inv}) is a component that aims to compensate the initial cost of the engine. Following the type of the installation and the year of commissioning, a value for R_{inv} is attributed, expressed in €/MW. This value has to be multiplied by the nominal power of the installation

- The operation remuneration (R_o) is a component that aims to compensate the operation costs of the engine. Following the type of the installation and the year of commissioning, a value for R_o is attributed, expressed in €/MWh. This value has to be multiplied by the amount of electricity that is sold to the market

The values of R_{inv} and R_o are the same for the two mGTs but differ for the ICE. The values used in this work are the most recent ones available and are for engines installed in 2016 operating in the year 2019 with a nominal electrical power below 500 kW [39]. R_{inv} is from the year 2019 and is equal to 179,578 €/MW for the mGTs and to 98,922 €/MW for the ICE. R_o is the value for the 2nd semester of 2019 and is equal to 74.755 €/MWh$_\mathrm{e}$ for the mGTs and to 75.288 €/MWh$_\mathrm{e}$ for the ICE [40]. R_{inv} and R_o are updated each year (R_o is updated each trimester following the gas price).

5.1.2 Belgium

In Belgium, the policies for energy subsidies are divided between the three regions. The method that has been used for sizing the demand takes into account the climate and the averaged consumption per dwelling in Belgium. Since Belgium is a small country, the climate does not change from one region to another and thus the demand of the users is considered the same in each region. With different policies but with the same demand, it gives the opportunity to understand the effects of different ways of attributing cogeneration subsidies. In Wallonia and in Brussels, Green Certificates (GC) are given for renewable energy and cogeneration. In Flanders, the authorities give specific cogeneration certificates.

Brussels

The region of Brussels promotes cogeneration energy through green certificates as defined in a decree from October 2021 [41] which modifies a precedent decree from 2001. The green certificates in Brussels are emitted and given by BRUGEL. Each green certificate is given for every block of 217 kg of saved CO_2 [42].

For an engine running with natural gas and distributing its production to several residential clients, a coefficient multiplicator of 1.5 is applied to the total result of green certificates attributed [42, 43]. The reference electrical efficiency is 0.55 and the reference thermal efficiency is 0.9. The number of green certificates is given by the following formula [42]:

$$N = 1.5 \cdot \left(\frac{E \cdot 0.217}{0.55} + \frac{Q \cdot 0.217}{0.9} - Fuel \cdot 0.217 \right) \ / \ 217 \tag{5.1}$$

where N is the number of green certificates,
1.5 is the coefficient for cohousing with natural gas,
E is the total produced electricity expressed in kWh,
Q is the total produced heat expressed in kWh,
Fuel is the used quantity of fuel expressed in kWh.

Companies buy those green certificates for 65 €/GC for Engie [44] and for 75 €/GC for EDF Luminus (EDF limits to 50 certificates per year) [45]. A price of 65 €/GC has thus been chosen in the following steps of this thesis.

Wallonia

The region of Wallonia promotes cogeneration energy through green certificates as defined in a decree from April 2019 [46] which modifies a precedent decree from 2006. The green certificates in Wallonia are emitted and given by the energy section of the Wallonia public service (SPW Energie). Each green certificate is given for every block of 456 kg of saved CO_2.

The number of green certificates is given thanks to the following formula [47] :

$$N = tCV \cdot Eenp \tag{5.2}$$

where N is the number of green certificates,
tCV is the number of green certificates that can be given per produced MWh of electricity, expressed in GC/MWh and it is calculated as $tCV = min(cap, kCO2 \cdot kECO)$ with the cap equal to 2.5 CV/MWh, kCO2 is computed thanks to a simulator from the SPW and represents the CO_2 saving rate and is limited to 2 for engines below 5 MW, kECO is the economic coefficient and is equal to 1 for our engines [48],
Eenp is the total produced electricity, expressed in MWh.

The kCO2 is computed thanks to the simulator from the SPW :

- For the ICE unit, kCO2 equals 0.488
- For the dry mGT, kCO2 equals 0.591
- For the humidified mGT, kCO2 equals 0.421

Companies like Engie and EDF Luminus buy these GCs at 65 €/MWh [49, 45] and this value is used in the following of this work.

Flanders

The region of Flanders promotes cogeneration through specific cogeneration certificates delivered by VREG, the regulations authority for the energy in Flanders. This is defined in a decret from 2009, the energy decree [50]. One cogeneration certificate is given for each block of 1,000 kWh of heat and electricity savings but this number is multiplied by the applicable grouping factor.

The number of certificates is given by the following formula [51] :

$$N = WKB \cdot Bf \tag{5.3}$$

where N is the number of certificates,
Bf is the grouping factor equal to 0.263 in the case of engines between 200 $\mathrm{kW_e}$ and 1 $\mathrm{MW_e}$ running with natural gas [52],
WKB is the heat and energy savings and is computed as [53] :

$$WKB = \frac{E}{\eta_e} + \frac{Q}{\eta_{th}} - F \tag{5.4}$$

with E, the total produced electricity, expressed in kWh,
Q, the total produced heat, expressed in kWh,
F, the total quantity of used fuel, expressed in kWh,
η_e is the reference electrical efficiency and is equal to 50%,
η_{th} is the reference thermal efficiency and is equal to 90%.

Companies like Elia buy these cogeneration certificates. There is a minimal price at which these certificates can be sold. This minimal price is equal to 31 € per certificate for natural gas engines [54].

5.2 Results

In the precedent chapter, the engines were studied under a generic point of view to assess the best case in which they should run. This section focuses on two different countries and their specific policies for cogeneration. Thus, realistic parameters should be chosen. The gas prices and the electricity prices are the ones of reference in the previous chapter and the maintenance costs and the discount rate are also the same as in the previous chapter. But the electricity price factor has to be chosen in order to be more realistic. Its value for Spain is estimated at 0.2 and its value for Belgium is estimated at 0.15 [1]. As mentioned before, these values of electricity price factor are low and not profitable at all, leading most of the time to very low IRRs or negative ones or even to no IRR at all. This later is especially true for the ICE and the humidified mGT.

Without subsidies, no project is profitable. With policies, projects become profitable. The results are depicted on Fig. 5.1.

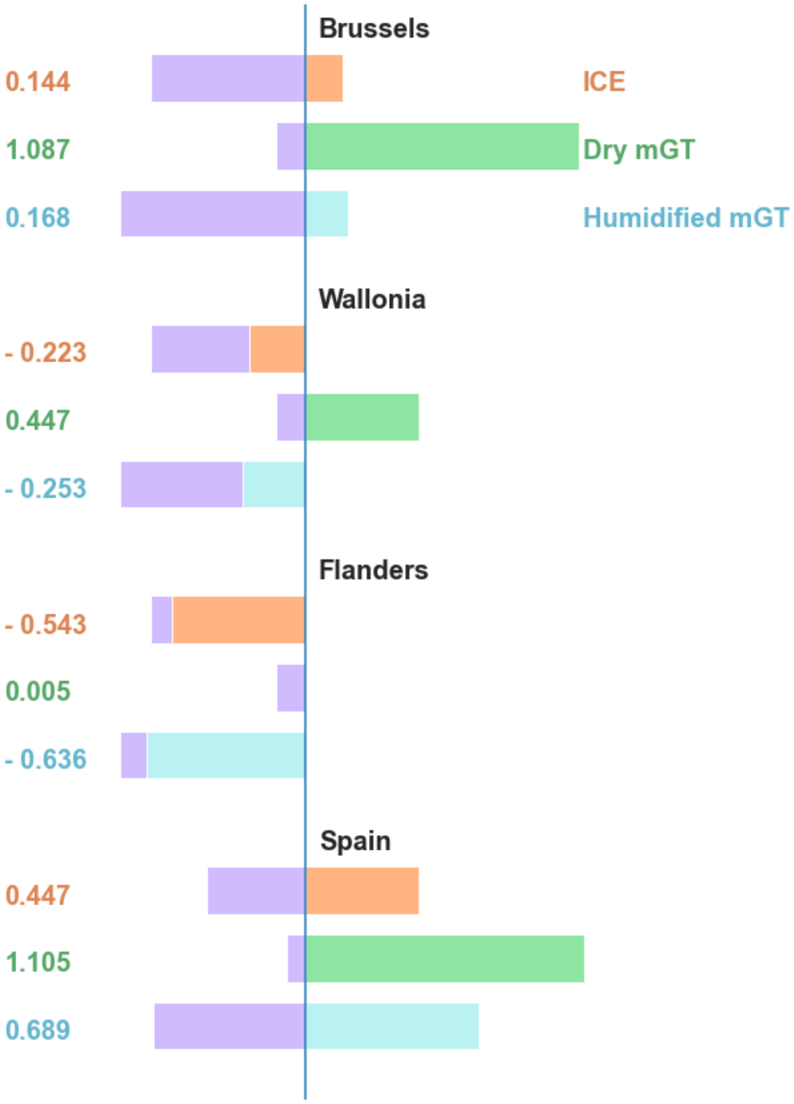

Figure 5.1: Effects of the different policies on the resulting NPVs until the end of the lifetime of each engine, in each region, the NPVs are expressed in [1,000,000 €]. In mauve, the NPVs without policies, in orange the ICEs NPVs with policies, in green the dry mGTs NPVs with policies and in blue the humidified mGTs NPVs with policies. Spain is the best region where the policies permit to get profitable. In Belgium, Brussels is the region where NPVs with policies are the highest

In Belgium, the region that gives the highest subsidies is Brussels. The results for the number of GC and subsidies in each region of Belgium for the different engines is resumed in the table 5.1. In Brussels, the dry mGT is the engine that receives the biggest number of GC, just ahead of the humidified mGT. In Brussels, GCs are given following the number of blocks of 217 kg of CO_2 saved. The ICE does not receive as much GCs because its thermal global efficiency (44.82%) is lower than the one of the dry mGT (54.39%). The humidified mGT has also a lower thermal efficiency (41.4%) but it runs all year round and so produces more but also saves more CO_2 which explains that the number of GCs attributed is bigger for the humidified mGT than for the ICE. These different subsidies lead to positive NPVs for all engines. The dry mGT beats the two other technologies thanks to the higher subsidies it receives and to its higher NPV without policies.

Table 5.1: Results for the subsidies in Belgium : Brussels is the region that gives the highest subsidies

	Engine	Number of GC attributed per year	Price per GC [€]	Subsidy [€/year]
Brussels	ICE	1,800	65	117,000
	Dry mGT	2,513		163,345
	Humidified mGT	2,421		157,365
Wallonia	ICE	931	65	60,515
	Dry mGT	1,178		76,580
	Humidified mGT	1,295		84,175
Flanders	ICE	407	31	12,617
	Dry mGT	536		16,616
	Humidified mGT	571		17,701

In Wallonia, it is the humidified mGT that receives the highest subsidies. The number of GCs attributed is proportional to the total produced electricity each year. Since the humidified mGT runs all year which is not the case for the ICE and the dry mGT, it produces more electricity than the two other technologies. This number of GCs is also proportional to kCO2, the CO_2 saving rate. It is computed from the annual electrical efficiency and the annual thermal efficiency. Its value is higher for the dry mGT, then for the ICE and eventually for the humidified mGT. The humidified mGT having a higher production but a way lower kCO2, it receives only a bit more GCs than the dry mGT. The ICE has an electrical production equivalent to the one of the dry mGT but has a lower thermal efficiency, thus a lower kCO2 and thus it receives less GCs than the dry mGT. Unfortunately, the subsidies are not enough to make the ICE and the humidified mGT profitable. But the dry mGT, which has a higher NPV without policies, becomes profitable when subsidies are received.

In Flanders, the directives are hard and thus, only the dry mGT is profitable but with a very low NPV. In this region, the system to receive cogeneration certificates is similar to Brussels. A certificate is given following a CHP saving but the reference value for the electrical reference efficiency is slightly different from Brussels (50% in Flanders compared to 55% in Brussels). Also, for natural gas engines, there is a grouping factor of 0.263 which reduces the number of certificates that are attributed. Since the humidified mGT has a good electrical efficiency and that the reference electrical efficiency in Flanders is lower than in Brussels, the humidified mGT receives a little bit more certificates than the dry mGT. But the combination of a factor of 0.263 in Flanders and a factor of 1.5 in Brussels makes that the number of certificates given in Flanders is way lower than in Brussels. And the minimum price per GC is also lower than the price in Brussels. All this leads to low subsidies compared to the two other regions of Belgium. These low subsidies mean that it is almost impossible to achieve profitability.

In Spain, the subsidies are divided in two components. The results for Spain are depicted in Fig. 5.2. The first component, R_{inv}, is proportional to the nominal electrical power of the installation but the reference value is different between motor and turbines. This component is thus the same for both mGTs and lower for the ICE. The second component, R_o, is proportional to the yearly electrical production. The reference value is slighty higher for motor engines. Thus, this value is a bit higher for the ICE compared to the dry mGT. Since the production of the humidified mGT is way higher than the one of the two other engines, its value of R_o is almost three times bigger. R_o compensates well for the maintenance costs but not for the operation costs. Indeed, the fuel costs are approximately five to seven times the values of R_o. But despite these high fuel costs, the NPVs are all positive when subsidies are applied. The highest NPV is obtained for the dry mGT but it should be remembered that its lifetime is 27 years compared to 9 years for the humidified mGT. The value of the NPV of the dry mGT after nine years is lower than the one of the humidified mGT.

Table 5.2: Results for the subsidies in Spain : the humidified mGT is the engine that receives the highest subsidy. The fuel costs are extremely high in comparison with R_o

	Fuel costs [€]	Maintenance costs [€]	R_{inv} [€]	R_o [€]
ICE	339,261	16,615	39,568	59,290
Dry mGT	389,975	13,706	71,831	56,211
Humidified mGT	727,876	42,989	71,831	153,012

5.3 Conclusion

In conclusion to this chapter, the policies in the different studied regions aim to provide subsidies and to invest in cogeneration and renewable energy in order to compete against conventional energy sources. But these policies differ from one region to another and so they have not the same effects.

In Spain, the subsidies improve significantly the profitability of the projects for the three different engines. Despite high fuel costs, the subsidies permit to offset these expenses. The humidified mGT is the solution that offers the highest NPV if its lifetime is taken into account. The two other technologies are still also profitable.

In Belgium, the situation is different following the regions. Despite the same demands, the different policies in each region lead to different subsidies attributed and to different profitability. Brussels is the region that offers the highest subsidies and the dry mGT is the engine that receives most of the subsidies and that achieves the highest NPV. In Wallonia, harder policies are applied since more CO_2 must be saved in order to receive a GC which leads to less GCs attributed and to less subsidies. This implies that only the dry mGT achieves profitability. And in Flanders, the policies are hard for natural gas engines. A grouping factor is applied that shrinks the number of certificates which leads to lower subsidies and to difficulty to reach profitability.

Overall, subsidies play a crucial role in determining the economic feasibility of cogeneration projects. Spain is the most favorable region and in Belgium, Brussels is the msot generous region in attributing subsidies. This shows that well-designed subsidy schemes help to promote sustainable energy practice and to invest in renewable energy and cogeneration systems.

Chapter 6

Conclusion

This work aims to assess the economic feasibility of humidified mGTs through the Aurelia A400 model. This engine has a wet mode which enables it to run when the heat demand is very low. These humidified engines allow to decouple heat and electricity production. They work in cogeneration when the heat demand is sufficient and when the heat demand is low, water injection allows to use the heat from the exhaust gases to increase their electrical efficiency. By doing so, they are able to run all year which is not the case for the other CHP technologies. In this work, the technology of liquid water injection has been studied for the humidified mGT.

An economic model that takes in inputs the hourly demands of heat and electricity throughout a year for domestic users in different countries and uses NPV and IRR metrics to assess the profitability and the economic performances of the cogeneration units has been developed. The humidified mGT was compared to an ICE and a dry mGT.

First, different demands have been compared, the profitability has been assessed for Brussels, Madrid and Riga. These three cities have different climates and so different demand curves. In Brussels and in Riga, the heat demand is different from winter and summer and the electricity demand is constant along the year but the electricity demand is smaller. In Madrid, the heat demand is also splitted between summer and winter but the electricity demand is divided between summer and winter with more electricity consumption during summer because of the use of air conditioning. While the advantages of the humidified mGTs are less evident in Brussels and Riga, it proved itself to be a promising solution in Spain if the market conditions are not to rough. And despite not having been studied in the rest of the thesis, the biogas engine showed interesting results thanks to the low biogas price.

Subsequently, a sensitivity analysis has been performed to show the impact of the different parameters. The electricity and gas prices are by far the most important parameters that have an influence on the profitability. A high electricity price and a low gas price lead to the best economic viability of the technologies. But that does not imply that the humidified mGT outperforms the other technologies. If the gas price is low, the best engine is the humidified mGT but if it is high, the best engine is the dry mGT. And if the electricity price is high, the best technology is the humidified mGT but if it is low, the best solution is the dry mGT. Another significant parameter is the electricity price factor. Results show that obviously, if the electricity is sold to the grid at a high price, it increases the profitability. This is particularly true for the humidified mGT which produces a lot of electricity in wet mode and especially when it is located in Spain.

The primary energy saving of those technologies has also been assessed. Results show that all technologies have positive PES. But the dry mGT is the engine that achieves the highest PES while the humidified mGT achieves a lower PES. This latter comes because the humidified mGT runs all year and when the mGT runs in wet mode, its overall efficiency is almost equal to its electrical efficiency which is low and leads to lower PES. This explains why the mGT and ICE primary energy saving is the same no matter the region but in Spain, the PES of the humidified mGT is 5% lower than in Belgium or in Latvia. The PES of the biogas units have been measured in Brussels and thanks to their high efficiencies and the lower reference efficiencies, the biogas units achieve high energy savings.

Ultimately, the impact of different policies has been studied in Spain and in the three different regions of Belgium. In Spain subsidies are given with two components, one that compensates for the investment cost and the other for the operation costs. And in Belgium, different certificates are given with different conditions. Brussels is the most generous region in Belgium. In Spain, all three technologies become profitable thanks to the subsidies. The dry mGT has the highest NPV but after 27 years of service. At the decommissioning of the humidified mGT, the dry mGT has a lower NPV. In Belgium, the subsidies advantage the dry mGT which is profitable in the three regions. And Brussels is the only region where all technologies are profitable.

In conclusion, the economic profitability depends on several parameters : the heat and electricity demands, the gas and electricity prices, the electricity price factor, and the discount rate but also on the policies and subsidies attributed in each country. This study highlights that the region where the humidified mGT outperforms in a better way the other technologies is in Spain. Indeed, in Madrid, the humidified mGT runs all year long producing a lot of electricity in summer thanks to the wet mode which allows it to fulfill the higher electricity demand and to sell the excess of electricity to the grid and the Spanish subsidies are sufficient to allow all technologies to become profitable.

Bibliography

[1] Marina Montero Carrero. «Decoupling heat and electricity production from micro gas turbines : numerical, experimental and economic analysis of the micro humid air turbine cycle». PhD thesis. Brussels, Belgium: Université libre de Bruxelles, Mar. 2018 (cit. on pp. 3, 18, 26, 52).

[2] Jingqi Li and Yulong Li. «Micro gas turbine: Developments, applications, and key technologies on components». In: *Propulsion and Power Research* 12.1 (2023), pp. 1–43. ISSN: 2212-540X. DOI: `https://doi.org/10.1016/j.jppr.2023.01.002`. URL: `https://www.sciencedirect.com/science/article/pii/S2212540X23000123` (cit. on pp. 4–7).

[3] Marco Nascimento, Lucilene de, Eraldo Santos, Eli Gomes, Fagner Goulart, Elkin Gutierrez, and Ruben Miranda. «Micro Gas Turbine Engine: A Review». In: June 2013. ISBN: 978-953-51-1166-5. DOI: `10.5772/54444` (cit. on p. 4).

[4] Reyhaneh Banihabib and Mohsen Assadi. «The Role of Micro Gas Turbines in Energy Transition». In: *Energies* 15 (Oct. 2022), p. 8084. DOI: `10.3390/en15218084` (cit. on pp. 4–8, 19).

[5] European Turbine Network (ETN). *Micro Gas Turbine Technology Summary : Research an Development for European Collaboration.* `https://etn.global/wp-content/uploads/2018/02/MGT-Technology-Summary-final-for-the-website.pdf` (cit. on pp. 4, 6, 7).

[6] Roberto Capata and Enrico Sciubba. «The concept of the gas turbine-based hybrid vehicle: system, design and configuration issues». In: *International Journal of Energy Research* 30.9 (June 2006), pp. 671–684. DOI: `https://doi.org/10.1002/er.1178` (cit. on p. 6).

[7] P.A. Pilavachi. «Mini- and micro-gas turbines for combined heat and power». In: *Applied Thermal Engineering* 22.18 (2002), pp. 2003–2014. ISSN: 1359-4311. DOI: `https://doi.org/10.1016/S1359-4311(02)00132-1`. URL: `https://www.sciencedirect.com/science/article/pii/S1359431102001321` (cit. on p. 6).

[8] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D'haeseleer. «Distributed generation: definition, benefits and issues». In: *Energy Policy* 33.6 (2005), pp. 787–798. ISSN: 0301-4215. DOI: `https://doi.org/10.1016/j.enpol.2003.10.004`. URL: `https://www.sciencedirect.com/science/article/pii/S0301421503003069` (cit. on p. 6).

[9] A. F. Massardo, C. F. McDonald, and T. Korakianitis. «Microturbine/Fuel-Cell Coupling for High-Efficiency Electrical-Power Generation ». In: *Journal of Engineering for Gas Turbines and Power* 124.1 (Feb. 2000), pp. 110–116 (cit. on p. 7).

[10] J. B. Schroeder. «Closed Brayton cycle advanced central receiver solar-electric power system. Volume 1: executive summary. Final report». In: (Nov. 1978). DOI: `10.2172/5654323`. URL: `https://www.osti.gov/biblio/5654323` (cit. on p. 7).

[11] Philip Barker and Robert Mello. «Determining the impact of distributed generation on power systems: Part 1 - Radial distribution systems». In: vol. 3. Feb. 2000, 1645–1656 vol. 3. ISBN: 0-7803-6420-1. DOI: `10.1109/PESS.2000.868775` (cit. on p. 8).

[12] N. Hadjsaid, J.-F. Canard, and F. Dumas. «Dispersed generation impact on distribution networks». In: *IEEE Computer Applications in Power* 12.2 (1999), pp. 22–28. DOI: `10.1109/67.755642` (cit. on p. 8).

[13] Ward De Paepe, Marina Montero Carrero, Svend Bram, Alessandro Parente, and Francesco Contino. «Towards higher micro Gas Turbine efficiency and flexibility — Humidified mGTs: A Review.» In: *Journal of Engineering for Gas Turbines and Power* 140 (Nov. 2017). DOI: `10.1115/1.4038365` (cit. on pp. 8–13).

[14] Toussaint Williamson, Mike Luker, and R. Hack. «Microturbine Performance Improvement Through the Implementation of Inlet Air Cooling». In: Jan. 2005. DOI: `10.1115/GT2005-68377` (cit. on p. 11).

[15] M. Renzi, F. Caresana, L. Pelagalli, and G. Comodi. «Enhancing micro gas turbine performance through fogging technique: Experimental analysis». In: *Applied Energy* 135 (2014), pp. 165–173. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2014.08.084`. URL: `https://www.sciencedirect.com/science/article/pii/S0306261914008952` (cit. on p. 11).

[16] Ward De Paepe, Frank Delattin, Svend Bram, and Jacques De Ruyck. «Water injection in a micro gas turbine – Assessment of the performance using a black box method». In: *Applied Energy* 112.C (2013), pp. 1291–1302 (cit. on p. 11).

[17] Ward De Paepe, Francesco Contino, Frank Delattin, Svend Bram, and Jacques De Ruyck. «Optimal waste heat recovery in micro gas turbine cycles through liquid water injection». In: *Applied Thermal Engineering* 70 (Sept. 2014), pp. 846–856. DOI: `10.1016/j.applthermaleng.2014.05.089` (cit. on pp. 11, 12).

[18] Jong Jun Lee, Mu Sung Jeon, and Tong Seop Kim. «The influence of water and steam injection on the performance of a recuperated cycle microturbine for combined heat and power application». In: *Applied Energy* 87.4 (2010), pp. 1307–1316. ISSN: 0306-2619. DOI: `https://doi.org/10.1016/j.apenergy.2009.07.012`. URL: `https://www.sciencedirect.com/science/article/pii/S0306261909003018` (cit. on pp. 11, 12).

[19] Frank Delattin, Svend Bram, Sofie Knoops, and Jacques De Ruyck. «Effects of steam injection on microturbine efficiency and performance». In: *Energy* 33 (Feb. 2008), pp. 241–247. DOI: `10.1016/j.energy.2007.09.007` (cit. on p. 12).

[20] Rao A. D. «Process for producing power». In: *US patent no. 4829763* (Dec. 1989) (cit. on p. 12).

[21] M. Montero Carrero, W. De Paepe, A. Parente, and F Contino. «T100 mGT converted into mHAT for domestic applications: Economic analysis based on hourly demand». In: *Applied Energy* 164 (2015), pp. 1019–1027 (cit. on p. 13).

[22] Ward De Paepe, Marina Montero Carrero, Svend Bram, Francesco Contino, and Alessandro Parente. «Waste heat recovery optimization in micro gas turbine applications using advanced humidified gas turbine cycle concepts». In: *Applied Energy* 207.C (2017), pp. 218–229 (cit. on p. 13).

[23] Ward De Paepe, Frank Delattin, Svend Bram, Francesco Contino, and Jacques De Ruyck. «A Study on the Performance of Steam Injection in a Typical Micro Gas Turbine». In: vol. 5. June 2013. DOI: `10.1115/GT2013-94569` (cit. on p. 13).

[24] Marina Montero Carrero, Ward De Paepe, Jan Magnusson, Alessandro Parente, Svend Bram, and Francesco Contino. «Experimental characterisation of a micro Humid Air Turbine: assessment of the thermodynamic performance». In: *Applied Thermal Engineering* 118 (May 2017), pp. 796–806. DOI: `10.1016/j.applthermaleng.2017.03.017` (cit. on p. 13).

[25] M. Malkämaki et al. «Design of a 400 KW gas turbine prototype». In: *ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition.* June 2016 (cit. on p. 13).

[26] M. Malkämaki et al. «A High Efficiency microturbine concept». In: *11th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics.* Mar. 2015 (cit. on pp. 14, 26, 27).

[27] *Technical specification, agenitor 406 EG / 50Hz.* Heek, Germany: 2G Energy AG (cit. on p. 15).

[28] *Technical specification, agenitor 408 BG / 50Hz.* Heek, Germany: 2G Energy AG (cit. on p. 15).

[29] Aggelos Gaitanis, Francesco Contino, and Ward De Paepe. «Real Time Micro Gas Turbines Performance Assessment Tool: Comprehensive Transient Behavior Prediction With Computationally Effective Techniques». In: *Journal of Engineering for Gas Turbines and Power* 145.3 (Dec. 2022), p. 031006. ISSN: 0742-4795. DOI: `10.1115/1.4055785`. eprint: `https://asmedigitalcollection.asme.org/gasturbinespower/article-pdf/145/3/031006/6954076/gtp\_145\_03\_031006.pdf`. URL: `https://doi.org/10.1115/1.4055785` (cit. on p. 16).

[30] The European Parliament and the Council of the European Union. «Directive 2012/27/EU of the European Parliamen and of the council on energy efficiency». In: *Official Journal of the European Union* (Oct. 2012) (cit. on p. 24).

[31] The European Parliament and the Council of the European Union. «Commission Delegated Regulation (EU) 2015/2402 reviewing harmonised efficiency reference values for separate production of electricity and heat». In: *Official Journal of the European Union* (Oct. 2015) (cit. on p. 24).

[32] Open Energy Information. *Datasets file.* `https://openei.org/datasets/files/961/pub/`. Last accessed : 2023-07-03 (cit. on p. 28).

[33] Codeminders. *Weather similarity.* `https://www.codeminders.com/weather_similarity/`. Last accessed : 2023-07-03 (cit. on p. 28).

[34] Odyssee-Mure. *Energy consumption per dwelling.* `https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/electricity-consumption-dwelling.html`. Last accessed : 2023-07-03 (cit. on pp. 28, 30).

[35] Eurostat - European Commission. *Electricity price statistics.* `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics`. Last accessed : 2023-07-03 (cit. on pp. 32, 44).

[36] Eurostat - European Commission. *Natural gas price statistics.* `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics`. Last accessed : 2023-07-03 (cit. on pp. 32, 44).

[37] International Energy Agency (IEA). *Biogas price statistics.* `https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/sustainable-supply-potential-and-costs`. Last accessed : 2023-07-03 (cit. on p. 35).

[38] Energía y Turismo Ministerio de Industria. «Real Decreto 413/2014, de 6 de junio, por el que se regula la actividad de producción de energía eléctrica a partir de fuentes de energía renovables, cogeneración y residuos.» In: *Agencia Estatal Boletin Oficial del Estado* 140 (June 2014), pp. 43876–43978 (cit. on p. 49).

[39] Energía y Turismo Ministerio de Industria. «Orden IET/1045/2014, de 16 de junio, por la que se aprueban los parámetros retributivos de las instalaciones tipo aplicables a determinadas instalaciones de producción de energía eléctrica a partir de fuentes de energía renovables, cogeneración y residuos.» In: *Agencia Estatal Boletin Oficial del Estado* 150 (June 2014), pp. 46430–48190 (cit. on pp. 49, 50).

[40] Energía y Turismo Ministerio de Industria. «Orden TED/990/2022, de 11 de octubre, por la que se establecen los parámetros retributivos para el periodo comprendido entre el 1 de octubre de 2018 y el 30 de junio de 2019 como consecuencia de la disposición adicional octava del Real Decreto-ley 15/2018, de 5 de octubre, y por la que se revisan los valores de la retribución a la operación correspondientes al primer semestre natural del año 2019.» In: *Agencia Estatal Boletin Oficial del Estado* 253 (Oct. 2022), pp. 143305–143474 (cit. on p. 50).

[41] Gouvernement de la Région de Bruxelles-Capitale. *28 Octobre 2021 - Arrêté du Gouvernement de la Région de Bruxelles-Capitale modifiant l'arrêté du Gouvernement de la Région de Bruxelles-Capitale du 17 décembre 2015 relatif à la promotion de l'électricité verte.* Available at `http://www.ejustice.just.fgov.be/eli/arrete/2021/10/28/2021022387/justel`. Accessed : 2023-08-07 (cit. on p. 50).

[42] BRUGEL. *Mécanisme des certificats verts.* `https://www.brugel.brussels/themes/energies-renouvelables-11/mecanisme-des-certificats-verts-35`. Accessed : 2023-08-07 (cit. on p. 50).

[43] BRUGEL. *Conditions pour la certification.* `https://www.brugel.brussels/themes/energies-renouvelables-11/conditions-pour-la-certification-286`. Accessed : 2023-08-07 (cit. on p. 50).

[44] ENGIE. *Vente de vos Certificats Verts - Région de Bruxelles-Capitale.* `https://www.engie.be/fr/certificatsverts`. Accessed : 2023-08-07 (cit. on p. 51).

[45] EDF Luminus. *Rachat de certificats verts à des particuliers*. `https://www.luminus.be/fr/particuliers/electricite-gaz-naturel/rachat-certificats-verts/`. Accessed : 2023-08-07 (cit. on p. 51).

[46] Gouvernement wallon. *11 AVRIL 2019. - Arrêté du Gouvernement wallon modifiant l'arrêté du Gouvernement wallon du 30 novembre 2006 relatif à la promotion de l'électricité produite au moyen de sources d'énergie renouvelables ou de cogénération*. Available at `https://www.ejustice.just.fgov.be/cgi/article_body.pl?language=fr&caller=summary&pub_date=19-05-06&numac=2019202162`. Accessed : 2023-08-07 (cit. on p. 51).

[47] SPW Energie. *Estimation du nombre de certificats verts en fonction du coefficient Keco*. `https://energie.wallonie.be/fr/estimation-du-nombre-de-certificats-verts-en-fonction-du-coefficient-keco.html?IDC=10276&IDD=135639`. Accessed : 2023-08-07 (cit. on p. 51).

[48] SPW Energie. *Keco applicables depuis le 1er janvier 2019*. `https://energie.wallonie.be/fr/keco-applicables-depuis-le-1er-janvier-2019.html?IDD=135668&IDC=10276`. Accessed : 2023-08-07 (cit. on p. 51).

[49] ENGIE. *Vente de vos Certificats Verts - Région Wallonne*. `https://www.engie.be/fr/certificatsverts-wallonie/`. Accessed : 2023-08-07 (cit. on p. 51).

[50] Vlaamse Codex. *Decreet houdende algemene bepalingen betreffende het energiebeleid*. Available at `https://codex.vlaanderen.be/portals/codex/documenten/1018092.html`. Accessed : 2023-08-07 (cit. on p. 52).

[51] Vlaamse Overheid. *Berekening warmte-krachtcertificaten*. `https://www.vlaanderen.be/bouwen-wonen-en-energie/groene-energie/certificatensteun-voor-groene-energie-en-wkk/warmte-krachtcertificaten/berekening-warmte-krachtcertificaten`. Accessed : 2023-08-07 (cit. on p. 52).

[52] Vlaamse Overheid. *Bandingfactor en onrendabele top*. `https://www.vlaanderen.be/bouwen-wonen-en-energie/groene-energie/certificatensteun-voor-groene-energie-en-wkk/bandingfactor-en-onrendabele-top`. Accessed : 2023-08-07 (cit. on p. 52).

[53] Vlaamse Overheid. *Warmte-krachtbesparing (WKB)*. `https://www.vlaanderen.be/bouwen-wonen-en-energie/groene-energie/certificatensteun-voor-groene-energie-en-wkk/warmte-krachtcertificaten/berekening-warmte-krachtcertificaten/warmte-krachtbesparing-wkb`. Accessed : 2023-08-07 (cit. on p. 52).

[54] Vlaamse Codex. *Decreet houdende algemene bepalingen betreffende het energiebeleid : Artikel 7.1.6. - 08/01/2023*. `https://codex.vlaanderen.be/Zoeken/Document.aspx?DID=1018092&param=inhoud&AID=1111517`. Accessed : 2023-08-07 (cit. on p. 52).

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain
Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | **www.uclouvain.be/epl**