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ESCUELA TÉCNICA DE INGENIERÍA (ICAI)

TECHNO-ECONOMICS OF CHP AND HVAC TECHNOLOGIES AT CONSUMER LEVEL

Autor: María Luisa Orozco Moyá

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Pablo Dueñas Martínez

Madrid

Junio 2018

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ESCUELA TÉCNICA DE INGENIERÍA (ICAI)

TECHNO-ECONOMICS OF CHP AND HVAC TECHNOLOGIES AT CONSUMER LEVEL

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Madrid

Junio 2018

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Orozco Moyá

TECHNO-ECONOMICS OF CHP AND HVAC TECHNOLOGIES AT CONSUMER LEVEL

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TECHNO-ECONOMICS OF CHP AND HVAC TECHNOLOGIES AT CONSUMER LEVEL

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Director: Chaves Ávila, José Pablo.
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Collaborating Institute: Instituto de Investigación Tecnológica (IIT) ICAI
Technical Institute of Massachusetts (MIT)

Executive Summary

The aim of this Project is the study of the integration and economic benefits of CHP technologies in residential buildings. In order to integrate them in the best possible way, optimization software will be used to compare the total cost function of each of them and the price of electricity from the market.

Using less pollutant technologies it would not only be possible to reduce the harm buildings do to the environment, but also reduce the costs of electricity in the medium term.

Key terms – Internal Combustion Engines (ICE), Fuel cells (FC), PVPC ("Precio Voluntario para el Pequeño Consumidor" which is the voluntary price for the small consumer and refers to the default electricity tariff for the small consumers).

Residential consumption in Spain represents the 35.1% of the total electricity demand in the country and the 24.9% of the total consumption of natural gas. This makes improvements regarding this consumption worth studying.

One of the activities that will have a major impact on the energy consumption in this sector is the integration of CHP technologies using natural gas as fuel. This would also permit, as it has been mentioned before, an important reduction of emissions.

This thesis takes as a basis some previous master thesis developed in this topic. For being able to gather information in order to draw some relevant conclusions regarding the integration of CHP technologies in residential consumption, a reference model has been used: Distributed Energy Resources Customer Adoption (DER-CAM), certain changes have been introduced in order to achieve the demand while minimizing the costs associated with investment and operation. The new features and changes in the code provide the user with the ability to interact with the building in terms of connection and disconnection times of CHP technologies.

This study uses computational tools available at IIT of Universidad Pontificia Comillas in Madrid and the Distributed Energy Resources Customer Adoption Model (DER-CAM), a software tool developed by Lawrence Berkeley National Laboratory. This software tool includes Distributed Generation (DG), which evaluates demand response such as demand shifting in microgrids.

The project development pursues the objectives described in the previous section using General Algebraic Modelling System (GAMS) and DER-CAM.

The objective function of this study case is the total energy cost. This total cost involves the initial investment, and the variable costs of having the CHP and HVAC technologies functioning for 5 years. The value of the objective function for different cases is represented in Table 1, the most representative case is when investments are free and the investment decisions are based purely on the costs for the different technologies and the prices and tariffs considered. In every of the cases when the investment of each technology is forced, the program invests on one machine per year. In every case the power of these machines is of 30 kW since that is the maximum demand of the building.

	Total Electricity Consumption (MWh)	Total Natural Gas Consumption (MWh)	Total Capital Cost Discrete Tech (k$)	Total Costs (k$)
ICE	606,67	9.014,00	480,00	2.853,88
MT	699,39	8.828,07	645,00	2.841,82
FC	877,93	7.217,77	1.500,00	2.861,15
Absorption Chiller	1.785,73	3.372,58	105,00	2.836,90
All technologies considered	**658,99**	**7.301,18**	**246,00**	**2.948,45**
Base Case	1.787,33	7.948,27	-	2.735,25

Table 1 - Value for the objective function in the different study cases

As it is seen in Table 1, the worst option is fuel cells since their investment price is much higher than that of the rest of technologies, whereas the absorption chillers imply the cheapest option. With respect to absorption chillers, because they can only cover the cooling demand, the electricity consumption from the network is the highest for them.

ICE and MTs are the options with which the least electricity is purchased from the network, since both the ICE and the MT are capable of covering a great part of the total demand.

For the base case, in which electricity is directly purchased from the network, the total electricity consumption is the highest. There exists a natural gas consumption since it is needed for heating objectives, the total cost of this case are the lowest given the fact that no additional investment must be done.

The results of the first study case in which all the technologies are considered can be seen in Figure 1and Figure 2.

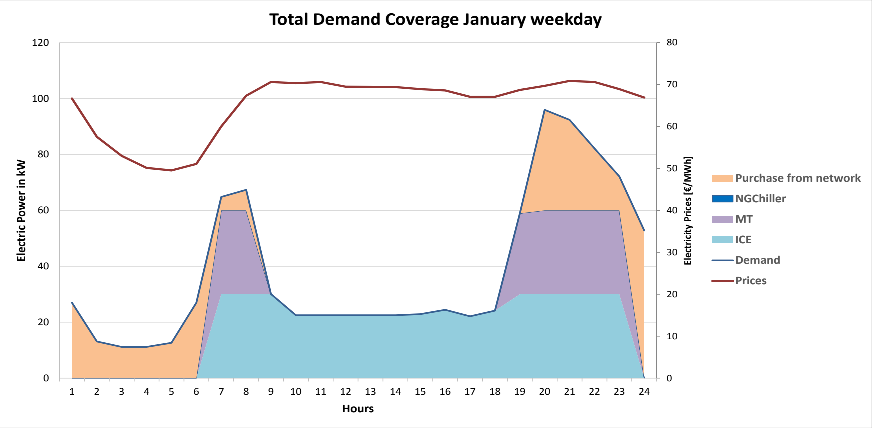

Figure 1 - Total demand coverage January weekday

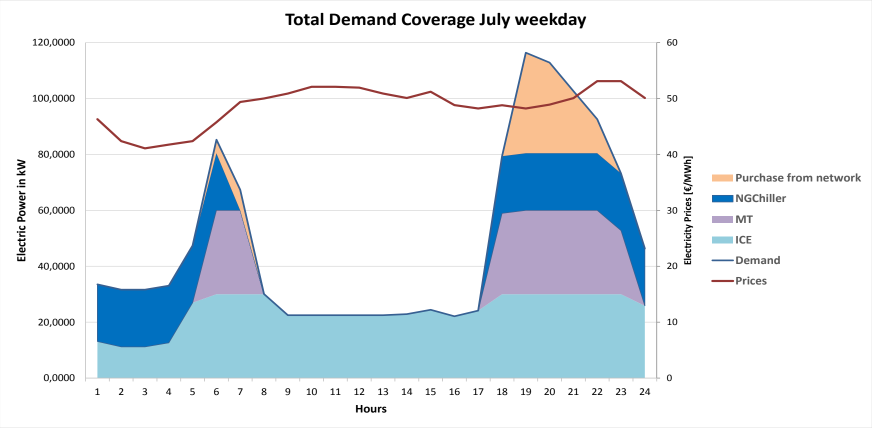

Figure 2 - Total demand coverage July weekday

The results of the operation of all of the technologies show that absorption chillers only cover the cooling demand, which is why they do not operate during the month of January. Internal combustion engines operate even when the demand is lower than their maximum capacity, the same as it happens for Micro Turbines. Fuel cells on the other hand are not profitable compared to the rest of technologies and this is why they do not operate when their investment is not forced.

In Figure 3 the operation of each of the technologies separately for the month of January can be seen. Internal combustion engines operate to cover the maximum possible demand, the same as Micro Turbines. Regarding the Fuel Cells, although when studied in the case of a free investment they do not operate, when their investment is forced they do, but only when the demand is more than 30 kW which is their maximum power.

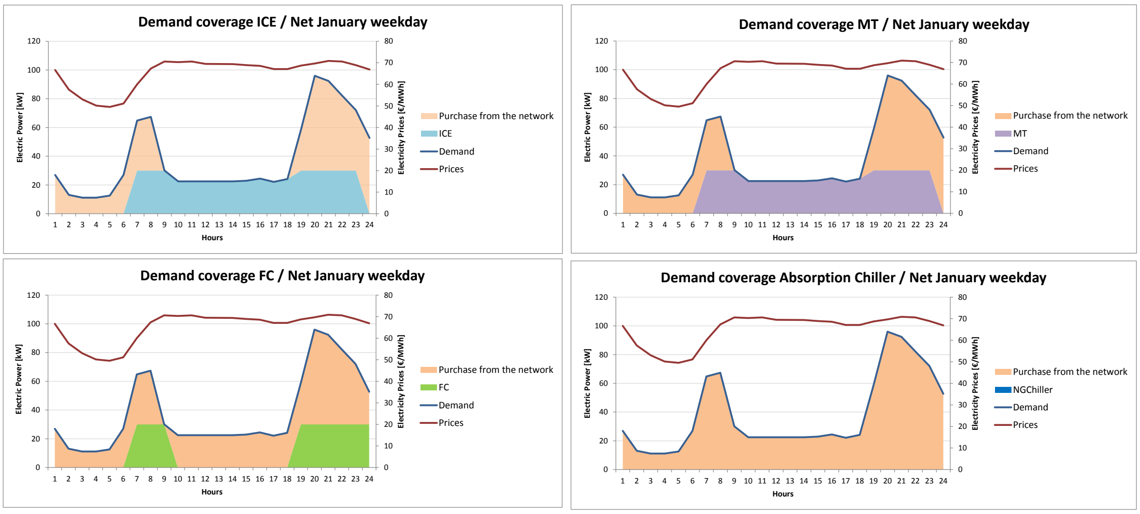

Figure 3 - Demand coverage for the month of January for each of the technologies separately

Absorption chillers do not operate during a normal winter day since there is no cooling demand to cover.

In Figure 4 the demand coverage during the month of July for each of the technologies separately can be seen. The differences which can be found with the January coverage are that because of the increase in electricity prices, both ICEs and MTs do operate during a longer period of time.

Because of the increase in electricity prices for the month of July, Fuel Cells do also operate during a longer period of time, but always operating at their maximum power. Finally, because there is a cooling demand during the month of July, absorption chillers operate to cover it.

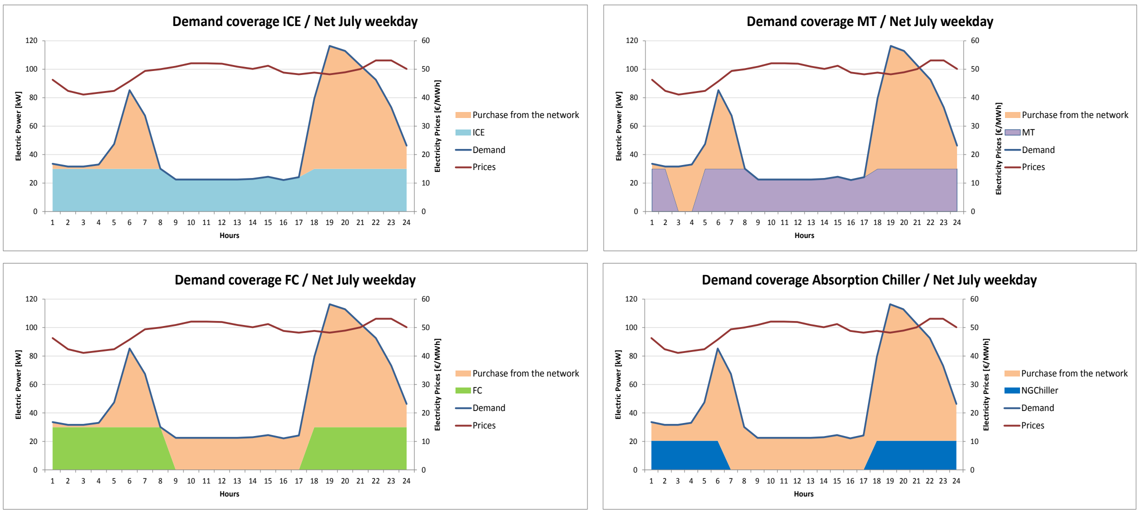

Figure 4 - Demand coverage for the month of July for each of the technologies separately

Certain conclusions have been drawn.

- The option of having all the technologies is the one with the cheapest objective function because every technology is covering what they do best in terms of providing energy to the building and meeting the building needs and the rest is been gathered from the network.
- ICEs always operate, even when the demand is less than its maximum capacity.
- Micro turbines, as ICEs, usually operate, but when the price of electricity is sufficiently low, it is better to purchase the electricity from the network instead of producing it with a micro turbine, differently of what happens with ICEs.
- Finally, FCs, only work when the demand is the same as its maximum capacity or higher, which means that when the demand is less than 30 kW the demand is covered with electricity purchased from the network. The same for January, for the low prices of 2h and 5h, it is more profitable to take it from the network than to use the fuel cell.
- The absorption chiller only covers the cooling demand, but when the price of purchasing the electricity from the network is sufficiently low, it stops being profitable.
- The case which implies the best option for the objective function is that of having all the technologies together since each of them can generate in its best period.

TECNO-ECONOMÍA DE LAS TECNOLOGÍAS DE CHP Y HVAC A NIVEL DE CONSUMIDOR

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Resumen ejecutivo

El principal objetivo de este Proyecto es el estudio de la integración y los beneficios económicos de las tecnologías CHP en diferentes edificios residenciales. Para poder integrarlos de la mejor manera posible, se ha utilizado un software de optimización para comparar la función de costes totales de cada una de las tecnologías con el precio de la electricidad en el mercado.

Utilizando tecnologías menos contaminantes será posible, no sólo reducir el daño causado en la atmósfera por la demanda de los edificios, sino también hallar una reducción de costes a medio plazo.

Términos clave – Motor de combustión interna (ICE), Células de Combustible (FC), PVPC ("Precio Voluntario para el Pequeño Consumidor" que es el precio voluntario para todos los pequeños consumidores y se refiere a la tarifa estándar de electricidad para los mismos).

El consumo residencial en España representa el 35.1% de la demanda total de electricidad del país y el 24.9% del consumo total de gas natural. Esto hace que las mejoras en relación a este consumo sean dignas de estudio.

Una de las actividades que tendrían un impacto severo en este consumo sería la integración de tecnologías CHP que usen gas natural como combustible. Esto tendría también como resultado, como ya ha sido mencionado con anterioridad, una importante reducción de las emisiones.

Este estudio utiliza como base algunas tesis de fin de máster donde la gestión óptima del suministro eléctrico integra vehículos eléctricos. Para poder recopilar información y sacar conclusiones acerca de la integración de dichas tecnologías CHP en el consumo residencial, se ha utilizado un modelo de referencia: "Distributed Energy Resources Customer Adoption (DER-CAM)". Se han realizado ciertos cambios para llegar a la demanda en cuestión a la par que se reducen los costes relativos a inversión y mantenimiento y operación.

El estudio realizado utiliza herramientas computacionales que se encuentran disponibles en el Instituto de Investigación de la Universidad Pontificia de Comillas (IIT) así como el modelo de recursos de distribución de energía (DER-CAM), una herramienta llevada a cabo por el laboratorio nacional de Lawrence Berkeley. Dicha herramienta incluye generación distribuida.

El desarrollo del Proyecto persigue el objetivo descrito en la sección anterior utilizando el sistema de modelado algebraico general (GAMS), así como el software DER-CAM.

Como ya se ha comentado con anterioridad, esta tesis se basa en algunos proyectos de fin de máster anteriores que desarrollaban este tema. Los nuevos cambios realizados en el código antes descrito permiten al usuario una interacción con el edificio, siendo esto el tiempo de conexión y desconexión de las tecnologías CHP.

La función objetivo de este estudio es el coste total de la energía. Dicho coste total incluye la inversión inicial y los costes variables de tener tecnologías tanto CHP como HVAC funcionando durante cinco años. El valor de la función objetivo para los distintos casos de estudio está representada en la

. El caso más representativo es aquel en el que todas las tecnologías están "libres" (sin forzar la inversión en ninguna de ellas) y las decisiones de inversión son basadas en los costes de las distintas tecnologías, así como en las tarifas consideradas. El resto de casos representan la operación de cada tecnología de manera individual.

	Consumo total de electricidad (MWh)	**Consumo total de Gas Natural (MWh)**	**Coste total de tecnologías discretas (k$)**	**Costes totales (k$)**
Motor	606,67	9.014,00	480,00	2.853,88
Micro Turbina	699,39	8.828,07	645,00	2.841,82
Célula de Cble.	877,93	7.217,77	1.500,00	2.861,15
Enfriador de absorción	1.785,73	3.372,58	105,00	2.836,90
Inversión libre	**658,99**	**7.301,18**	**246,00**	**2.948,45**
Caso Base	1.787,33	4.948,27	-	2.735,25

Table 2 - Valor de la función objetivo para los distintos casos de estudio

Como se puede apreciar en la Table 1, la peor opción es aquella de las células de combustible ya que su precio de inversión es el más caro con diferencia, mientras que el enfriador de absorción es la opción más barata. Debido a que los enfriadores solo cubren la demanda proveniente de refrigeración, es la opción que más electricidad consume de la red ya que durante los meses de invierno no existe demanda que puedan cubrir.

Tanto los motores como las microturbinas representan las opciones con las que menos electricidad se toma de la red, ya que ambos son capaces de producir una gran parte del total de la demanda.

En el caso base, en el que se toma toda la electricidad de la red, no existen gastos debidos a tecnologías discretas, por lo que el coste total es el más bajo al no necesitarse una inversión inicial. Existe un consumo de gas natural ya que para suministrar calefacción se necesita dicho combustible.

Los resultados del primer caso de estudio, en el que todas las tecnologías son tenidas en cuenta, están representados en las Figure 5 y Figure 6.

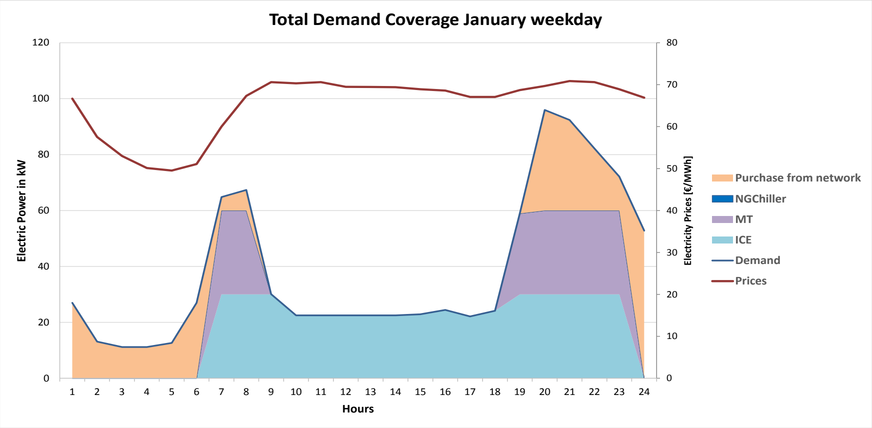

Figure 5 - Cobertura de la demanda con todas las tecnologías durante un día semanal del mes de enero

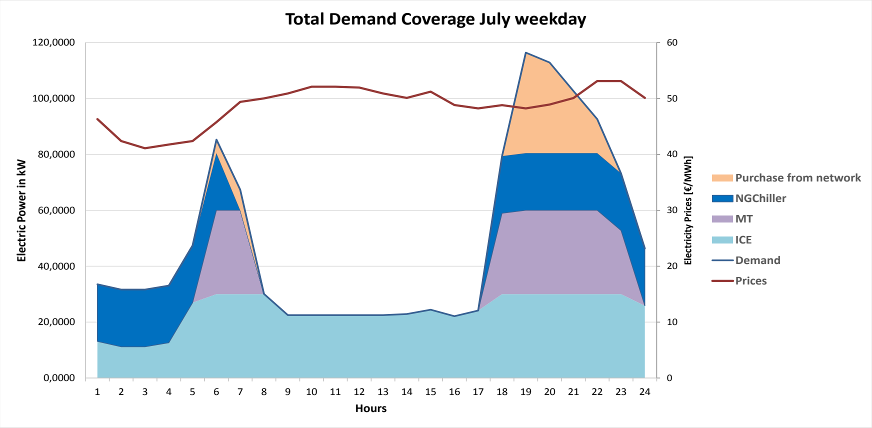

Figure 6 - Cobertura de la demanda un día de la semana de julio

El resultado de la operación de todas las tecnologías muestra que los enfriadores solo cubren la demanda de refrigeración, que es por lo que durante el mes de enero no se encuentran operando. Los motores de combustión interna operan incluso cuando la demanda es más baja que su potencia máxima, lo mismo que ocurre con las microturbinas. Por el contrario, las células de combustible no son rentables comparadas con el resto de tecnologías y es por lo que no se encuentran en operación en ninguno de los dos meses cuando la inversión no es forzada.

En la Figure 7 ha sido representada la operación de cada una de las tecnologías por separado para un día de la semana del mes de enero. Los motores de combustión interna operan para cubrir la cantidad máxima de demanda posible, lo mismo que sucede con las microturbinas. Con respecto a las células de combustible, aunque es cierto que cuando se invierte libremente no operan, al estudiarse por separado sí que lo hacen, pero solo cuando la demanda es mayor o igual que su potencia máxima. Los enfriadores no operan en el mes de enero debido a la ausencia de demanda de refrigeración.

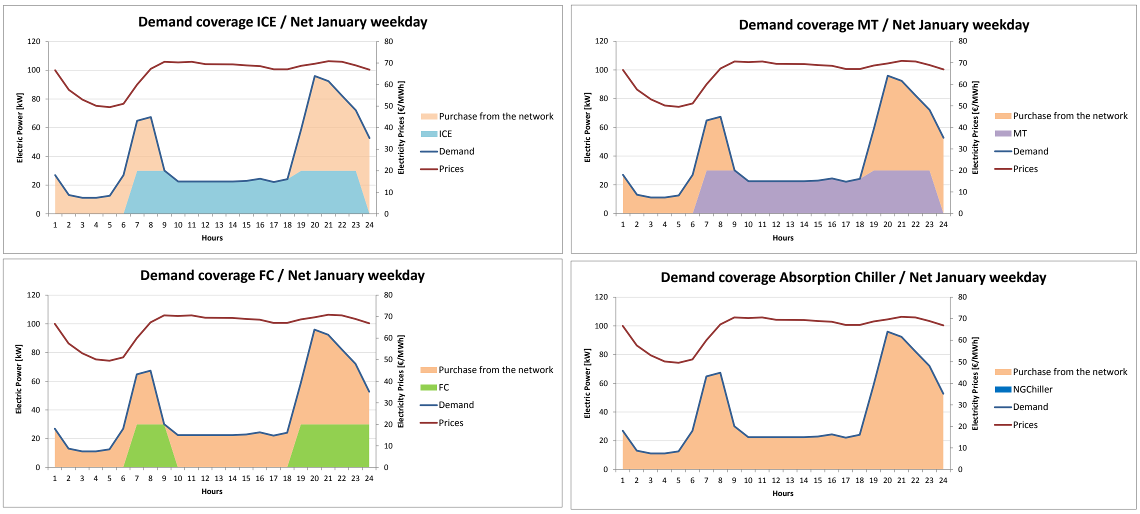

Figure 7 - Demanda cubierta con cada una de las tecnologías por separado para el mes de enero

En la Figure 8, se ve la demanda del mes de julio cubierta con cada una de las tecnologías por separado. Se pueden encontrar diferencias con respecto al mes de enero tanto para los motores de combustión interna como para las microturbinas, que operan durante más periodos horarios. Este hecho reside en que los precios de la electricidad son mayores en julio que en enero.

Debido a este incremento de precios, las células de combustible también operan durante más periodos horarios en el mes de julio, aunque siempre aportando su potencia máxima de 30 kW. Finalmente, los enfriadores de absorción sí que operan durante el mes de julio al haber en este una demanda de refrigeración.

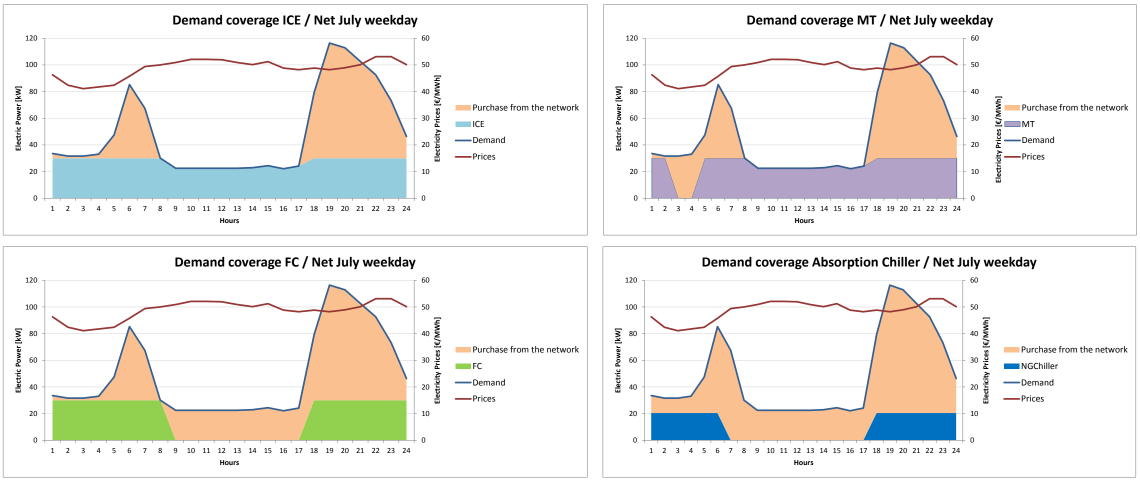

Figure 8 - Demanda cubierta con cada una de las tecnologías por separado para el mes de julio

Se ha llegado a una serie de conclusiones.

- La opción con la función de coste más barata es aquella de tener todas las tecnologías, esto se debe a que al tenerlas todas, cada una cubre la parte de la demanda que más se asemeja a su operación, tomando el resto de la red.
- El motor de combustión interna es siempre rentable, incluso cuando la demanda es menor que su capacidad máxima.
- Las microturbinas, así como los motores de combustión interna, suelen ser rentables, salvo cuando los precios de la electricidad en la red son suficientemente bajos, en cuyo caso es mejor comprar de la red.
- Las células de combustible operan cuando se estudian solas porque en el caso de todas las tecnologías no son rentables, y cuando la demanda es mayor o igual que su potencia máxima. Al igual que en las micro turbinas, en las franjas horarios en las que en enero la energía se compra muy barata, es más rentable tomarla de la red que tener la célula operando.
- El enfriador de absorción solo cubre la demanda de refrigeración, aunque cuando el precio de la electricidad es suficientemente bajo, también deja de ser rentable.

ESCUELA TÉCNICA DE INGENIERÍA (ICAI)

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Junio 2018

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UNIVERSIDAD PONTIFICIA DE COMILLAS

ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

TECHNO-ECONOMICS OF CHP AND HVAC TECHNOLOGIES AT CONSUMER LEVEL

DOCUMENT I - Report

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Pablo Dueñas Martínez

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1. Introduction

During the last two decades, there has been a great understanding of the greenhouse effect by the world population. The sea level has objectively increased and the global warming is a fact. These, combined with the fact that the planet is running out of fossil fuels, are the reasons why new, pioneer technologies have been invented and existing ones, have been changed or rethought. The aim of this project is to review the CHP (combined heat and power) and HVAC (heating, ventilation and air conditioning) technologies that are currently available in the market and, selecting the main parameters that characterize them, and capture their operation through an optimization model.

On the CHP side, three different technologies will be object of study in this thesis. The first is internal combustion engines (ICE), the second is micro turbines and the third is fuel cells. The fuel with which they operate is natural gas. A state of art of all three technologies is presented in order to describe the actual state of these technologies. The study emphasizes in characteristics such as initial investment, operating and maintenance costs, description of the operation and pollutant emissions.

On the HVAC side, heat pumps will be the unique object of study as main representative of this technology. Heat pumps are in addition expected to play a relevant role to provide space conditioning services due to their efficiency. As in the case above, the study emphasizes in characteristics such as initial investment, operating and maintenance costs, and description of the operation.

Once all the data of the technologies is gathered and explained, this will be used to create an optimization model. The aim of this model is to be able to draw conclusions regarding the optimal use of these technologies in residential buildings.

2. State of the art

2.1. CHP Technologies

A description of the actual state of each of the technologies studied in this project is presented as follows. A description of the operation, followed by the emissions produced and the main costs that characterize them is done for each of the technologies.

2.1.1. Internal Combustion engine (ICE)

2.1.1.1. Operation

One of the main sources of producing energy throughout history has been releasing energy from a fuel and air mixture by the process of burning. This particular epigraph is based on the internal combustion engines (ICE), whose principal characteristic is that the burning of this fuel and air mixture mentioned before occurs within the engine itself. There are two types of ICEs, the first one, which follows the Otto thermodynamic cycle (spark ignition gasoline engine) and the second one, governed by the Diesel cycle (compression ignition diesel engine). In Figure 9, the p-V diagrams for both cycles have been plotted. It can be seen how, in Otto cycle, heat addition happens at constant volume, while in Diesel cycle, heat is added at constant pressure. It is also important to mention the fact that, in Otto cycle, the combustion begins due to the spark in the cylinder when the piston reaches the top dead center (tdc, place nearest to the crankshaft), and is instantaneous. While, in diesel cycle the fuel auto ignites because it is introduced when the cylinder is full of hot compressed air, and combustion is time consuming.

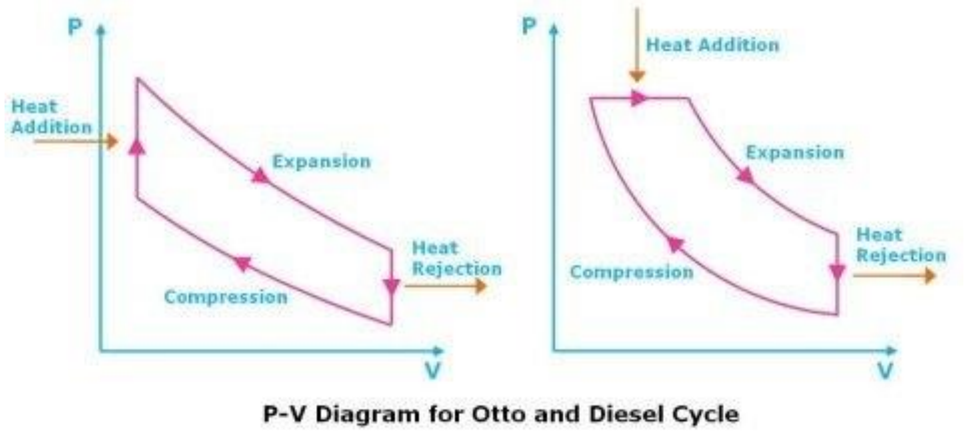

Figure 9- Otto and Diesel Thermodynamic cycles (Tarun Raj Gupta, 25 August 2016) [1]

Figure 10 shows the different pieces which form an internal combustion engine.

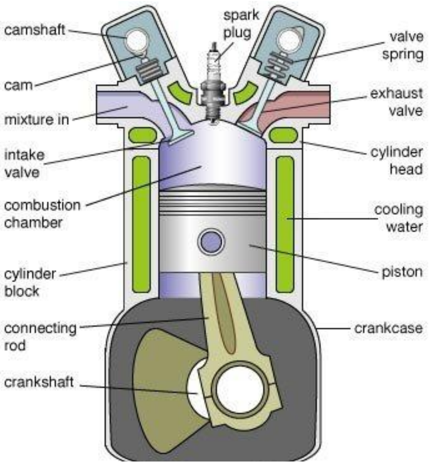

Figure 10 - Internal combustion engine

The operating cycle of internal combustion engines, which thermodynamically speaking is the same for the Otto and Diesel cycles, consists of four main strokes or movements of the piston, which is the same as two movements of the crankshaft. The piston strokes will be described as follows.

- Intake stroke

  The first stroke, also called intake stroke, is controlled by the admission of air and fuel inside the combustion chamber through the intake valve. The piston is moved towards the crankshaft while this admission takes place. It is important to say that the movement of the intake valve is governed by the difference of pressure between the atmosphere and the combustion chamber.

- Compression stroke

  During the compression stroke both admission and exhaust valves are closed, leaving a given space for the combustion process to take place. Once the piston is as near as possible to the crankshaft, it starts moving away from it, thus, increasing its pressure due to the shortage of space.

- Power stroke

  It is in this precise stroke that the compression ignition engines and the spark ignition engines can be differentiated. When the piston is the furthest away from the crankshaft is the moment when the pressure is the highest. In the case of a compression ignition engine, the increase in pressure makes the fuel and air mixture combust by itself, whereas in the case of the spark ignition engines, a spark plug is needed in order to make the mixture explode.

- Exhaust stroke

During the exhaust stroke the volume occupied by the combustion gases increases, thus increasing the pressure inside the combustion chamber, this increase in the pressure makes the piston move and transforms the thermal energy into work. At the end of the exhaust stroke, the combustion chamber is full of the remaining gases from the explosion. The exhaust valve opens due to a change in the pressure of the chamber in relation to the atmospheric one (the same as with the admission valve), and these combustion gases are pushed outside, thus leaving the chamber clean of gases and prepared for the beginning of another cycle with the intake stroke.[2]

2.1.1.2. Emissions

One of the main concerns about internal combustion engines is related to the emissions. Whenever combustion happens, carbon dioxide is formed. If there is not enough air for the combustion reaction to be completed, carbon monoxide is also formed because of the unburned hydrocarbon. Due to the high temperatures reached during the cycle, undesirable nitrogen oxides (NO_x) are also emitted. In Table 3, the data concerning the emissions in engines burning natural gas as a fuel have been represented.

As it can be seen, for the nominal capacity studied, the data of post catalyst emissions is the one presented in Table 3. However, it may be possible to add certain substances to the chemical reaction (combustion in this case) in order to accelerate it and reduce the emissions of pollutants.

Emissions	
Electrical Efficiency (%HHV)	*27.0 %*
Engine Combustion	*Rich*
Post Catalyst Emissions	
NO_x (lb/MWh)	*0.070*
CO (lb/MWh)	*0.200*
VOC(lb/MWh)	*0.100*
CO_2 Net (lb/MWh)	*499*

Table 3- Emissions of Internal Combustion Engines [3]

2.1.1.3. Costs

This section provides forecasts for the installed cost of natural gas engines. The total cost is split into the investment and installation costs, the operation and maintenance costs and the consumption of fuel considering its efficiency. The capital costs depend on the nominal capacity of the engine because this study is focused on an apartment building, and considers an average peak consumption for each individual household between 4.5 kW and 7 KW, the assumption will be made that the nominal capacity needed will be around 30 KW.

Table 4 presents these main costs for internal combustion engines.

Capital Cost, $/KW	
Nominal Capacity	*100 KW*
Equipment Costs in 2013 ($/KW)	
Gen Set Package	*$1,400*
Heat Recovery	*$250*
Interconnect/Electrical	*$250*
Total Equipment	*$1,900*
Labor/Materials	*$500*
Total Process Capital	*$2,400*
Project and Construction Management	*$125*
Engineering and Fees	*$250*
Project Contingency	*$95*
Project Financing	*$30*
Total Plan Costs ($/KW)	*$2,900*

Table 4 - Costs of Internal Combustion Engines [4]

The operating and maintenance costs depend on the annual operating hours, which are expressed in terms of annual electricity generation. Table 5 shows the operation and maintenance costs of a 100KW nominal capacity engine.

Operating and Maintenance Costs	
Nominal Capacity [KW]	*100*
Service Contract	*$0,023-$0,025*
Consumables	*Included*
Total O&M Costs, 2013 $/KWh	*$0,023-$0,025*

Table 5 - Operating and Maintenance costs of internal combustion engines [5]

2.1.2. Micro turbine

2.1.2.1. Operation

A micro turbine is, as it can be told by its name a small turbine, which ranges in size from 30 to 330 KW.

Figure 11 will be used as a reference for explaining the operation of micro turbines. Air enters the compressor in 1. When it has reached certain conditions of pressure and temperature, it is conducted to the combustion chamber, 2, where fuel is introduced, in this case, natural gas. The combustion takes place inside the combustion chamber and the exhaust gases are passed down to the gas turbine, 3, whose blades move because of the kinetic energy with which the gases make their entrance. This rotation work made by the blades is used to move the axes of an electric generator, 4. The temperature of the exhaust gases when they come out from the gas micro turbine, 5, are used to heat sanitary hot water using for it a heat exchanger.

One of the most interesting parameters for this study case, when referring to operation, is how the efficiency changes. Figure 12, plots the changes in efficiency depending on load in micro turbines.

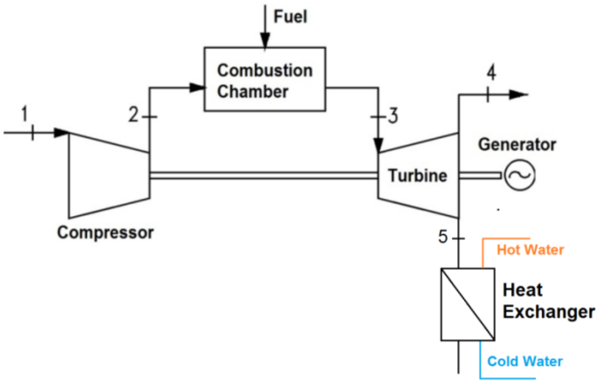

Figure 11 - Schematic representation of a micro turbine [6]

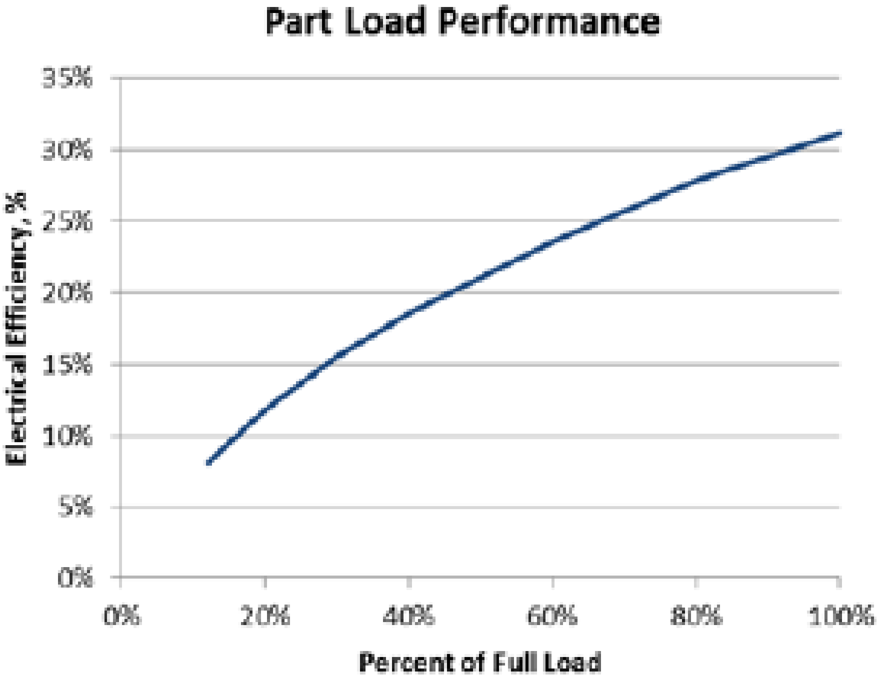

Figure 12 - Graph showing Efficiency vs Load in micro turbines [7]

In addition, Figure 13 plots the behavior of efficiency depending on net power.

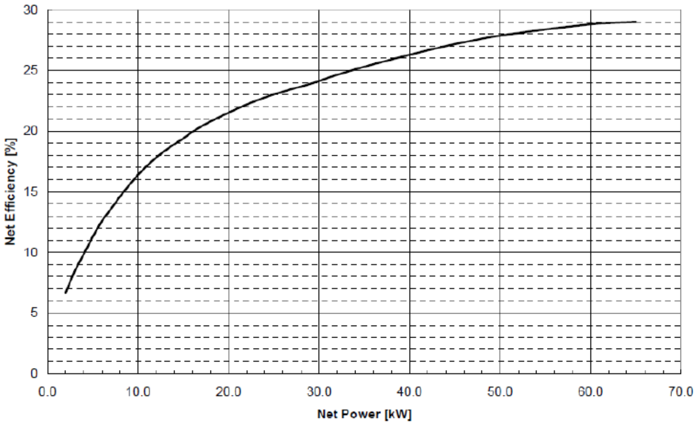

Figure 13 - Graph showing net efficiency vs net power in micro turbines [8]

2.1.2.2. Emissions

As said before, the project's objective is to optimize the behavior of a building with different types of customers when using distributed energy resources. For example, for an apartment building, whose demand is typically around 30 KW, Table 6 presents the characteristics of a 30 KW micro turbine.

Micro Turbine Characteristics	
Nominal Electricity Capacity (KW)	*30*
Fuel Imput (MMBtu/hr)	*0.434*
Electric Efficiency (%)	*24.4%*
CHP Characteristics	
Exhaust Flow (lbs/sec)	*0.68*
Exhaust Temperature (ºF)	*530*
Heat Exchanger Exhaust Temperature (ºF)	*190*
Heat Output (MMBtu/h)	*0.21*

Table 6 - Characteristics of a 30KW micro turbine [9]

Table 7, presents the data of the emissions of a 30 KW micro turbine.

Emissions	
Electrical Efficiency (%HHV)	23.6%
Recovered Thermal Energy (KW)	61.0
NO_x (lb/MWh)	0.16
CO (lb/MWh)	1.8
VOC(lb/MWh)	0.23
CO_2 Net (lb/MWh)	727

Table 7 - Emissions of a 30 KW micro turbine [10]

The range of temperature in micro turbines varies from 260 to 320 ºC, which means they usually do not achieve too high temperatures which would mean a high emission of NO_x particles.

2.1.2.3. Costs

As it was done for internal combustion engines, the main costs for installing and maintaining a micro turbine as a generator is represented in Table 8.

Capital Cost, $/KW	
Nominal Capacity	30 KW
Equipment Costs in 2013 ($/KW)	
Gen Set Package	$1,770
Heat Recovery	$450
Fuel Gas Compression	$290
Total Equipment ($/KW)	$2,689
Labor/Materials	$753
Project and Construction Management	$300
Engineering and Fees	$300
Project Contingency	$127
Project Financing	$23
Total Plan Costs ($/KW)	$4,300

Table 8 - Costs for a 30 KW micro turbine

2.1.3. Fuel Cell

2.1.3.1. Operation

A fuel cell is an electrochemical device in which the chemical energy of a fuel is transformed into electricity using an electrochemical reaction.

A fuel cell is separated into two main parts, as it can be seen in Figure 14, the anode and the cathode. Certain chemical processes happen in these two parts, oxidation, which can be described as the loss of electrons by a chemical element and reduction which, in its contrary, is the gain of electrons by a chemical element. Oxidation occurs in the anode, while reduction occurs in the cathode.

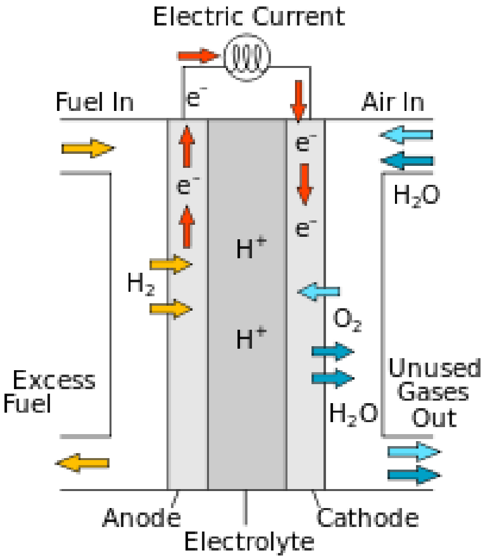

Figure 14 - Fuel cell [11] (R. Dervisoglu)

In the case of cells whose main fuel is hydrogen, the operation is as follows. In this particular case of study, hydrogen is obtained from natural gas. The anode gives hydrogen, which is then divided into protons and electrons. Protons travel through the membrane to the cathode, where they react with the oxygen present in the air to make water vapor. Meanwhile, electrons are outside the battery supplying electric energy, with a voltage which oscillates between 0.6 and 0.8 V depending on the loading point.

The main difference between a fuel cell and a normal battery is that, normal batteries are energy storage devices which keep producing energy while they have enough fuel inside. The fuel cell, on the other hand, is prepared to admit oxidant and fuel continuously in order to be producing electricity without a break.

There are different types of combustion cells, each of which has different nominal capacities. In this case, the PEMFC (Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Membrane) will be the chosen one. The reason for selecting this particular type of cell is that they can have an electric capacity of around 40 KW, which suits the project objective.

2.1.3.2. Emissions

The electrochemical process taking place inside the combustion cells is a high efficiency one due to the fact that it doesn’t have to undergo any thermal or mechanical processes which are usually less efficient. In this case, the efficiency of the process is normally round 40-60% if it is not used in cogeneration, while, when using the residual heat to produce sanitary hot water the efficiency can be between 85-90%. The values of the emissions of fuel cells are represented in Table 9

Emissions	
Electrical Efficiency (%HHV)	*47%*
NO_x (lb/MWh)	*0.01*
SOx (lb/MWh)	*0.0001*
CO (lb/MWh)	*Negligible*
VOC(lb/MWh)	*Negligible*
CO_2 Net (lb/MWh)	*980*

Table 9 - Emissions in fuel cells [12]

2.1.3.3. Costs

Table 10 shows some of the main costs regarding fuel cells.

Capital Cost, $/KW	
Nominal Capacity	*30 KW*
Total Equipment Costs in 2014 ($/KW)	*$10,000*
O&M Costs ($/MWh)	*$45*

Table 10 - Capital Costs for a 30 KW fuel cell

Table 11 plots the behavior of electric power when changing the stack load in fuel cells. As it can be seen, fuel cells have a much better behavior when working at half load than when doing it at full load.

	Full Load	Half Load
Efficiency by cell volts	40%	46%
System Efficiency	41%	50%
H2 consumption rate, N litres/min	67 L/min	29 L/min

Table 11 - Experimental results for behavior of fuel cells at half and full load [13]

Figure 15 plots the behavior of efficiency when power is altered. It can be seen that efficiency reaches its maximum when power is more or less 10KW, and then starts to decrease slowly.

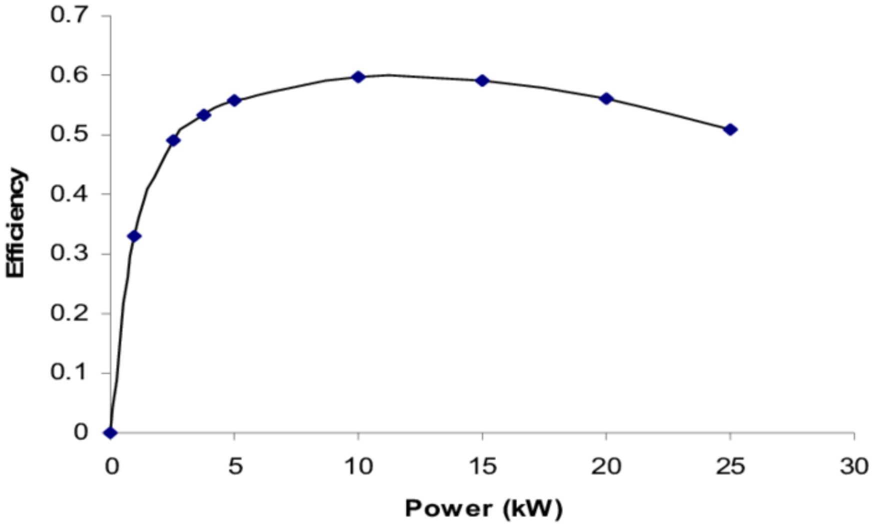

Figure 15 - Efficiency vs. Power in fuel cells

2.2. HVAC Technologies

2.2.1. Absorption Chiller

2.2.1.1. Operation

Absorption chillers use heat energy to generate chilled water that can be used for air conditioning or process cooling applications. The principle behind an absorption process is to separate and recombine two fluids (refrigerant and absorbent) to create a cooling effect. Usually, absorption chillers are either NH3-H20 (ammonia-water) cycle or LiBr (Lithium bromide) cycle.

In the first cycle, water acts as the absorbent while ammonia water solution acts as the refrigerant. In the latter cycle, lithium bromide is the absorbent and water is the refrigerant.

In Figure 16 the simple cycle in which the absorption chiller is based can be seen.

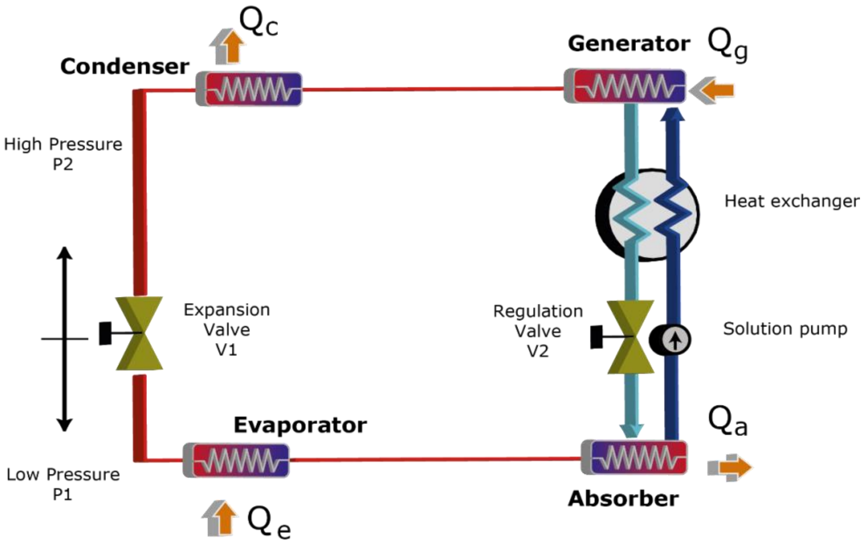

Figure 16 – Simple operation cycle of an absorption chiller

The different parts forming an ammonia water absorption chiller cycle are described as follows.

<u>Generator:</u> in the generator, a heat source produces ammonia vapor from a strong ammonia solution. Before the ammonia (refrigerant) vapor enters the condenser, it passes through a rectifier for dehydration. The generator, which is basically the heat source, can either be a combustion chamber in which natural gas is burned or use the heat of the exhaust gases of CHP technologies. In this particular case it will be treated as an independent technology which means it will have as a generator a natural gas combustion chamber. In further studies it will be mentioned how introducing the

absorption chiller using the exhaust gases of CHP technologies as a fuel could possibly reduce emissions and variable costs.

Absorption chiller systems are classified by single-, double- or triple-stage effects, which indicate the number of generators in the given system. The greater the number of stages, the higher the overall efficiency. Double-effect absorption chillers typically have a higher first cost, but a significantly lower energy cost, than single-effects, resulting in a lower net present worth. Triple-effect systems are under development.[14]

Condenser: the now dehydrated and high-pressure ammonia enters the condenser where it changes its state from vapor to liquid. After cooling, it goes through a throttle valve (expansion valve) and pressure and temperature is reduced. The new values must be below what the evaporator (next stage) maintains.

Evaporator: the evaporator, which is essentially the cold refrigerated space, appears now. The cooled ammonia enters the evaporator, absorbs heat and then leaves as saturated ammonia vapor.

Absorber: as the vapor enters the absorber, it is exposed to a spray of weak ammonia-water solution. The weak solution in turns becomes a strong solution. The pump directs the new solution to the generator through the regenerator (may also be referred to as heat exchanger). By the time the solution arrives, it has already attained generator/condensing pressure. The process starts again.[15]

2.2.1.2. Emissions

Absorption chiller emissions depend on the application. If the chiller is integrated with a CHP system and driven by thermal energy from the CHP system, there are no incremental emissions from the absorption chiller. If, on the other hand, it is a standalone unit that is direct fired, emissions will depend on the fuel used to produce thermal energy to drive the system and the specific combustion technology used for direct firing. Natural gas, which is relatively low cost and clean burning, is a common fuel used for direct firing. For direct firing, absorption chillers can use low NOx burner technologies and other emission control measures to comply with local air quality requirements as needed.[16]

Absorption chillers traditionally have been recognized for quiet, vibration-free operation and low emissions. Also, they use water instead of chlorofluorocarbons as the refrigerant, giving absorption technology an environmental advantage. A breakdown of the total emissions in absorption chillers using natural gas as a fuel has been represented in Table 12.[17]

	Emissions
Electrical Efficiency Hot (%HHV)	*88 %*
Electrical Efficiency Cold (%HHV)	*110%*

Post Catalyst Emissions	
NO_x (lb/MWh)	*0.070*
CO (lb/MWh)	*0.200*
VOC(lb/MWh)	*0.100*
CO_2 Net (lb/MWh)	*499*

Table 12 - Emissions and efficiency of absorption chillers using natural gas as a fuel

2.1.4.3. Costs

The cost of an absorption chiller, as it happens with the other technologies, depends on its capacity. The investment price can vary in between 600 and 700 $/kWh depending on the characteristics of the chiller; being it more expensive when it is used either for cooling, heating and warm water or cheaper when only used for cooling. Its variable costs depend as much on operating and maintenance costs as on fuel costs.

In order to synthetize the information about absorption chillers, in Table 13 the data concerning its operation has been exposed.

Investment Cost	*600 – 700 $/kWh*
Fixed Costs	*0 $*
Operation&Maintenance	*0.022 $/kWh*

Table 13 - Direct fire absorption chiller characteristics

As it can be seen, not only the maintenance and the investment costs but also the emissions for absorption chillers are very similar to that of internal combustion engines; this is because the way in which the fuel is burned is near to identical in both of them.

3. Operational Functioning

In order to be able to use the most adequate technology in each case, important information related to different restrictions regarding CHP technologies has to be taken into account. As absorption chillers do not have particular constraints, they will not be part of this section.

3.1. Internal Combustion Engine

One of the advantages of the internal combustion engine's technology is their quick starting time, approximately the same as in fuel cells. Besides, they have a quick response to changes in the power demand and quite a long useful life.

Their main disadvantage is that they have to be stopped at certain time intervals; hence, they would need maintenance every 500 – 2,000 hours.

Recommended service for internal combustion engines is comprised of routine short interval inspections/adjustments and periodic replacement of engine oil and filters, coolant, and spark plugs (typically 500 to 2,000 hours). An oil analysis is part of most preventative maintenance programs to monitor engine wear. A top-end overhaul is generally recommended between 8,000 and 30,000 hours of operation, it entails a cylinder head and turbocharger rebuild. A major overhaul is performed after 30,000 to 72,000 hours of operation and involves piston/liner replacement, crankshaft inspection, bearings, and seals. [20]

3.2. Micro Gas Turbine

Regarding the micro gas turbine, if it is switched on from a cold state, its axis must be spinning at 1 rpm during a certain number of hours. This is so because a quick variation in temperature could originate certain deformations which would bring along, not only undesired vibrations, but, in the worst case, even the blocking of the axis. It is also necessary to be sure that there is not any gas bag inside the turbine before it starts working at normal speed. Therefore, after the initial *warming up*, the turbine must be spinning at a velocity of 500 rpm during 5-10 minutes.

Once the two tasks described above are completed, it would be possible to increase the velocity of the turbine axis until the desired one. Nonetheless, while the speed is been increased, there are certain critical velocities which are better avoided. In order to reduce the time the turbine is spinning at these velocities, the speed slope can be increased in these points. With the goal of achieving a soft start and controlling the speed at any moment, a variable frequency drive must be used; this device controls the velocity of the generator very precisely in each moment.

It is important to note that the time needed in order to start the turbine when it is not completely cold is shorter, taking around 1.5 hours instead of the 6 hours required when it started from cold. [21]

In relation to the maintenance of the micro turbines, the daily maintenance includes visual inspection by site personnel of filters and general site conditions. Typically, routine inspections are required every 4,000 hours to insure that the turbine is free of excessive vibration due to worn bearings, rotors, and damaged blade tips. Inspections generally include on-site hot gas path boroscope inspections and non-destructive component testing using dye penetrant and magnetic particle techniques to ensure the integrity of components. The combustion path is inspected for fuel nozzle cleanliness and wear, along with the integrity of other hot gas path components.

A gas turbine overhaul is needed every 25,000 to 50,000 hours depending on service and typically includes a complete inspection and rebuild of components to restore the gas turbine to nearly original or current (upgraded) performance standards. A typical overhaul consists of dimensional inspections, product upgrades and testing of the turbine and compressor, rotor removal, inspection of thrust and journal bearings, blade inspection and clearances and setting packing seals.

Gas turbine maintenance costs can vary significantly depending on the quality and diligence of the preventive maintenance program and operating conditions. Although gas turbines can be cycled, cycling every hour triples maintenance costs versus a turbine that operates for intervals of 1,000 hours or more. In addition, operating the turbine over the rated capacity for significant periods of time will dramatically increase the number of hot path inspections and overhauls. Gas turbines that operate for extended periods on liquid fuels will experience shorter than average overhaul intervals.[22]

The economic viability of micro-CHP is, first and foremost, dependent upon the efficiency and size of the unit being adequate to the building. Excessive energy consumption could lead to a higher energy cost. Micro gas turbines are very flexible in terms of the ratio of heat to electricity production, hence being adaptable to the different users' needs. [23]

Since there is no specific data regarding the response of micro turbines to power demand, the values have been calculated using Figure 17.

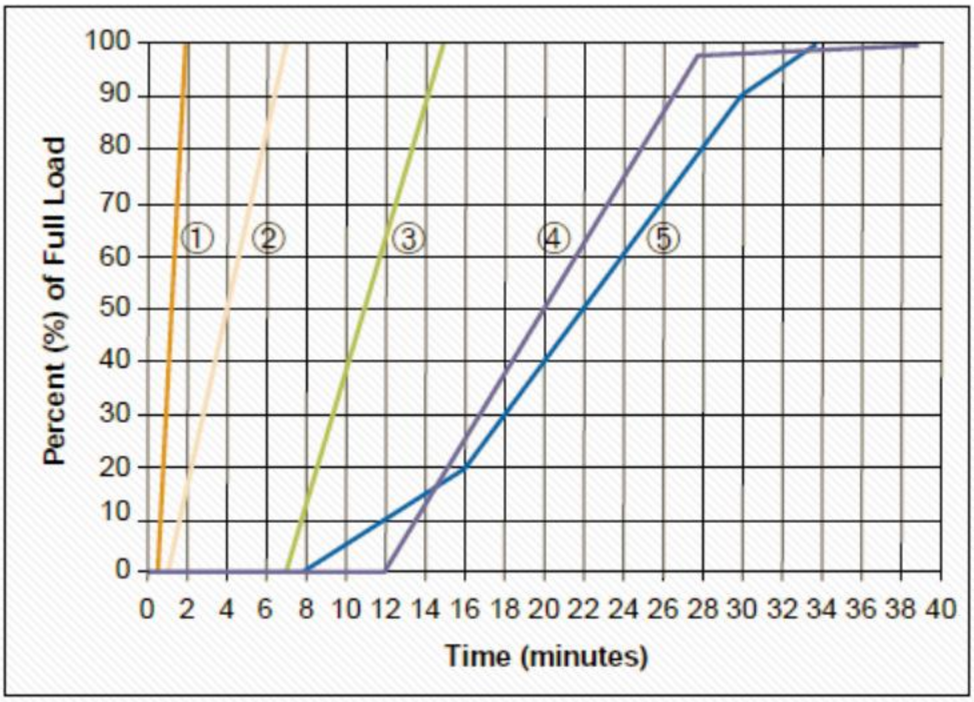

Figure 17- Load response with time in micro gas turbines

The worst study case has been studied and the value of the response has been calculated as follows bearing in mind that the needed power is of 30 MW.[24]

$$\Delta D = \frac{0.9 * 30MW - 0.2 * 30MW}{14\ minutes} = \frac{1.5MW}{minute} \rightarrow 40\ sec/MW$$

3.3. Fuel Cells

Fuel cells have a strong regulation regarding the storage and convertion of hydrogen, which is an important advantage. However, since in the case considered here the hydrogen will be produced using natural gas, certain security measures must be taken given that the fuel cell is supposed to be working for the production of energy in a building. That is, if there is any functioning problem the health of the building residents could be affected.

The problems related to the storage have been considered, but fuel cells present other disadvantages. The initial investment and installation costs are very high and their useful life short, compared to that of the other technologies.

Regarding the maintenance of fuel cells, the costs will vary with the type of cell, size and maturity of the equipment. The global annual maintenance could be said to be approximately 3% of its global cost. [25]

Major overhauls include shift catalyst replacement (3 to 5 years), reformer catalyst replacement (5 years), and stack replacement (5 to 10 years). Details of full maintenance contracts (covering all recommended service) and costing are not generally available, but are stimated at 0.7 to 2.0 cents/kWh excluding the stack replacement cost sinking fund. Recommended service is comprised of routine short interval inspections/adjustments and periodic replacement of filters (at intervals of 2000 to 4000 hours).[26]

In the case of fuel cells, the starting time is normally from 2 to 5 minutes. The response to variations in the power demand is of less than 3 seconds for 1 MW, which makes it the technology with the quickest answer of the three studied. [27]

3.4. Comparison

Once the advantages and disadvantages of the three studied technologies have been described separately, Table 14, will make the comparison of the different parameters of each technology easier.

	ICE	**Micro Turbine**	**Fuel Cell**
Starting Time	*2 – 5 mins*	*1.5 h warm* *6 h cold*	*2 – 5 mins*
Frequency of maintenance	*500 – 2 000 h*	*4000 h*	*2 000 – 4 000 h*
Major overhaul frequency	*30 000 – 72 000 h*	*25 000 – 50 000 h*	*40 000 – 80 000 h*
Response to power demand	*7 – 10 sec*	*60 sec*	*<3 sec*
Lifetime	*15 years*	*25 – 35 years*	*6 – 10 years*
Investment Cost	*2 900 $/kWh*	*4 300 $/kWh*	*10 000 $/kWh*
Maintenance Cost	*0.02 $/kWh*	*0.016 $/kWh*	*0.045 $/kWh*
Efficiency	*27%*	*24.4%*	*47%*

Table 14 - Parameters regarding the studied technologies

As it had been mentioned above, the main objective of these technologies would be to cover the demand of a certain apartment building. The demand has a big variation during the day since the energy necessities at different hours are different. One of the main points the chosen technology should fulfill is to be able to respond to variations in the power demand. This is why it would be useful to study the capacity of each technology to pass from zero to the maximum load. In Figure 18 the percentage of an hour each technology need in order to achieve the full load has been represented.

It should also be taken into account that the machine is probably going to be on the rooftop, which means it will suffer extreme temperatures during winter and summer. Finally, the starting time should be more or less quick for the objective of changing the normal electricity and hot water supplies for the chosen technologies to be as optimal as possible.

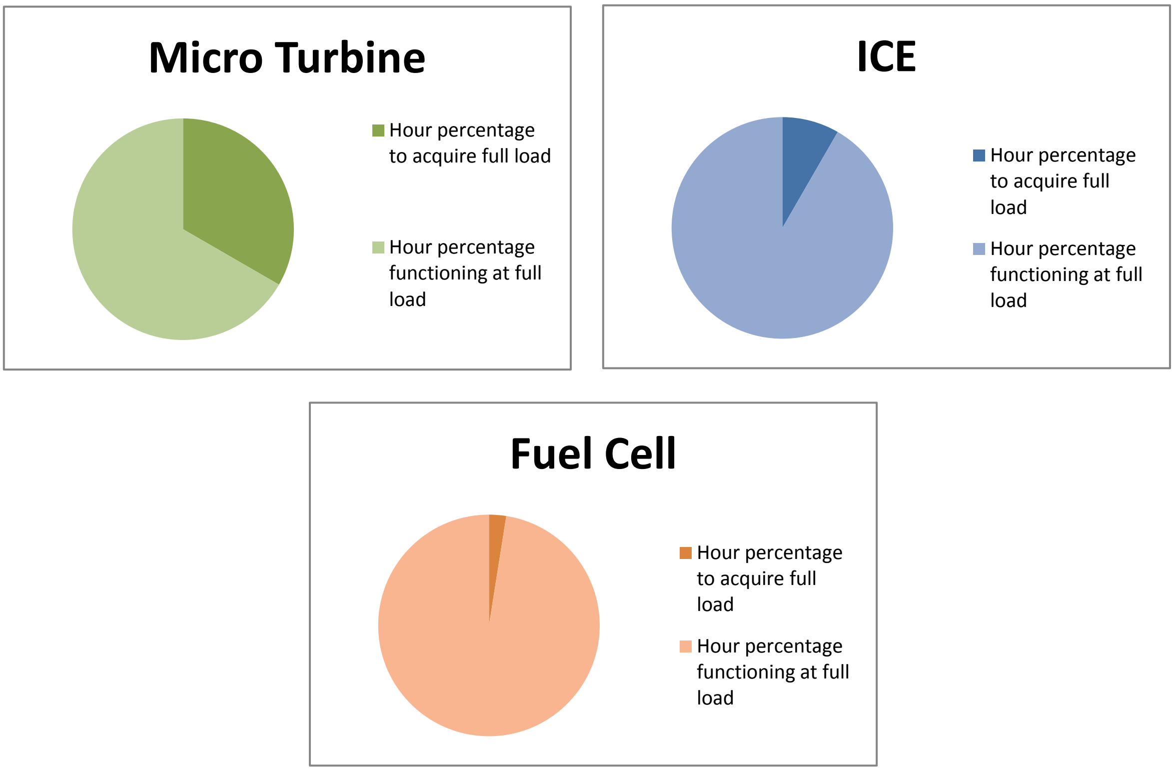

Figure 18 - Response of the different studied technologies to power demand with time

4. Case Study

As it has been said before, residential consumption in Spain represents the 35.1% of the total electricity demand in the country and the 24.9% of the total consumption of natural gas. In Figure 19 the total annual electricity demand in Spain has been represented.

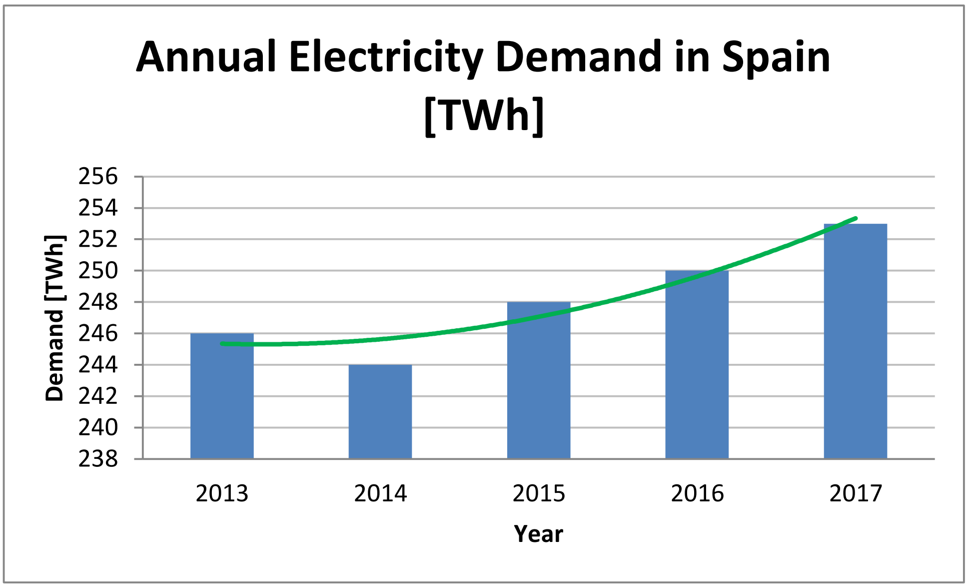

Figure 19 - Annual Electricity Demand in Spain [TWh]

Using this data, the annual residential consumption representing the 35.1% of the total demand has been represented in Figure 20.

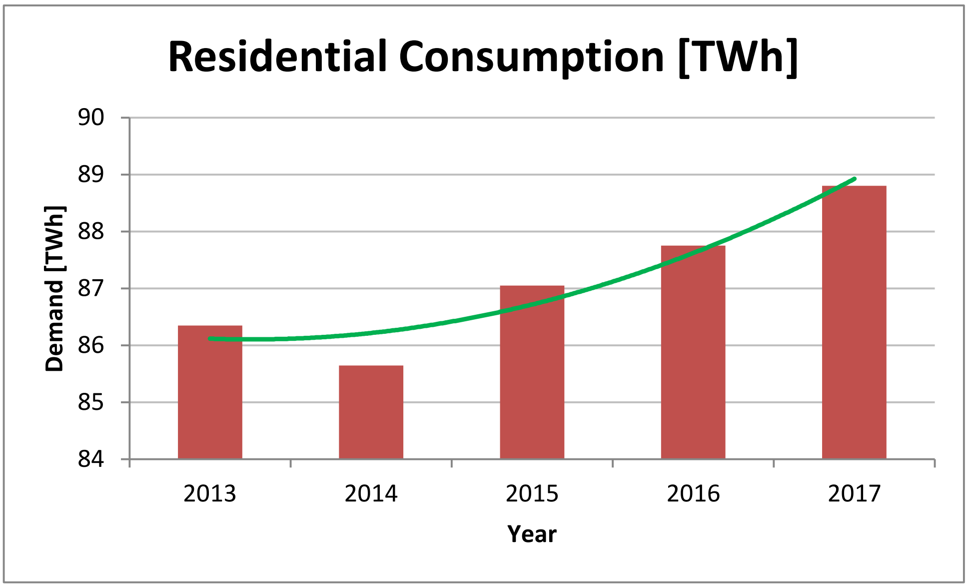

Figure 20 - Residential Consumption in Spain

One of the activities that will have a major impact on the energy consumption in this sector is the integration of CHP technologies using natural gas as fuel. This would also permit, as it has been mentioned before, an important reduction in emissions. This is the reason why the project consists in replacing the use of electricity and hot water from the net, for the three studied technologies. Optimizing the economic function in order to know which of the technologies is more suitable depending on its characteristics.

A more particular description of the case study taking place will be described as follows. The building which is the center of the case study is a residential building in the heart of the city of Madrid. Some parameters regarding the climate in this city must be taken into account in order to achieve the framing the project. The values regarding the average temperature of the city during the year 2017 are shown in Figure 21.

In order to be able to optimize the total cost, which is the main objective of this thesis, it is necessary for us to know the residential tariffs in Spain. In the next paragraph there is a brief explanation of how the prices of the electricity are organized, and the different existing tariffs, residents in a building could choose.

After the liberation of the electric market in 2009, the consumer can choose in between hiring the electricity tariff either with a reference commercial company or with a commercial company which forms part of the free market. In the regulated market the prices of electricity are fixed by the government using for it the values of "Red Eléctrica España" (which is a group which acts as the operator of the electric system in the global electricity market). In the free market, prices are fixed by each of the companies depending on the different tariffs.

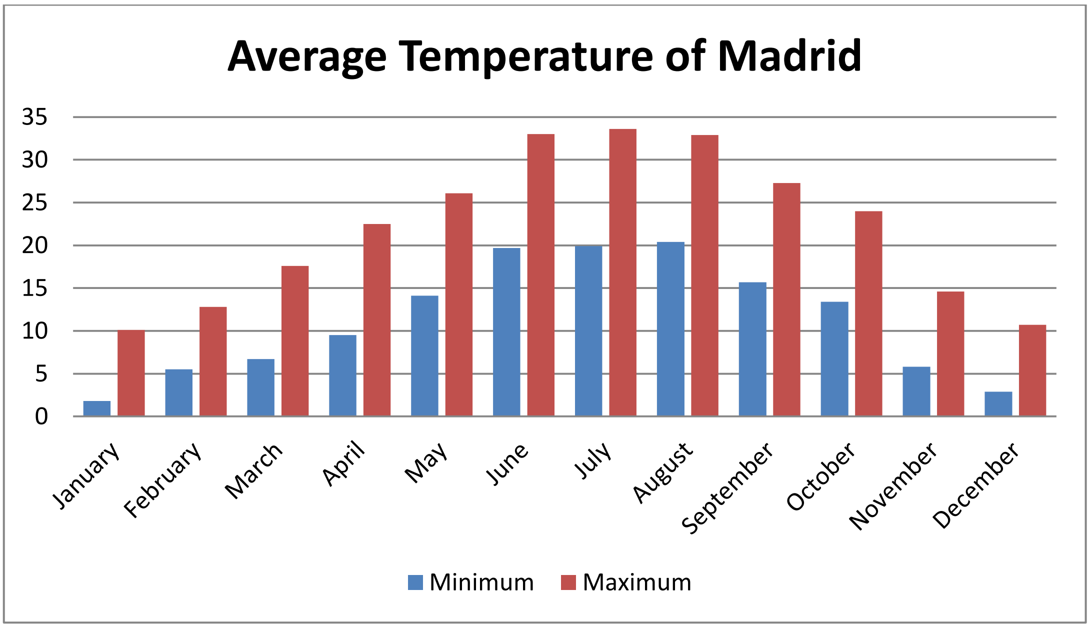

Figure 21 - Average Temperature of Madrid year 2017[28]

This case study is based on the particular case of the regulated market. There are two very different types of tariffs, the first one is called PVPC and the second is the annual fixed tariff (which every commercial electricity company is forced by the government to offer). The difference in between them is shown in Table 15.

PVPC Tariff	**Annual Fixed Tariff**
The electricity price is fixed by the government using data of REE	Once this tariff has been chosen, one year of permanency with the commercial electricity company is assumed.
The electricity price measured in [€/KWh] is calculated regarding the electric pool	The fixed price is stablished by each of the companies and is updated throughout the year.
The electricity price changes with the hour, having each day 24 different prices.	The consumer will normally pay a 20% more compared to the bills of the PVPC tariff.
It is possible to know next day's price from 20h.	The best advantage of this tariff is the certainty of knowing what the receipt value will be.

Table 15 - Regulated Electricity Market Tariffs

The tariff used in the case study is the PVPC one. There are two different modes of registering the spent electricity, depending on the kind of meter box used. The first one is the hourly tariff, which measures how much electricity was consumed by hour and gives it its specific price. This tariff uses a digital meter box. Whereas the second tariff, consists in calculating an average daily price and uses an analogical meter box.[29]

The electric bill is divided into different parts. The component due to capacity and the one due to energy consumed. The PVPC and the annual tariff are the ones which can be chosen for the energy component, which is the one paid due to the consumed electricity.

While capacity component is due to the hired power, you pay it always, even when you don't consume during one complete month it is necessary for you to pay it; you are paying for the use of the transport and distribution networks and for the regulated costs.

As it has been mentioned before, the way in which the electric dispatch functions, makes the price of electricity dependent on the total demand. This is why it has been thought that a representation of the Spanish demand in different situations should be made. In Figure 22, a plot of the different demands depending on the season and the day of the week can be seen, which would help us to understand the changes in the electricity price.

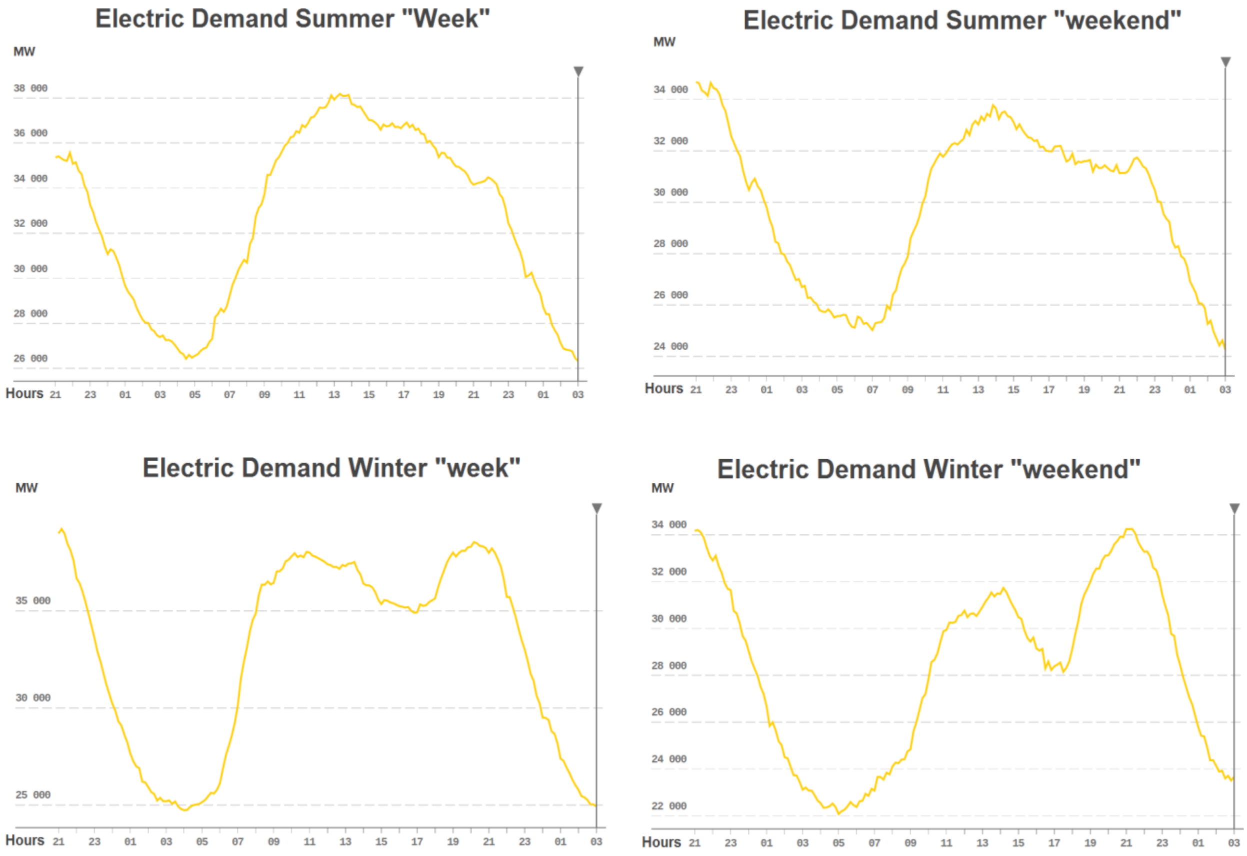

Figure 22 - Electric demand for winter and summer depending on the weekday

Once the demand has been seen, a monthly representation of the price of electricity in the last natural year has been represented in Figure 23. It is possible to find not only the average price, but also the minimum and maximum, the former of which is represented in blue, while the latter in red.

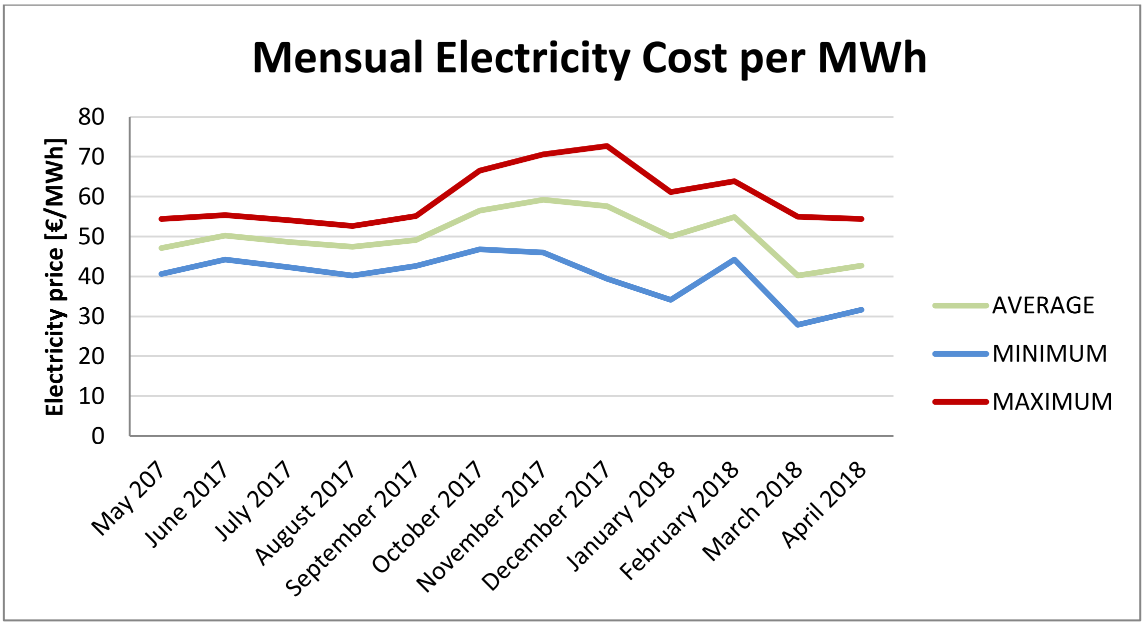

Figure 23 - Electricity Monthly Cost[30]

As furthermore information, a representation of the cost of electricity for a week day and a weekend day for both summer and winter is shown in Figure 24.

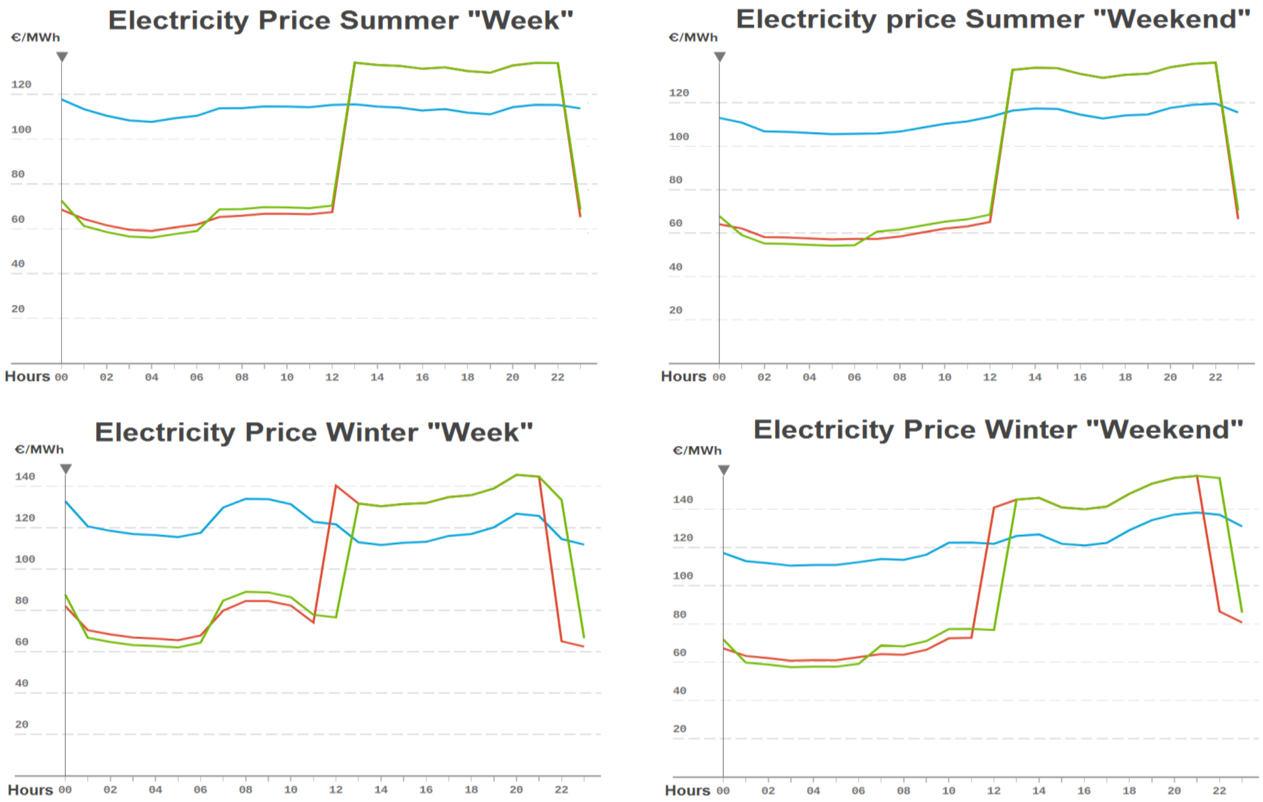

Figure 24 - Daily Price of Electricity in Spain in winter and summer during the week and weekend

The maximum demand for a residential building has been taken to be of 30 kW. This is the reason why the characteristics and costs of all the studied technologies are those of a 30 kW power machine.

The three CHP studied technologies, as it has been mentioned before, are the Internal Combustion Engine (ICE), the Micro Turbine (MT) and the Fuel Cell (FC). All of them have different characteristics which make the optimization study reasonable. In order to be able to formulate the objective function, certain data is necessary for each of the technologies; this data is found in Table 16.

	ICE	Micro Turbine	Fuel Cell
Investment	*2900 $/kW*	*4300 $/kW*	*10,000 $/kW*
Fixed Costs	*0 $/kW*	*0 $/kW*	*0 $/kW*
Variable Costs	*0.0827 $/kWh*	*0.0747 $/kWh*	*0.1037 $/kWh*
Life Time	*15 years*	*25-35 years*	*6-10 years*
Maintenance	*0.024 $/kWh*	*0.016 $/kWh*	*0.045 $/kWh*
Efficiency	*27%*	*24.4%*	*47%*

Table 16 - Important data regarding the studied technologies

Further explication of the data needs to be done. The investment is the cost of buying and setting up the technology so it can start working. The fixed costs are those costs paid only for having the technology installed, for example the amortization. In this particular case these costs will be supposed to be zero since the initial costs have already been taken into account in the investment. The only costs which vary with time are those dependent on the maintenance and operation of the machines and those on quantity of energy produced, which, at the same time, depend on the quantity of fuel used. So it could be said that the variable costs are an addition to the costs due to operation and maintenance and the price of natural gas, which is of 0.0587 $/kWh[31]. The addition of both has been represented in Table 17.

	O&M Costs [$/kWh]	Fuel Costs [$/kWh]	Total Variable Costs [$/kWh]
ICE	*0.0240*	*0.0587*	*0.0827*
MicroTurbine	*0.0160*	*0.0587*	*0.0747*
Fuel Cell	*0.0450*	*0.0 587*	*0.1037*

Table 17 - Variable Costs of the different technologies

With the objective of making a more thorough study, the insertion of a HVAC technology has also been studied. The technology we are talking about is the Absorption Chiller, whose operation, costs and emissions have already been described before.

The three CHP studied technologies, as it has been mentioned before, are the Internal Combustion Engine (ICE), the Micro Turbine (MT) and the Fuel Cell (FC). All of them have different characteristics which make the optimization study reasonable. In order to be able to formulate the objective function, certain data is necessary for each of the technologies; this data is found in Table 16.

The characteristics regarding absorption chillers have been represented in Table 18.

Investment Cost	**600 – 700 $/kWh**
Fixed Costs	*0 $*
Variable Costs	*0.0807 $/kWh*
Lifetime	*20 years*
Operation&Maintenance	*0.022 $/kWh*
Efficiency Cold	*110%*
Efficiency Hot	*88%*

Table 18 - Characteristics of direct fired absorption chillers

As it has been done for the CHP technologies, a decomposition of the variable costs has been made. The same as in the case of CHP, there a cost for operation and maintenance and a cost due to the natural gas fired inside the combustion chamber of the absorption chiller, this disaggregation of costs can be seen in Table 19.

	O&M Costs [$/kWh]	Fuel Costs [$/kWh]	Total Variable Costs [$/kWh]
Absorption Chiller	*0.022*	*0.0587*	*0.0807*

Table 19 - Decomposition of variable costs in direct fired absorption chillers

5. Results

This section presents relevant results for the case studies, considering the investments and operation of the different technologies. The monthly price of natural gas is of 0,05 €/kWh and the electricity price per hour and month is found in Table 24 and Table 25. There are three possible ways of producing the necessary electricity for satisfying the building demand. The first one is purchasing all the electricity from the network, in which case, the prices will be those of the PVPC tariff described before and the emissions those related with the total production of electricity in Spain. The second, would be using CHP technologies to generate the power needed and the third, using an absorption chiller.

As it has already been explained at the beginning of the thesis, optimization software programmed in GAMS has been used to treat the data correctly, in particular, a program called DER-CAM has been the one used to study the optimal solution.

The objective function of this study case is the total cost. This total cost involves the initial investment, and the variable costs of having the technologies functioning for 5 years.

In order to study which of the different possibilities would have a better objective function certain cases have been ran in the program. The most important case is the one where all technologies have been considered. After which, more particular cases where the investment of each technology is forced have been made. In those cases the program invests on one machine per year. In every case the power of these machines is of 30 kW since that is the maximum demand of the building.

	Total Utility Electricity Consumption (MWh)	**Total Natural Gas Consumption (MWh)**	**Total Capital Cost Discrete Tech (k$)**	**Total Costs (k$)**
ICE	*606,67*	*9.014,00*	*480,00*	*2.853,88*
MT	*699,39*	*8.828,07*	*645,00*	*2.841,82*
FC	*877,93*	*7.217,77*	*1.500,00*	*2.861,15*
Absorption Chiller	*1.785,73*	*3.372,58*	*105,00*	*2.836,90*
All technologies considered	***658,99***	***7.301,18***	***246,00***	***2.948,45***
Base Case	*1.787,33*	*4.948,27*	-	*2.735,25*

Table 20 - Value for the objective function in the different study cases

As it can be seen, the technology which implies the lowest accumulative capital cost is the absorption chiller, this is because its investment cost is much lower than that of the rest of technologies.

Since the absorption chiller is only able to produce the cooling demand, it makes sense that the total electricity purchased from the network, in order to cover the demand, for this technology is the highest one. The same idea can be taken to explain the natural gas consumption. The technology which covers the highest percentage of the demand on itself, which is the internal combustion engine, is the one whose accumulative natural gas consumption is the highest, whereas for the absorption chiller which is the technology covering the least part of the demand, this cost is the lowest.

Not only the total costs, but also the optimal function is lower for the case in which all the technologies are considered. This is the reason why three of the technologies function whenever all of them are considered. If these costs had been higher than that of a certain technology on its own, only that technology would be operating in the “all technologies” case.

It should be mentioned that Fuel Cells do not operate in the general case because of their elevated investment cost. A general study of how much this cost should decrease in order for them to operate in the general case has been made.

The price for which Fuel Cells start operating in the case where the investment is free, is of 3000 S/kWh. Which means for investing prices higher than that, fuel cells do not cover the demand in the general case. Since the normal investing price for them is of 10,000 $/kWh, in the general case they are never operating.

The first studied case has been that of considering all the CHP technologies, absorption chillers and purchase from the network. The results obtained for the months of January and July are represented in the Annex in Table 28 and Table 29 respectively. These two months are the ones chosen to represent the results in detail since they represent the extreme operation conditions of winter and summer.

Figure 25, presents how the total demand is covered by the different technologies during the month of January. Fuel Cells are not contributing to the satisfaction of this demand. This is because the investment cost of fuel cells is much greater than that for the rest of technologies, which makes them not to be considered in the optimized cost solution.

Since during the month of January there is no cooling demand, the Absorption Chiller does not work for this month.

As it can be seen in Table 24, the electricity price reaches its minimum from 1h to 6h, this results in the demand directly purchasing from the network, more profitable. Since the objective function of this program is the economic function, it makes sense that in this interval the demand is directly covered by the network.

On the other hand, in between covering the rest of the demand either with ICEs or MT, the program chooses at first ICEs, and whenever it needs further electricity production it uses MTs. This can be seen for hours 7 to 8 and 19 to 23. This makes sense since the total capital costs for Internal Combustion Engines is much smaller than that regarding Micro Turbines.

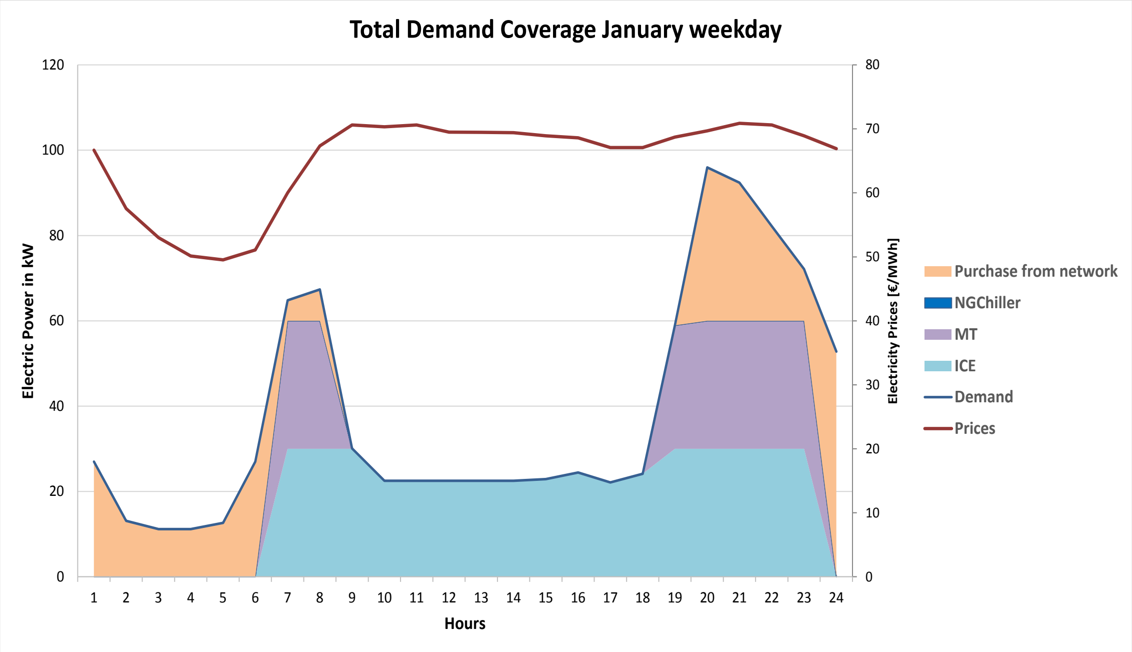

Figure 25 - Total demand coverage January weekday

In the same way, the coverage of the demand during a July weekday has been plotted in Figure 26, the same as in January, the Fuel cells are not producing electricity.

During the month of July the building only gathers electricity from the network when both the ICE and the MT are already covering their maximum electric power. This is because it is more profitable to purchase electricity for a more expensive price than investing in another CHP technology. As a matter of fact, it can also be seen that the total cooling demand is been covered by the absorption chiller by itself. This means the “electricity-only” demand has been covered by ICEs, MTs and the purchase from the network, while the cooling demand is completely covered by the absorption chiller on its own. This makes sense since, as it has been said before, “Absorption chillers use heat energy to generate chilled water that can be used for air conditioning or process cooling applications”.

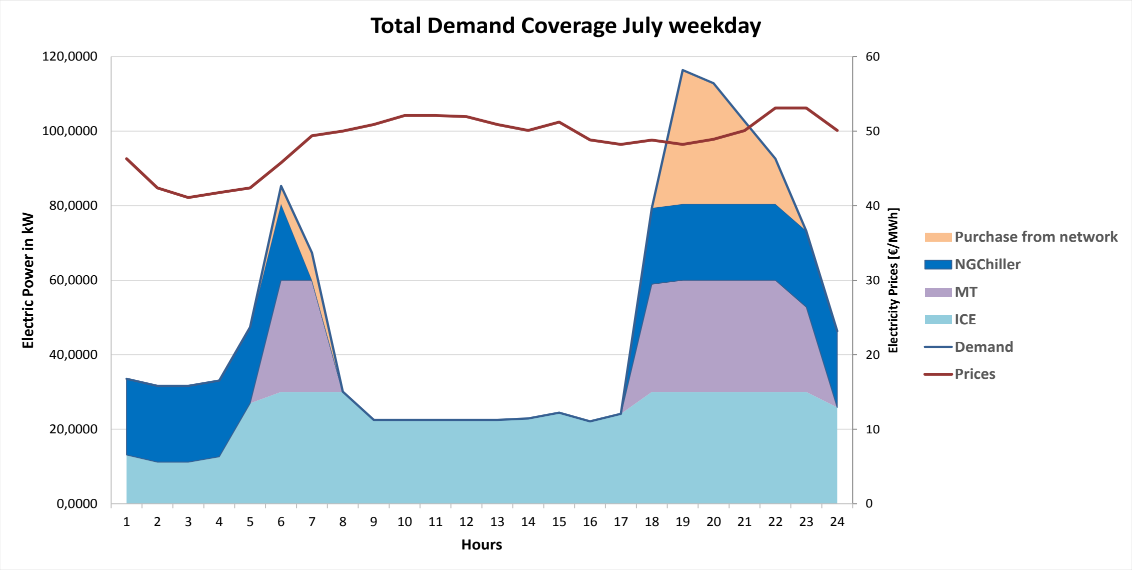

Figure 26 - Total demand coverage July weekday

In order to be able to study how each technology operates on its own, an investment has been forced for each of them separately. The results for the ICE and MT for the month of January can be found in Table 30, the ones for the same month and FCs and Absorption Chillers, in Table 31. Whereas those corresponding to ICE and MT for the month of July are present in Table 32, and for the FCs and Absorption Chiller for the same month in Table 33.

It can be seen from the results represented in Figure 27 that the electricity is purchased from the ICE whenever it is less than 30 kW (the maximum power of the engine) and it completes the demand purchasing from the network whenever it is more than that quantity. This is because it is more worthwhile to produce the energy using an ICE than purchasing it from the network.

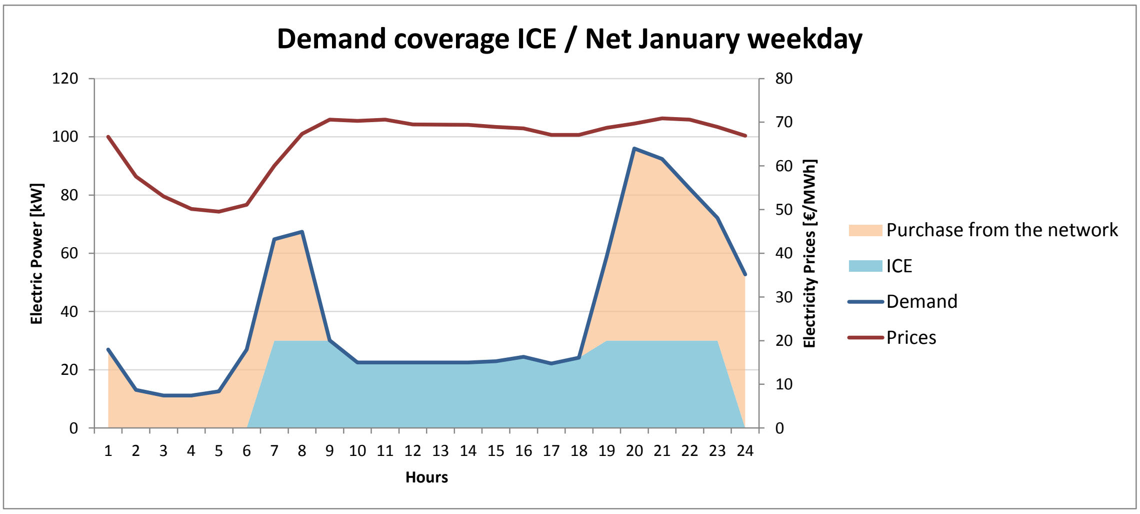

Figure 27 - Demand covered by ICE and Network in a January weekday

In the case of Micro Turbines, the results are the same as for the ICE. As it can be seen in Figure 28, internal combustion engines are more profitable than micro turbines, but when the micro turbine is studied on itself, it is better to cover the demand using it.

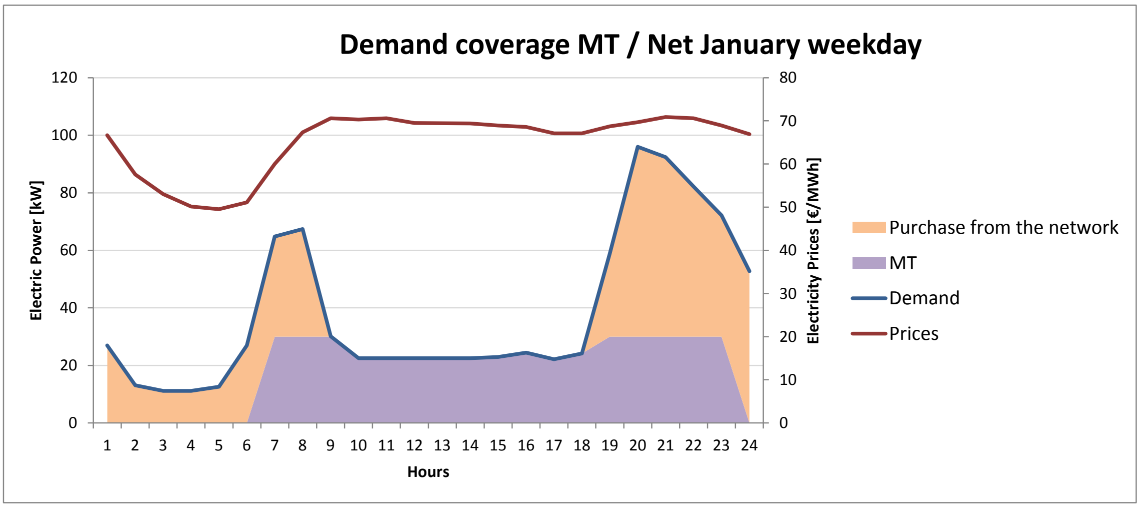

Figure 28 - Demand covered by MT and Network in a January weekday

The performance of Fuel Cells is seen in Figure 29. For the intervals from 2h to 5h and from 10h to 18h it doesn't use fuel cells to produce electricity but instead purchases it from the network. The reason for the first interval is that the price of electricity is very low in those hours since the total demand of the country is low. This makes it cheaper to cover the demand purchasing it from the network than using a fuel cell to produce it. On the other hand, for the second interval, even if the electricity price is high, it purchases directly from the network. This is because it isn't profitable to use a fuel cell for producing less than its maximum power and during this interval the demand is less than 30 kW.

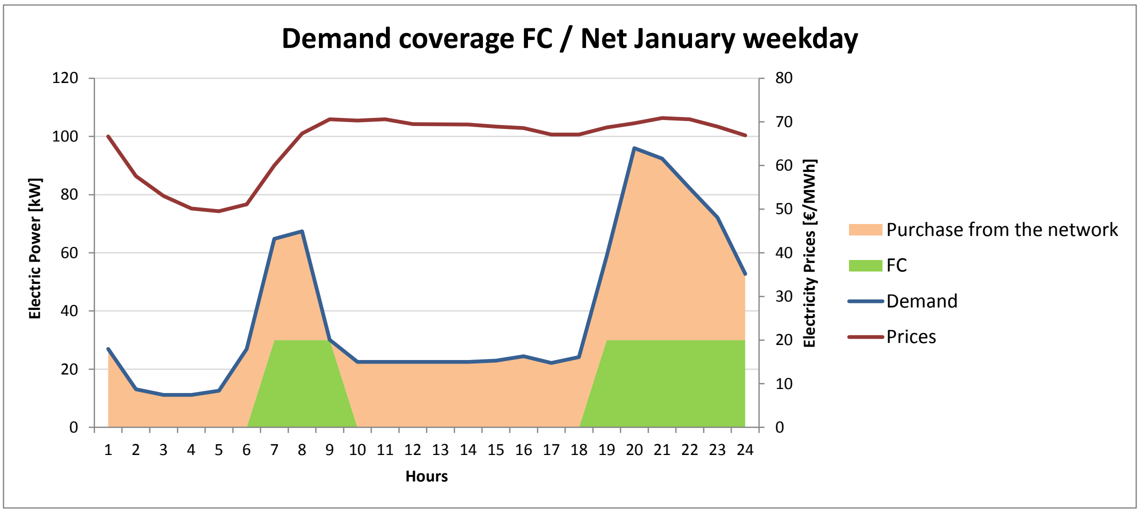

Figure 29 - Demand covered by FC and Network in a January weekday

It is not necessary to plot the results regarding the month of January for the operation of Aborption Chillers since, because there is no cooling demand, all of the electricity only demand is gathered from the network.

The same way as in January, the ICE is always profitable. Even when the demand is less than 30 kW, it is covering it, which differentiates it from the FC. It is also important to say that if the demand is greater than 60 kW which would be equivalent to two units of the internal combustion engine; it is more profitable to gather the electricity from the network than to have a second unit, which, at the end, is the same which happened for January.

Regarding Figure 30, it is interesting to note that, differently from January, the actuation of Micro turbines in the month of July is different to that of Internal Combustion Engines. The reason for this difference is the change in the price of electricity from one month to the other. The Micro Turbine is not functioning in hours 3 and 4, this is because the price for the electricity during these two hours in January is of 0.10246 and 0.09982 respectively whereas in the month of July it is of 0.155445 and 0.15463 respectively. This makes it worth producing the electricity with the ICE, but not with the MT, due to their difference in price.

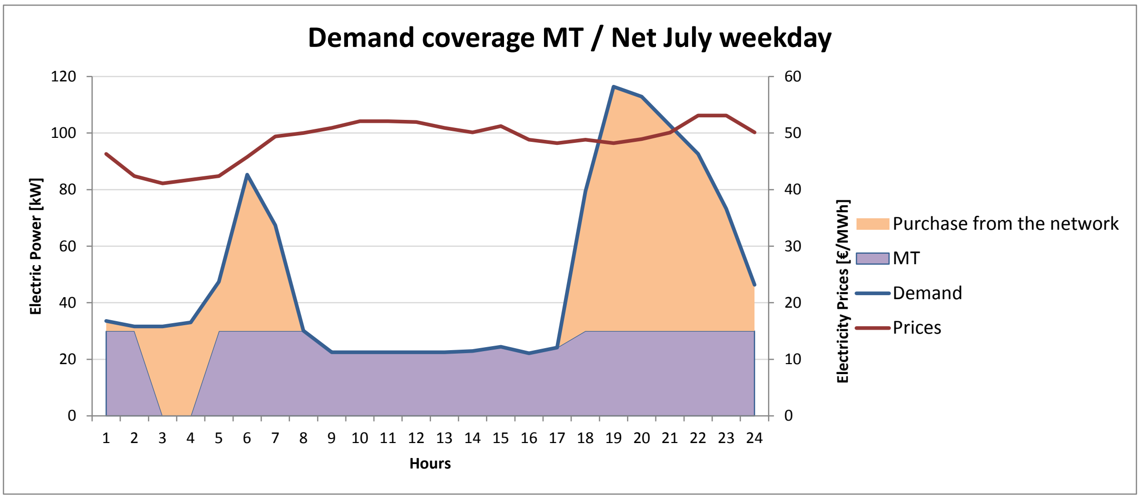

Figure 30 - Demand covered by MT and Network in a July weekday

In the case of the Fuel Cell found in Figure 31, the same as in January, it produces electricity only when the demand is 30 kW or more, this is because it is not profitable for it to work producing less than its maximum power. On the other hand, the differences found with January, is that for hours in between 2 and 5, the Fuel Cell is producing, whereas in January it isn't. To find the explanation for this action, a look must be taken to the prices of electricity, Table 21. There is a difference in between them which makes it worth using the Fuel Cell in July, but not in January.

€/kWh	January	July
2h	*0,10900*	*0,15876*
3h	*0,10246*	*0,15545*
4h	*0,09982*	*0,15463*
5h	*0,10946*	*0,15641*

Table 21 - Electricity prices from 2h to 5h in January and July [31]

All these hourly prices are represented for each month in the graphics making it easier to see when the prices are sufficiently low or too high.

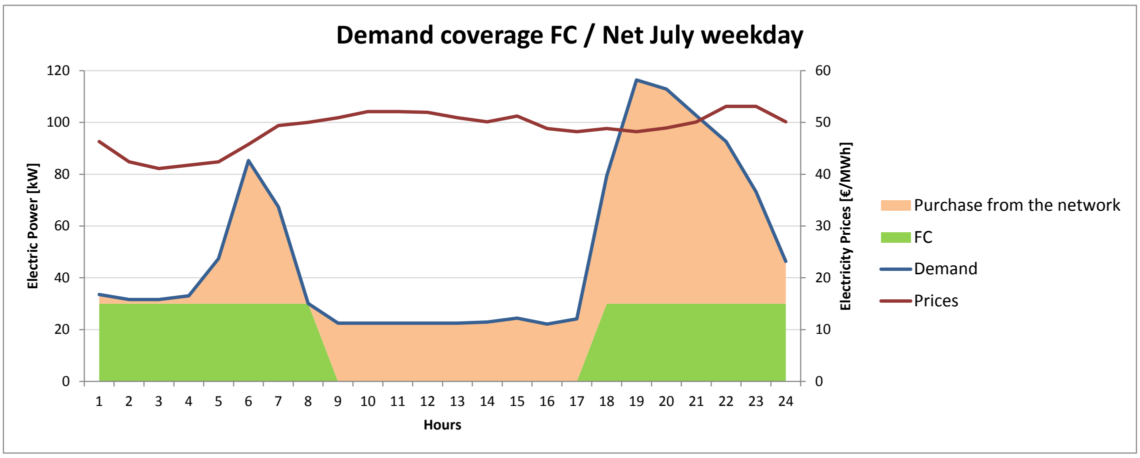

Figure 31 - Demand covered by FC and Network in a July weekday

When speaking about Absorption Chillers, differently from January, where there was no cooling demand, in this case they are covering the cooling demand and nothing else than the cooling demand when they are functioning.

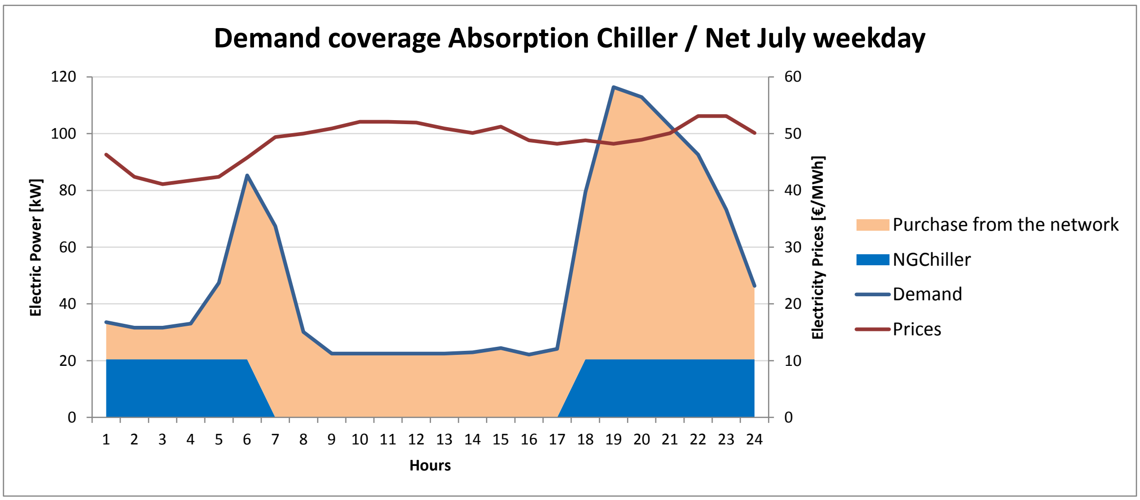

Figure 32 - Demand covered by Absorption Chillers and Network in a July weekday

6. Conclusions

Residential consumption in Spain represents the 35.1% of the total electricity demand in the country and the 24.9% of the total consumption of natural gas. In Figure 19 the total annual electricity demand in Spain has been represented. Using this data, the annual residential consumption representing the 35.1% of the total demand was of 88,7 TWh for year 2017.

The first studied case has been that of considering all the CHP technologies, absorption chillers and purchase from the network. These two months are the ones chosen to represent the results in detail since they represent the extreme operation conditions of winter and summer. The second studied case is that of the operation of each technology on its own, an investment has been forced for each of them separately.

Since the objective function of this thesis is the total cost function, its results are worth commenting. The technology which results in the highest electricity consumption is the absorption chiller, this is because of the fact that it only covers the cooling demand while the rest has to be purchased from the network.

The most expensive case, as it has already been said is the one where Fuel Cells operate on their own, purchasing the rest from the network. This is because the investment cost of fuel cells is higher than that of the rest of technologies. As it was thought from the beginning, the option which brings the lower costs is that in which there is a free investment; this is because each technology is operating in the interval in which they can be more useful.

Once the costs have been studied and the operation data for each of them has been plotted, certain conclusions have been drawn.

- The option of having all the technologies is the one with the cheapest objective function because every technology is covering what they do best in terms of providing energy to the building and meeting the building needs and the rest is been gathered from the network.
- ICEs always operate, even when the demand is less than its maximum capacity.
- Micro turbines, as ICEs, usually operate, but when the price of electricity is sufficiently low, it is better to purchase the electricity from the network instead of producing it with a micro turbine, differently of what happens with ICEs.
- Finally, FCs, only work when the demand is the same as its maximum capacity or higher, which means that when the demand is less than 30 kW the demand is covered with electricity purchased from the network. The same for January, for the low prices of 2h and 5h, it is more profitable to take it from the network than to use the fuel cell.
- The absorption chiller only covers the cooling demand, but when the price of purchasing the electricity from the network is sufficiently low, it stops being profitable.

- The case which implies the best option for the objective function is that of having all the technologies together since each of them can generate in its best period.

7. Further Studies

7.1. Using Heat Pumps

Because of the reason that not all possible optimization options have been studied, we would like to describe some further technologies which could lead to new conclusions. The first of these options would be the one of using not only absorption chillers but also **heat pumps** as a HVAC technology.

Heat pumps are Heating Ventilating and Air Conditioning (HVAC) electrical[33] devices which extract heat from one place and transfer it to another. They transfer heat by circulating a refrigerant through a cycle of evaporation and condensation. A compressor pumps the refrigerant between two heat exchanger coils. In one coil, the refrigerant is evaporated at low pressure and absorbs heat from its surroundings. The refrigerant is then compressed and sent to the other coil, where it condenses at high pressure. At this point, it releases the heat it absorbed earlier in the cycle.[34]

It has been studied that for each kW of electricity consumed by a heat pump, about 4 kW of thermal energy is generated, which corresponds to a 300% efficiency. [35]

GHP installations need no fossil fuel, do not use combustion processes to generate heat and thus produce no air polluting substances. This is the environmental advantage of GHP systems. The heat pump (HP), a basic system component, needs auxiliary power to accomplish the temperature rise needed in the system. In most cases, HPs are driven by electric power.

Which means with these systems the use of fossil primary energy sources can be avoided, since heat pumps are usually driven by electric components the origin of the electricity and the corresponding CO2 emissions must be considered. [36]

These are the reasons why heat pumps are HVAC technologies which could be taken into account for the optimization study.

7.2. Using Exhaust Fired Chillers

The absorption chiller, as it was described in the section of HVAC technologies, can either be direct fired with a fuel like natural gas, or exhaust fired. The former is the one included in this thesis. We would like to propose the latter as a means of reducing the variable costs (in which the cost of fuel is included) at the same time that the emissions are reduced because there is only one fuel burning machine working.

Exhaust fired absorption chillers directly use waste heat from the Gas/diesel engine or turbine exhaust gases, micro turbine or fuel cell which helps in making air-conditioning almost free of cost. It also reduces the initial capital cost of the system, by downsizing the engine size; as additional power units required for electrical chillers is eliminated.[37]

A scheme of how it would be if we had an exhaust absorption chiller at the same time that micro turbines can be seen in Figure 33.

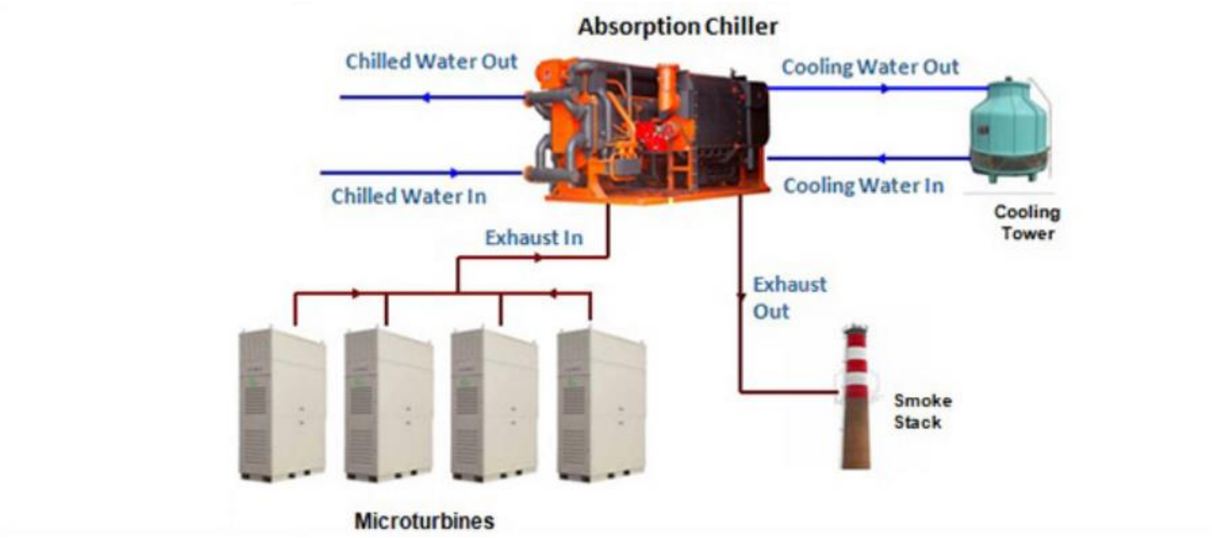

Figure 33 - Scheme of an Exhaust Absorption Chiller working with Micro Turbine gases

Hence the study of integration of absorption chillers with CHP technologies could lead to the improvement in emissions, thus been more environmentally friendly, and the reductions of fuel costs.

7.3. Other types of buildings

The buildings which form this case study are residential buildings, and the demand curve has certain characteristics. If the buildings had been shopping centers, cinemas, etc the demand would be different. The buildings in which there are lots of people at the same time need to follow certain ventilation rules, which changes their demand in comparison to residential ones. The studied technologies could be applied to this case study in order to know whether the optimization function changes for different demands.

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TECHNO-ECONOMICS OF CHP AND HVAC TECHNOLOGIES AT CONSUMER LEVEL

DOCUMENT II - Annex

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1. Annex - Data

	2013	2014	2015	2016	2017
Annual Electricity demand in Spain [TWh]	246	244	248	250	253
Residential Consumption [TWh]	86,346	85,644	87,048	87,75	88,803

Table 22 - Annex - Annual total and residential electricity demand in Spain

Average Temperature Madrid [ºC]		
	Minimum	Maximum
January	1,8	10,1
February	5,5	12,8
March	6,7	17,6
April	9,5	22,5
May	14,1	26,1
June	19,7	33
July	19,9	33,6
August	20,4	32,9
September	15,7	27,3
October	13,4	24
November	5,8	14,6
December	2,9	10,7

Table 23 – Annex - Average temperature of the city of Madrid 2017

Electricity Price (€/kWh) weekday	January	February	March	April	May	June	July	August	September	October	November	December
1h	0,12552	0,10294	0,11202	0,08988	0,11382	0,17233	0,16663	0,17443	0,17828	0,21786	0,21775	0,24213
2h	0,10900	0,09413	0,09991	0,08138	0,10527	0,16309	0,15876	0,16548	0,17162	0,20427	0,20586	0,22668
3h	0,10246	0,08494	0,09519	0,07794	0,10024	0,15898	0,15545	0,16086	0,16904	0,19548	0,20055	0,21683
4h	0,09982	0,08307	0,09423	0,07851	0,09880	0,15886	0,15463	0,15914	0,16905	0,19420	0,19796	0,21409
5h	0,10946	0,09330	0,10026	0,08486	0,10601	0,16633	0,15641	0,16133	0,17263	0,20819	0,20922	0,22303
6h	0,13110	0,11891	0,11969	0,10917	0,12515	0,18034	0,16368	0,17404	0,18940	0,24485	0,24236	0,25324
7h	0,17495	0,15748	0,14268	0,13520	0,14362	0,19009	0,18506	0,18365	0,21032	0,26595	0,27704	0,29535
8h	0,20386	0,17085	0,15713	0,15125	0,15680	0,20012	0,19384	0,19502	0,21641	0,27144	0,29010	0,30873
9h	0,20776	0,17586	0,15969	0,15764	0,15632	0,19263	0,20072	0,20273	0,22025	0,27216	0,28679	0,30741
10h	0,21140	0,17162	0,15512	0,14663	0,15413	0,19233	0,20105	0,20006	0,21708	0,27259	0,28482	0,30664
11h	0,20625	0,16174	0,14634	0,13788	0,15274	0,19079	0,20086	0,19890	0,21494	0,26771	0,27976	0,30025
12h	0,19850	0,15414	0,13972	0,13290	0,15292	0,19211	0,20257	0,20220	0,21417	0,26833	0,27482	0,29406
13h	0,19923	0,15319	0,13667	0,12847	0,15141	0,18962	0,20550	0,20458	0,21314	0,26691	0,27468	0,29387
14h	0,18789	0,14660	0,12814	0,12042	0,14760	0,18408	0,20160	0,20280	0,20844	0,26124	0,27092	0,29068
15h	0,18266	0,14086	0,12055	0,11413	0,14086	0,17818	0,19918	0,19691	0,20512	0,25551	0,26810	0,28909
16h	0,18654	0,14401	0,11748	0,10927	0,13715	0,17688	0,19812	0,19537	0,20506	0,25550	0,27051	0,29226
17h	0,20181	0,14998	0,12278	0,11256	0,14013	0,18014	0,19760	0,19532	0,20850	0,26040	0,28619	0,30649
18h	0,22151	0,16603	0,13380	0,11704	0,14037	0,17983	0,19189	0,19177	0,21041	0,26568	0,30264	0,32044
19h	0,23017	0,19334	0,16061	0,12535	0,14363	0,17981	0,18849	0,19236	0,21613	0,27273	0,30584	0,32008
20h	0,22193	0,18820	0,17463	0,14010	0,15018	0,18303	0,18967	0,19645	0,22130	0,28509	0,30375	0,31388
21h	0,21050	0,17356	0,16429	0,16098	0,16291	0,19185	0,19504	0,20653	0,22082	0,27474	0,29039	0,30281
22h	0,19459	0,15300	0,14794	0,13954	0,15235	0,19339	0,19512	0,20043	0,20671	0,25455	0,27014	0,29166
23h	0,17067	0,13456	0,13269	0,12176	0,13925	0,17921	0,18288	0,18594	0,18816	0,23994	0,25058	0,27898
24h	0,14592	0,12443	0,12731	0,10272	0,12686	0,17954	0,18431	0,18703	0,18766	0,23894	0,23761	0,26851
MINIMUM	0,09982	0,08307	0,09423	0,07794	0,09880	0,15886	0,15463	0,15914	0,16904	0,19420	0,19796	0,21409
AVERAGE	0,17639	0,14320	0,13287	0,11982	0,13744	0,18140	0,18621	0,18889	0,20144	0,25059	0,26243	0,28155

Table 24 – Annex - Minimum and average electricity price mer month [€/kWh]

Electricity Peak Price (€/kWh)	January	February	March	April	May	June	July	August	September	October	November	December
1h	0,20246	0,17532	0,17744	0,13986	0,18041	0,20444	0,21321	0,21560	0,21911	0,24345	0,27968	0,29970
2h	0,19008	0,17100	0,16362	0,13275	0,18041	0,20250	0,20439	0,20858	0,21600	0,23261	0,26411	0,28116
3h	0,18045	0,16790	0,15777	0,13050	0,18000	0,20111	0,19548	0,20561	0,21510	0,23022	0,25970	0,26667
4h	0,17964	0,16511	0,15750	0,12618	0,18041	0,19274	0,18450	0,20205	0,21321	0,22955	0,25650	0,25875
5h	0,18045	0,17105	0,16362	0,12735	0,18041	0,19800	0,18900	0,20003	0,21542	0,23855	0,25709	0,27536
6h	0,20295	0,18279	0,18545	0,14265	0,17028	0,20336	0,19800	0,20300	0,22050	0,27315	0,29970	0,30420
7h	0,24786	0,22185	0,20372	0,17663	0,18473	0,22491	0,20772	0,21191	0,22586	0,29750	0,32310	0,32261
8h	0,27707	0,22626	0,21771	0,19121	0,18905	0,22491	0,22055	0,21654	0,22793	0,30150	0,32270	0,33705
9h	0,28346	0,23400	0,22541	0,20894	0,18000	0,21285	0,22829	0,21645	0,23202	0,29912	0,31788	0,33260
10h	0,29088	0,22820	0,22541	0,20448	0,18671	0,21560	0,22500	0,21686	0,22950	0,30209	0,31500	0,33260
11h	0,27905	0,21299	0,21911	0,19121	0,18311	0,21461	0,22500	0,21911	0,22811	0,29642	0,31491	0,33089
12h	0,26960	0,21236	0,21546	0,18761	0,18671	0,21600	0,21911	0,22001	0,22950	0,29561	0,30465	0,32355
13h	0,26339	0,21236	0,21227	0,17861	0,18671	0,21573	0,22500	0,22028	0,22811	0,29561	0,30375	0,32166
14h	0,26096	0,20561	0,20777	0,16961	0,18419	0,21105	0,21393	0,21825	0,22361	0,29084	0,30848	0,31811
15h	0,26240	0,20430	0,20691	0,16043	0,18041	0,20813	0,21195	0,21443	0,22064	0,28661	0,30713	0,31568
16h	0,27711	0,20700	0,20259	0,15750	0,17991	0,20606	0,20871	0,21236	0,22064	0,28683	0,30461	0,31361
17h	0,27905	0,21668	0,20070	0,15611	0,17991	0,21380	0,21011	0,21101	0,22136	0,28971	0,31851	0,32990
18h	0,29250	0,22685	0,18909	0,15656	0,16736	0,20588	0,20754	0,21173	0,22298	0,29129	0,33242	0,33975
19h	0,30020	0,24998	0,22950	0,15989	0,17060	0,20250	0,20156	0,21461	0,24147	0,29732	0,32927	0,33750
20h	0,29399	0,25650	0,26915	0,18900	0,17231	0,21497	0,20084	0,21150	0,23616	0,31446	0,32630	0,33350
21h	0,28481	0,24998	0,23868	0,26100	0,19580	0,22329	0,21155	0,21672	0,23036	0,30110	0,31176	0,32445
22h	0,24948	0,21780	0,19845	0,20691	0,17393	0,22091	0,22613	0,21551	0,21722	0,28724	0,29561	0,31496
23h	0,23711	0,19800	0,19125	0,16200	0,16425	0,21614	0,21011	0,20250	0,20561	0,27675	0,28256	0,30789
24h	0,22545	0,19958	0,19211	0,16961	0,18090	0,21915	0,21551	0,22028	0,22064	0,27000	0,29250	0,31176
PEAK	0,30020	0,25650	0,26915	0,26100	0,19580	0,22491	0,22829	0,22028	0,24147	0,31446	0,33242	0,33975

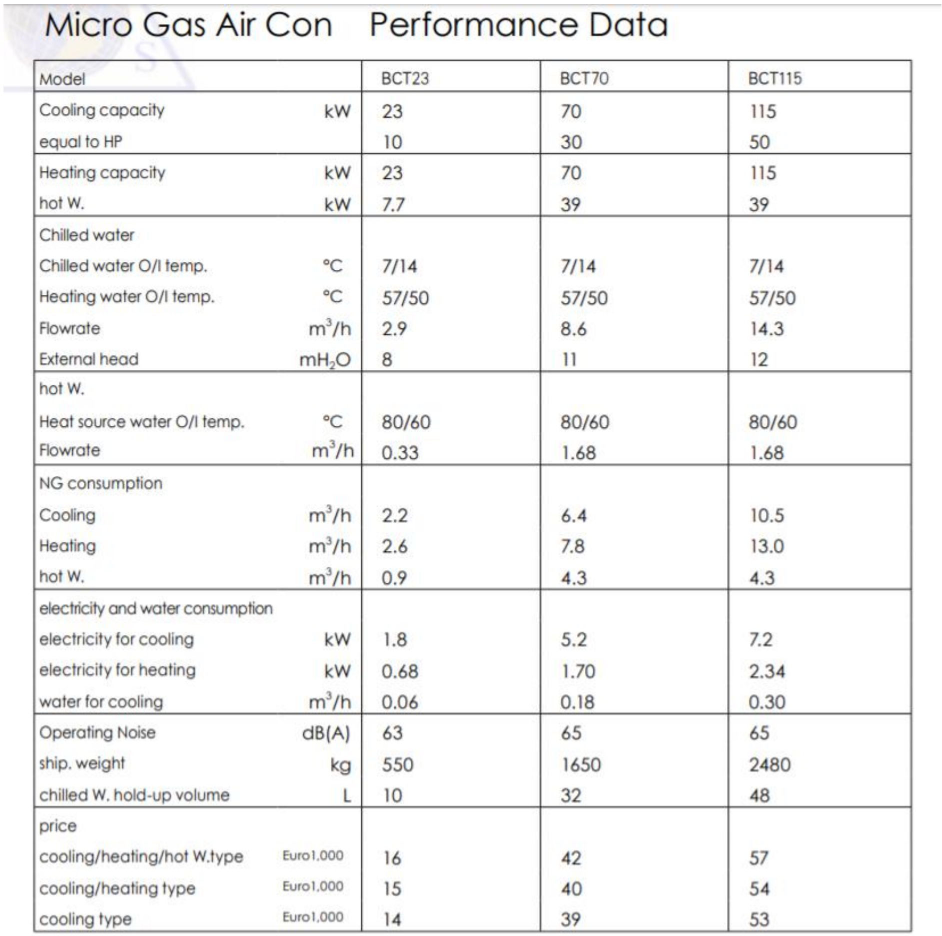
Table 25 - Annex - Peak electricity price per month [€/kWh]

Electricity-only Load [kW]	January	February	March	April	May	June	July	August	September	October	November	December
1h	26,9648	26,9648	16,3996	13,0980	13,0980	13,0980	13,0980	13,0980	13,0980	13,0980	26,9648	26,9648
2h	13,0980	13,0980	11,6312	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728	13,0980	13,0980
3h	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728	11,1728
4h	11,1728	11,1728	12,2693	12,6119	12,6119	12,6119	12,6119	12,6119	12,6119	12,6119	11,1728	11,1728
5h	12,6119	12,6119	23,5460	26,9629	26,9629	26,9629	26,9629	26,9629	26,9629	26,9629	12,6119	12,6119
6h	26,9629	26,9629	55,8081	64,8222	64,8222	64,8222	64,8222	64,8222	64,8222	64,8222	26,9629	26,9629
7h	64,8222	64,8222	66,7663	67,3739	67,3739	67,3739	67,3739	67,3739	67,3739	67,3739	64,8222	64,8222
8h	67,3739	67,3739	38,9656	30,0880	30,0880	30,0880	30,0880	30,0880	30,0880	30,0880	67,3739	67,3739
9h	30,0880	30,0880	24,3167	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	30,0880	30,0880
10h	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132
11h	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132
12h	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132
13h	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132	22,5132
14h	22,5132	22,5132	22,8111	22,9043	22,9043	22,9043	22,9043	22,9043	22,9043	22,9043	22,5132	22,5132
15h	22,9043	22,9043	24,0833	24,4517	24,4517	24,4517	24,4517	24,4517	24,4517	24,4517	22,9043	22,9043
16h	24,4517	24,4517	22,6768	22,1222	22,1222	22,1222	22,1222	22,1222	22,1222	22,1222	24,4517	24,4517
17h	22,1222	22,1222	23,6580	24,1380	24,1380	24,1380	24,1380	24,1380	24,1380	24,1380	22,1222	22,1222
18h	24,1380	24,1380	50,6505	58,9357	58,9357	58,9357	58,9357	58,9357	58,9357	58,9357	24,1380	24,1380
19h	58,9357	58,9357	87,1398	95,9537	95,9537	95,9537	95,9537	95,9537	95,9537	95,9537	58,9357	58,9357
20h	95,9537	95,9537	93,2453	92,3990	92,3990	92,3990	92,3990	92,3990	92,3990	92,3990	95,9537	95,9537
21h	92,3990	92,3990	84,6141	82,1814	82,1814	82,1814	82,1814	82,1814	82,1814	82,1814	92,3990	92,3990
22h	82,1814	82,1814	74,5446	72,1581	72,1581	72,1581	72,1581	72,1581	72,1581	72,1581	82,1814	82,1814
23h	72,1581	72,1581	57,3887	52,7733	52,7733	52,7733	52,7733	52,7733	52,7733	52,7733	72,1581	72,1581
24h	52,7733	52,7733	32,2443	25,8634	25,5226	25,8110	25,8634	25,5226	25,8110	25,5881	52,7733	52,7733

Table 26 - Annex - Electricity average hourly load per month

Cooling Load [kW]	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
1h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
2h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
3h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
4h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
5h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
6h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
7h	0,0000	0,0000	0,0000	0,7834	0,1281	0,0000	0,0000	0,0000	0,3024	0,0000	0,0000	0,0000
8h	0,0000	0,0000	0,0000	0,6309	0,1133	0,0054	0,0000	0,0000	0,3170	0,0000	0,0000	0,0000
9h	0,0000	0,0000	0,0000	0,3402	0,0640	0,0052	0,0000	0,0000	0,0991	0,0000	0,0000	0,0000
10h	0,0000	0,0000	0,0000	0,1855	0,0435	0,0000	0,0000	0,0000	0,0264	0,0000	0,0000	0,0000
11h	0,0000	0,0000	0,0000	0,0949	0,0217	0,0000	0,0000	0,0000	0,0120	0,0000	0,0000	0,0000
12h	0,0000	0,0000	0,0000	0,0445	0,0100	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
13h	0,0000	0,0000	0,0000	0,0251	0,0113	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
14h	0,0000	0,0000	0,0000	0,0149	0,0097	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
15h	0,0000	0,0000	0,0000	0,0072	0,0052	0,0000	0,0000	0,0000	0,0051	0,0000	0,0000	0,0000
16h	0,0000	0,0000	0,0000	0,0126	0,0118	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
17h	0,0000	0,0000	0,0000	0,0173	0,0089	0,0000	0,0000	0,0000	0,0052	0,0000	0,0000	0,0000
18h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
19h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
20h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
21h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
22h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
23h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000
24h	0,0000	0,0000	0,0000	20,4510	20,4510	20,4510	20,4510	20,4510	20,4510	0,0000	0,0000	0,0000

Table 27 - Annex - Cooling average hourly load per month



Micro Gas Air Con Performance Data

Model		BCT23	BCT70	BCT115
Cooling capacity	kW	23	70	115
equal to HP		10	30	50
Heating capacity	kW	23	70	115
hot W.	kW	7.7	39	39
Chilled water				
Chilled water O/I temp.	°C	7/14	7/14	7/14
Heating water O/I temp.	°C	57/50	57/50	57/50
Flowrate	m^3/h	2.9	8.6	14.3
External head	mH_2O	8	11	12
hot W.				
Heat source water O/I temp.	°C	80/60	80/60	80/60
Flowrate	m^3/h	0.33	1.68	1.68
NG consumption				
Cooling	m^3/h	2.2	6.4	10.5
Heating	m^3/h	2.6	7.8	13.0
hot W.	m^3/h	0.9	4.3	4.3
electricity and water consumption				
electricity for cooling	kW	1.8	5.2	7.2
electricity for heating	kW	0.68	1.70	2.34
water for cooling	m^3/h	0.06	0.18	0.30
Operating Noise	dB(A)	63	65	65
ship. weight	kg	550	1650	2480
chilled W. hold-up volume	L	10	32	48
price				
cooling/heating/hot W.type	Euro1,000	16	42	57
cooling/heating type	Euro1,000	15	40	54
cooling type	Euro1,000	14	39	53

Figure 34 – Annex - Performance Data of a micro gas turbine [41]

2. Annex - Results

2.1. Annex - Economic optimization considered (CHP technologies, Absorption Chiller and Purchase from the network)

				January				
	ICE	MT	FC	NGChiller	Purchase from network	Demand	Cooling	Electricity Only
1h	0,0000	0,0000	0,0000	0,0000	26,9648	26,9648	0,0000	26,9648
2h	0,0000	0,0000	0,0000	0,0000	13,0980	13,0980	0,0000	13,0980
3h	0,0000	0,0000	0,0000	0,0000	11,1728	11,1728	0,0000	11,1728
4h	0,0000	0,0000	0,0000	0,0000	11,1728	11,1728	0,0000	11,1728
5h	0,0000	0,0000	0,0000	0,0000	12,6119	12,6119	0,0000	12,6119
6h	0,0000	0,0000	0,0000	0,0000	26,9629	26,9629	0,0000	26,9629
7h	30,0000	30,0000	0,0000	0,0000	4,8222	64,8222	0,0000	64,8222
8h	30,0000	30,0000	0,0000	0,0000	7,3739	67,3739	0,0000	67,3739
9h	30,0000	0,0000	0,0000	0,0000	0,0880	30,0880	0,0000	30,0880
10h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
11h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
12h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
13h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
14h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
15h	22,9043	0,0000	0,0000	0,0000	0,0000	22,9043	0,0000	22,9043
16h	24,4517	0,0000	0,0000	0,0000	0,0000	24,4517	0,0000	24,4517
17h	22,1222	0,0000	0,0000	0,0000	0,0000	22,1222	0,0000	22,1222
18h	24,1380	0,0000	0,0000	0,0000	0,0000	24,1380	0,0000	24,1380
19h	30,0000	28,9357	0,0000	0,0000	0,0000	58,9357	0,0000	58,9357
20h	30,0000	30,0000	0,0000	0,0000	35,9536	95,9537	0,0000	95,9537
21h	30,0000	30,0000	0,0000	0,0000	32,3990	92,3990	0,0000	92,3990
22h	30,0000	30,0000	0,0000	0,0000	22,1813	82,1814	0,0000	82,1814
23h	30,0000	30,0000	0,0000	0,0000	12,1581	72,1581	0,0000	72,1581
24h	0,0000	0,0000	0,0000	0,0000	52,7733	52,7733	0,0000	52,7733

Table 28 - Annex - Economic optimization January. Considered technologies (CHP, Absorption Chiller and purchase from the network) [kW]

				July				
	ICE	**MT**	**FC**	**NGChiller**	**Purchase from network**	**Demand**	**Cooling**	**Electricity Only**
1h	13,0980	0,0000	0,0000	20,4510	0,0000	33,5490	20,4510	13,0980
2h	11,1728	0,0000	0,0000	20,4510	0,0000	31,6238	20,4510	11,1728
3h	11,1728	0,0000	0,0000	20,4510	0,0000	31,6238	20,4510	11,1728
4h	12,6119	0,0000	0,0000	20,4510	0,0000	33,0629	20,4510	12,6119
5h	26,9629	0,0000	0,0000	20,4510	0,0000	47,4139	20,4510	26,9629
6h	30,0000	30,0000	0,0000	20,4510	4,8222	85,2732	20,4510	64,8222
7h	30,0000	30,0000	0,0000	0,0000	7,3739	67,3739	0,0000	67,3739
8h	30,0000	0,0000	0,0000	0,0000	0,0880	30,0880	0,0000	30,0880
9h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
10h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
11h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
12h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
13h	22,5132	0,0000	0,0000	0,0000	0,0000	22,5132	0,0000	22,5132
14h	22,9043	0,0000	0,0000	0,0000	0,0000	22,9043	0,0000	22,9043
15h	24,4517	0,0000	0,0000	0,0000	0,0000	24,4517	0,0000	24,4517
16h	22,1222	0,0000	0,0000	0,0000	0,0000	22,1222	0,0000	22,1222
17h	24,1380	0,0000	0,0000	0,0000	0,0000	24,1380	0,0000	24,1380
18h	30,0000	28,9357	0,0000	20,4510	0,0000	79,3867	20,4510	58,9357
19h	30,0000	30,0000	0,0000	20,4510	35,9536	116,4047	20,4510	95,9537
20h	30,0000	30,0000	0,0000	20,4510	32,3990	112,8500	20,4510	92,3990
21h	30,0000	30,0000	0,0000	20,4510	22,1813	102,6324	20,4510	82,1814
22h	30,0000	30,0000	0,0000	20,4510	12,1581	92,6091	20,4510	72,1581
23h	30,0000	22,7732	0,0000	20,4510	0,0000	73,2243	20,4510	52,7733
24h	25,8634	0,0000	0,0000	20,4510	0,0000	46,3144	20,4510	25,8634

Table 29 - Annex - Economic optimization July. Considered technologies (CHP, Absorption Chiller and purchase from the network) [kW]

2.2. Economic optimization: Forced investment in certain technologies

JANUARY	Purchase from the network	ICE	Demand	Cooling	Electricity Only	Purchase from the network	MT	Demand	Cooling	Electricity Only
1h	26,9648	0,0000	26,9648	0,0000	26,9648	26,9648	0,0000	26,9648	0,0000	26,9648
2h	13,0980	0,0000	13,0980	0,0000	13,0980	13,0980	0,0000	13,0980	0,0000	13,0980
3h	11,1728	0,0000	11,1728	0,0000	11,1728	11,1728	0,0000	11,1728	0,0000	11,1728
4h	11,1728	0,0000	11,1728	0,0000	11,1728	11,1728	0,0000	11,1728	0,0000	11,1728
5h	12,6119	0,0000	12,6119	0,0000	12,6119	12,6119	0,0000	12,6119	0,0000	12,6119
6h	26,9629	0,0000	26,9629	0,0000	26,9629	26,9629	0,0000	26,9629	0,0000	26,9629
7h	34,8222	30,0000	64,8222	0,0000	64,8222	34,8222	30,0000	64,8222	0,0000	64,8222
8h	37,3739	30,0000	67,3739	0,0000	67,3739	37,3739	30,0000	67,3739	0,0000	67,3739
9h	0,0880	30,0000	30,0880	0,0000	30,0880	0,0880	30,0000	30,0880	0,0000	30,0880
10h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
11h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
12h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
13h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
14h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
15h	0,0000	22,9043	22,9043	0,0000	22,9043	0,0000	22,9043	22,9043	0,0000	22,9043
16h	0,0000	24,4517	24,4517	0,0000	24,4517	0,0000	24,4517	24,4517	0,0000	24,4517
17h	0,0000	22,1222	22,1222	0,0000	22,1222	0,0000	22,1222	22,1222	0,0000	22,1222
18h	0,0000	24,1380	24,1380	0,0000	24,1380	0,0000	24,1380	24,1380	0,0000	24,1380
19h	28,9357	30,0000	58,9357	0,0000	58,9357	28,9357	30,0000	58,9357	0,0000	58,9357
20h	65,9537	30,0000	95,9537	0,0000	95,9537	65,9537	30,0000	95,9537	0,0000	95,9537
21h	62,3990	30,0000	92,3990	0,0000	92,3990	62,3990	30,0000	92,3990	0,0000	92,3990
22h	52,1814	30,0000	82,1814	0,0000	82,1814	52,1814	30,0000	82,1814	0,0000	82,1814
23h	42,1581	30,0000	72,1581	0,0000	72,1581	42,1581	30,0000	72,1581	0,0000	72,1581
24h	52,7733	0,0000	52,7733	0,0000	52,7733	52,7733	0,0000	52,7733	0,0000	52,7733

Table 30 - Annex - Results of economic optimization forcing the investment of ICE and MT respectively for the month of January [kW]

JANUARY	Purchase from the network	FC	Demand	Cooling	Electricity Only	Purchase from the network	NGChiller	Demand	Cooling	Electricity Only
1h	26,9648	0,0000	26,9648	0,0000	26,9648	26,9648	0,0000	26,9648	0,0000	26,9648
2h	13,0980	0,0000	13,0980	0,0000	13,0980	13,0980	0,0000	13,0980	0,0000	13,0980
3h	11,1728	0,0000	11,1728	0,0000	11,1728	11,1728	0,0000	11,1728	0,0000	11,1728
4h	11,1728	0,0000	11,1728	0,0000	11,1728	11,1728	0,0000	11,1728	0,0000	11,1728
5h	12,6119	0,0000	12,6119	0,0000	12,6119	12,6119	0,0000	12,6119	0,0000	12,6119
6h	26,9629	0,0000	26,9629	0,0000	26,9629	26,9629	0,0000	26,9629	0,0000	26,9629
7h	34,8222	30,0000	64,8222	0,0000	64,8222	64,8222	0,0000	64,8222	0,0000	64,8222
8h	37,3739	30,0000	67,3739	0,0000	67,3739	67,3739	0,0000	67,3739	0,0000	67,3739
9h	0,0880	30,0000	30,0880	0,0000	30,0880	30,0880	0,0000	30,0880	0,0000	30,0880
10h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
11h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
12h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
13h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
14h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
15h	22,9043	0,0000	22,9043	0,0000	22,9043	22,9043	0,0000	22,9043	0,0000	22,9043
16h	24,4517	0,0000	24,4517	0,0000	24,4517	24,4517	0,0000	24,4517	0,0000	24,4517
17h	22,1222	0,0000	22,1222	0,0000	22,1222	22,1222	0,0000	22,1222	0,0000	22,1222
18h	24,1380	0,0000	24,1380	0,0000	24,1380	24,1380	0,0000	24,1380	0,0000	24,1380
19h	28,9357	30,0000	58,9357	0,0000	58,9357	58,9357	0,0000	58,9357	0,0000	58,9357
20h	65,9537	30,0000	95,9537	0,0000	95,9537	95,9537	0,0000	95,9537	0,0000	95,9537
21h	62,3990	30,0000	92,3990	0,0000	92,3990	92,3990	0,0000	92,3990	0,0000	92,3990
22h	52,1814	30,0000	82,1814	0,0000	82,1814	82,1814	0,0000	82,1814	0,0000	82,1814
23h	42,1581	30,0000	72,1581	0,0000	72,1581	72,1581	0,0000	72,1581	0,0000	72,1581
24h	22,7733	30,0000	52,7733	0,0000	52,7733	52,7733	0,0000	52,7733	0,0000	52,7733

Table 31 - Annex - Results of economic optimization forcing the investment of FC and Absorption Chiller respectively for the month of January [kW]

JULY	Purchase from the network	ICE	Demand	Cooling	Electricity Only	Purchase from the network	MT	Demand	Cooling	Electricity Only
1h	3,5490	30,0000	33,5490	20,4510	13,0980	3,5490	30,0000	33,5490	20,4510	13,0980
2h	1,6238	30,0000	31,6238	20,4510	11,1728	1,6238	30,0000	31,6238	20,4510	11,1728
3h	1,6238	30,0000	31,6238	20,4510	11,1728	31,6238	0,0000	31,6238	20,4510	11,1728
4h	3,0629	30,0000	33,0629	20,4510	12,6119	33,0629	0,0000	33,0629	20,4510	12,6119
5h	17,4139	30,0000	47,4139	20,4510	26,9629	17,4139	30,0000	47,4139	20,4510	26,9629
6h	55,2732	30,0000	85,2732	20,4510	64,8222	55,2732	30,0000	85,2732	20,4510	64,8222
7h	37,3739	30,0000	67,3739	0,0000	67,3739	37,3739	30,0000	67,3739	0,0000	67,3739
8h	0,0880	30,0000	30,0880	0,0000	30,0880	0,0880	30,0000	30,0880	0,0000	30,0880
9h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
10h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
11h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
12h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
13h	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132
14h	0,0000	22,9043	22,9043	0,0000	22,9043	0,0000	22,9043	22,9043	0,0000	22,9043
15h	0,0000	24,4517	24,4517	0,0000	24,4517	0,0000	24,4517	24,4517	0,0000	24,4517
16h	0,0000	22,1222	22,1222	0,0000	22,1222	0,0000	22,1222	22,1222	0,0000	22,1222
17h	0,0000	24,1380	24,1380	0,0000	24,1380	0,0000	24,1380	24,1380	0,0000	24,1380
18h	49,3867	30,0000	79,3867	20,4510	58,9357	49,3867	30,0000	79,3867	20,4510	58,9357
19h	86,4047	30,0000	116,4047	20,4510	95,9537	86,4047	30,0000	116,4047	20,4510	95,9537
20h	82,8500	30,0000	112,8500	20,4510	92,3990	82,8500	30,0000	112,8500	20,4510	92,3990
21h	72,6324	30,0000	102,6324	20,4510	82,1814	72,6324	30,0000	102,6324	20,4510	82,1814
22h	62,6091	30,0000	92,6091	20,4510	72,1581	62,6091	30,0000	92,6091	20,4510	72,1581
23h	43,2243	30,0000	73,2243	20,4510	52,7733	43,2243	30,0000	73,2243	20,4510	52,7733
24h	16,3144	30,0000	46,3144	20,4510	25,8634	16,3144	30,0000	46,3144	20,4510	25,8634

Table 32 - Annex - Results of economic optimization forcing the investment of ICE and MT respectively for the month of July [kW]

JULY	Purchase from the network	FC	Demand	Cooling	Electricity Only	Purchase from the network	NGChiller	Demand	Cooling	Electricity Only
1h	3,5490	30,0000	33,5490	20,4510	13,0980	13,0980	20,4510	33,5490	20,4510	13,0980
2h	1,6238	30,0000	31,6238	20,4510	11,1728	11,1728	20,4510	31,6238	20,4510	11,1728
3h	1,6238	30,0000	31,6238	20,4510	11,1728	11,1728	20,4510	31,6238	20,4510	11,1728
4h	3,0629	30,0000	33,0629	20,4510	12,6119	12,6119	20,4510	33,0629	20,4510	12,6119
5h	17,4139	30,0000	47,4139	20,4510	26,9629	26,9629	20,4510	47,4139	20,4510	26,9629
6h	55,2732	30,0000	85,2732	20,4510	64,8222	64,8222	20,4510	85,2732	20,4510	64,8222
7h	37,3739	30,0000	67,3739	0,0000	67,3739	67,3739	0,0000	67,3739	0,0000	67,3739
8h	0,0880	30,0000	30,0880	0,0000	30,0880	30,0880	0,0000	30,0880	0,0000	30,0880
9h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
10h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
11h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
12h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
13h	22,5132	0,0000	22,5132	0,0000	22,5132	22,5132	0,0000	22,5132	0,0000	22,5132
14h	22,9043	0,0000	22,9043	0,0000	22,9043	22,9043	0,0000	22,9043	0,0000	22,9043
15h	24,4517	0,0000	24,4517	0,0000	24,4517	24,4517	0,0000	24,4517	0,0000	24,4517
16h	22,1222	0,0000	22,1222	0,0000	22,1222	22,1222	0,0000	22,1222	0,0000	22,1222
17h	24,1380	0,0000	24,1380	0,0000	24,1380	24,1380	0,0000	24,1380	0,0000	24,1380
18h	49,3867	30,0000	79,3867	20,4510	58,9357	58,9357	20,4510	79,3867	20,4510	58,9357
19h	86,4047	30,0000	116,4047	20,4510	95,9537	95,9537	20,4510	116,4047	20,4510	95,9537
20h	82,8500	30,0000	112,8500	20,4510	92,3990	92,3990	20,4510	112,8500	20,4510	92,3990
21h	72,6324	30,0000	102,6324	20,4510	82,1814	82,1814	20,4510	102,6324	20,4510	82,1814
22h	62,6091	30,0000	92,6091	20,4510	72,1581	72,1581	20,4510	92,6091	20,4510	72,1581
23h	43,2243	30,0000	73,2243	20,4510	52,7733	52,7733	20,4510	73,2243	20,4510	52,7733
24h	16,3144	30,0000	46,3144	20,4510	25,8634	25,8634	20,4510	46,3144	20,4510	25,8634

Table 33 - Annex - Results of economic optimization forcing the investment of FC and Absorption Chiller respectively for the month of July [kW]