INTERNATIONAL HELLENIC UNIVERSITY

Optimal lay-out and operation of combined heat & power distributed generation systems in urban areas.

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Building Design

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THESSALONIKI – GREECE

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Abstract

This dissertation is written as a part of the MSc in Energy Building Design at the International Hellenic University. The aim of this thesis is to present the optimization process of different scenarios of the operation of mCCHP units (micro Combined Cooling Heating and Power units) which are located in urban areas. A wide range of system configurations is examined, from the traditional CCHP set up to the latest trends. In specific, a group of different buildings is used and simulations are executed in order to decide over the most efficient layout CCHP to address their electrical, heating (including domestic hot water) and cooling energy needs. This group of buildings consists of two residential detached buildings, one following the new regulation concerning the Greek energy building efficiency and one following the former one, a traditional multi-residential Greek building, known as Polykatoikia, a school unit and an office building. This group of buildings is located in four different Greek cities and thus, be tested in four different climatic conditions. The locations of Athens, Thessaloniki, Iraklion and Kastoria provide a deep insight on the heavy impact that climatic conditions can have on the efficiency and the optimal configuration of mCCHP systems. From an energy management point of view, a full scope of energy coupling, cooling, heating and power, is examined against only energy efficiency and not against other factors as operational or installation costs, as these parameters are changing significantly from country to country and constantly from time to time. Finally, a short term scale is considered and not the full extent of systems lifetime as it is assumed that from an energetic point of view, with a proper maintenance of the system, the deterioration of system efficiency, within the proposed lifetime, is minimal. At the same time, a lifetime evaluation of the system would include the aforementioned financial parameters, which, as it was said earlier, are beyond the scope of this thesis.

In this stage, the author would like to thank Mr. Martinopoulos for his patient guidance, encouragement and advice he has provided throughout each stage of this process.

Ioannis Moysiadis 11/05/2020

Contents

1 Introduction

It is a common truth that if the goals of the Paris Agreement [1] and the Doha Amendment [2] are to be met, we –as humanity- have to act immediately and proceed to radical changes in a wide spectrum of human activity. One of these sectors is the residential domain which comes second next to the transportation in the respective list of the most polluting sectors concerning CO_2 emissions and energy consumption globally and in Greece as well, as Figure 1 shows.

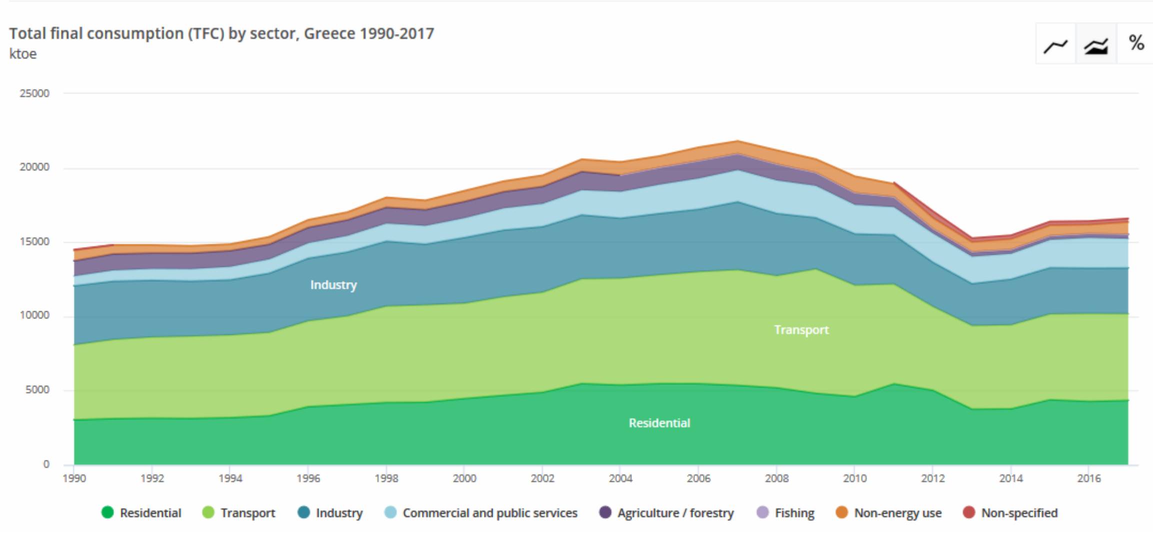

Figure1: Total final consumption by sector, Greece 1990-2017 (source: www.cogeneurope.eu)

Therefore, apart from the application of passive house design techniques and the improvment of the buildings envelope it is vital to increase the efficiency of the heating and cooling systems along with the on-site electrical power production of the building infrastructure. In other words, as stated in the literature [3], in order to reach the challenging targets and achieve NZeB (Net Zero Building) construction strict directions should be followed:

1) Introduction of minimum energy performance standards

2) Construction of new buildings with net zero energy consumption

3) Improvement of energy efficiency in existing buildings

4) Imposing building certificates

5) Improvement of energy performance of building envelope

Until now, the majority of the buildings all around the world are connected to the national or centralized grid to satisfy their needs for electrical power. At the same time, cooling and heating loads are satisfied by traditional Heating Ventilation and Air Conditioning (HVAC) systems using boilers for thermal energy production and cooling devices that consume in most of the cases electrical power. Moreover, these three building energy demands are mostly confronted independently and have no interconnection between them. In this thesis, systems that confront simultaneously, both the thermal and electrical energy demand will be reviewed.

Since the electrification of the urban areas, electrical power is provided to the buildings by the central power grid. At the same time, centralized power plants, which produce the electrical power, usually make no use of the produced waste heat while the transmission losses of electrical power between the production site and the final user are more than significant. Common fuels for the heating and cooling systems of buildings are fossil fuels, skyrocketing traditional system's gas emissions. These are the main reasons why governments all around the world, as it will be shown later in this thesis, provide financial incentives, with the view to introducing Combined Heat and Power (CHP) technologies and micro CCHP configurations to the building construction sector.

CHP was firstly introduced as the production unit of centralized power plants that combined electric power production and district heating. These power plants which nowadays are a very common way of electrical power production, consume fossil fuels as coal, oil and lately natural gas for their function. Along with the produced electric power, they take advantage of the waste heat producing hot water that is used to provide heating to the nearby cities. This production process increases the efficiency rate of the unit as some of the waste heat is used for heating and cooling purposes. These power plant units are the precursor of the micro CHP and micro CCHP units whose function and operational management is the subject of this thesis.

Micro CCHP units are a system configuration that secures the power and the thermal needs of a residential building or other types of individual buildings. In order to be classified as a micro CCHP, its capacity is usually below 50kW, according to European Commission [4]. These compact energy and power systems can be the center of the design of regional smart grids. In this type of grids, apart from the inherently higher efficiency rate, because of the minimum transmission losses and the ability of automated supervision and control of production and demands, consumers are in the center of the energy system as they are transformed from consumers to prosumers (consumers plus producers) with greater control of the consumption and the on-site production of energy. Brandoni [5] highlights the efficiency difference between the centralized CHP production, which is around 60%, and the local micro CHP efficiency, which can reach almost 90%.

Micro CCHP systems can use a diversified range of energy sources which are available locally and therefore match the local energy production with the consumption location. In other words, apart from matching their operation strategy with the local climatic conditions, they can match the fuel mixture and emission production with the needs of the local community concerning prices and costs, availability and the distribution path of the fuel. Last but not least, other financial and social or environmental issues can also be taken into consideration in the mCCHP design. Cities with a very specific environmental issue, e.g. increased level of Atmospheric Particulate Matter or smog, extreme price diversion of the different fuels or system installation because of state's financial policies or regional economic disparities within a city can be this kind of problems against which fuel flexibility can prove to be particularly beneficial.

Furthermore, mCHP units served by microgrids can become one of the main tools in order to confront renewable energy sources integration issues [6] with the view to decarbonizing heat and power production, saving primary energy and supporting the energy security. As the thesis will present, photovoltaic panels or high concentrating photovoltaic modules, wind turbines, solar thermal collectors and biofuels can be used as the mCCHP power generation units. At the same time, as a new trend in the economy worldwide, mCHP will be an innovative domain which can add value to the economy and create new job positions. Last but not least, an aspect that is beyond the scope of this paper, mCCHP systems, especially those powered by renewable energy sources, can be installed in rural, remoted areas without grid power infrastructure. In this way, the local demands can be satisfied in a cost efficient, clean, safe and reliable but above all financially affordable way.

Some of the CCHP systems benefits (the list is indicative and not exhaustive) are:

- Deliver multiple products (electrical power, heating and cooling, trigeneration or tetrageneration)
- Reduce primary energy consumption
- Reduce thermal losses (considerable use of waste heat)
- Reduce operational costs (construction and maintenance of the power grid)

- Improve energy supply reliability
- Improve energy sector security
- Reduce greenhouse gas emissions (especially with the integration of renewable energy systems)
- Provides peak saving and demand response services making the central power grid and electricity production more efficient.

Indicative of the importance of introducing CHP is that the U.S. Department of Energy (D.o.E.) in cooperation with the Environmental Protection Agency (E.P.A.) and the Combined Cooling Heating and Power Association (C.H.P.A.) put a CHP challenge into effect in 1998. In 1999, the D.o.E. then published the 'Combined Cooling Heating &Power for buildings 2020 Vision' which presented a timetable for CCHP development. A handful of annual conferences followed, resulting in the National CHP roadmap that included both central CHP energy production and smaller residential applications. Concerning micro CHP application, the highlight conference was held in 2003 resulting in the 'Micro-CHP Technologies Roadmap: Meeting 21st Century Residential Energy Needs,' document. The latest conference was held in 2011, resulting in the creation of the document 'Accelerating Combined Heat & Power deployment'[7]

EU is also raising awareness of environmental issues and the necessity of the diffusion of efficient energy and power production systems for buildings. For this reason EU has applied diverse strategic plans concerning all the spectrum of CHP applications, from large scale energy production to the building applications. The 'Small is beautiful' project has applied action-plans and incentives in order to direct building sector to the use of CHP and CCHP [8].

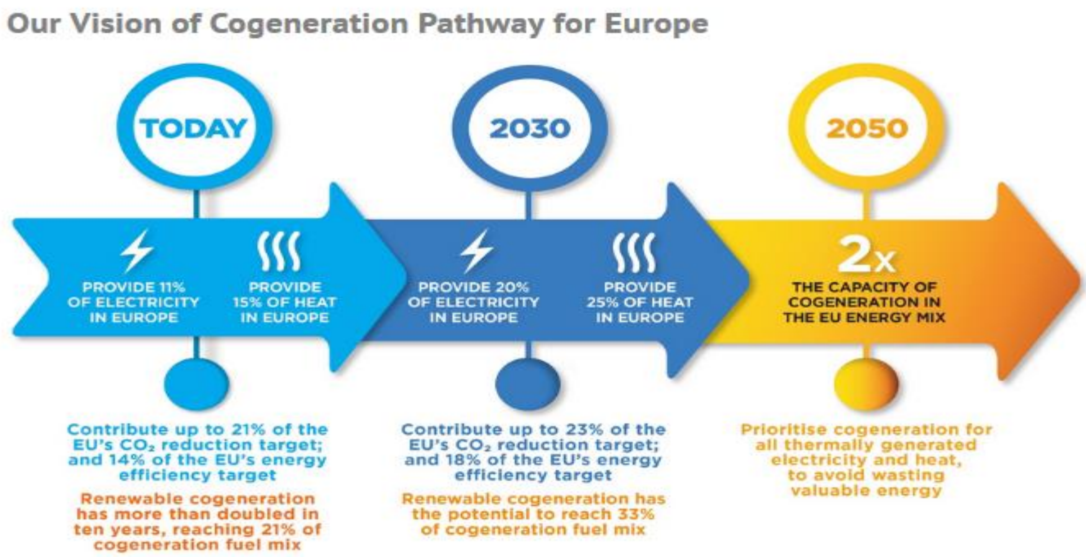

Figure 2: EU vision, (source: www.cogeneurope.eu)

EU declaration concerning mCHP technologies goes: 'Small installations empower European citizens, communities and SME's. Referring to small installations in Europe isn't just a consideration of scale. These small installations are very diverse and reflect the commitment of European countries towards smarter distributed business models, empowering energy consumers (households, hospitals, public buildings, hotels) to produce their own sustainable heat and electricity [8].

As all the aforementioned actions are indicative of the massive importance of the mCCHP technology, governments and organizations all around the world take actions towards the implementation of the micro CCHP in the building sector. New regulation and directives, such as the CHP Directive of the European Commission, assessed and monitored by the Cogeneration Observatory and Dissemination Europe [9] encourage the use of CCHP systems. Financial incentives are provided by governments and regulations restrict the use of fossil fuels for the power heating and cooling energy production throughout the European Union [10], as Table 2 shows. Last but not least, other support mechanisms such technical and technological support is provided by the EU comities in order to boost combined heat and power production in Europe. However, even with this global mobilization, there are numerous obstacles to be confronted.

Country	Tax support	Feed in tariff	Certificate scheme	Capital grant	Other Measures
Austria		X			X
Belgium	X		X		X
Bulgaria		X			X
Cyprus					X
Czech Rep.		X			X
Denmark		X			X
Estonia					X
Finland				X	X
France		X			X
Germany		X			X
Greece	X	X			X
Hungary		X			X
Iceland					X
Italy	X	X		X	
Latvia		X			X
Lithuania		X			X
Luxemburg	X				X
Malta	X				X
Netherlands	X	X		X	X
Poland			X		
Portugal				X	X
Romania		X		X	
Slovakia		X			
Slovenia		X			X
Spain	X	X			X
Sweden				X	X
UK	X	X		X	

Table 1: Financial Incentives and Measures around Europe

Installation costs and, in particular, the cost of the cogenerator unit is a discouraging factor for the wide spread of mCCHP systems. Undoubtedly, years of research and development of fossil fuel energy production, heating and cooling systems and the business competition between the manufacturers has led to the reduction of the installation and operational cost of the traditional cooling, heating and power production systems. There are, for instance, evaporative[11] or solar [12] cooling systems, ground pump systems that provide both heating and cooling [13] along with water heating systems [14] and numerous other HVAC installations . The traditional way for a building to acquire electrical power provider is from the centralized electrical power grid.

Moreover, fossil fuels are cheap -they were even cheaper in the past- and are available worldwide through a developed distribution network. Especially, in countries like Italy and Greece, where residential customers have limited usage of electricity concerning space heating, cooking and provision of hot water, CCHP technologies become even less financially effective [13] compared with the traditional systems. Last but not least, the variation of the temperatures inside and outside the buildings along with the irregular consumption profiles pose more problems to the sizing and the operational strategy of the

CCHP systems. On the contrary, fossil fuel boilers, electricity based HVAC systems and of course a connection to a central power distribution grid is an easier and safer way of securing the power and the thermal energy needed.

However, the environmental goals and the necessity to tackle environmental issues has brought us to the threshold of the CCHP development. Much research has been conducted over these issues and many solutions have been proposed throughout the literature. Clustering demands [16, 17], thermal energy and electrical power storage systems [18, 19], various commercial programming tools for control and supervision of smart grids based on optimization processes [20, 21] to name but a few. Clustering demands, in other words, providing energy to more than a dwelling can be a solution to the aforementioned problems and this technique will be implemented in this thesis for the calculation of the heating, cooling and electrical power demand of the simulations. The idea behind coupling residential buildings with commercial buildings and public services or hospitals and schools is to put together buildings with different occupational needs so as to create a steady, continuous and simultaneous electricity, cooling and heating demand to the maximum possible extend. The diverse selection of building types and occupational patterns allow that the operational pattern is not affected or dominated from a specific user. In this case we can avoid the partial loading of the CCHP system which leads to a significant decrease of the unit's efficiency and in cases of fossil fuels to the increase of the emissions of hazardous pollutants. At the same time, higher energy demands encourage the induction of the renewable energy sources which is pivotal in the chase of the various environmental goals, such as EU's Horizon 2020 Program (with its goals of 20% cut in greenhouse emissions, 20 % improvement in energy efficiency and 20% of renewable energy consumption) and its descendant Horizon Europe, with its five mission areas of general concern (Adaptation to climate change including societal transformation, Cancer, Climate neutral and smart cities, Healthy oceans, seas, coastal and inland waters, Soil health and food) [22].

Apart from the European Union policies, there are also national state policies that encourage the implementation of CHP units. The CHP deployment program of Ireland, the Promotion of CHP in Hungary, the Combined Heat and Power law and the 'Revision of the Combined Heat and Power Act (CHP Act)' of Germany, which are in forces and programs that are already concluded as the 'Combined Heat and Power Strategy to 2010' of the United Kingdom [23].

So, even though natural or fossil fuel gas turbines prevail in the mCCHP market for now, as it will be discussed later, the thesis is going to focus on the renewable energy sources integration. Therefore, the main interest will be on the mCCHP systems with PV for electrical power production and solar thermal sources for thermal energy. Solar thermal sources as input device for mCCHP systems in building sector are ideal as they are available all over the world, they are easy to be installed and integrated in both new and existing buildings and their annual efficiency is highly predictable. However, this contradicts the high intermittency of the renewable energy sources, both solar and wind based energy, which will be discussed later.

Of course, there are more sources which are considered as alternative energy sources as the biomass and wind, however, the simulations would be limited to what is widely known as green energy. There will be a brief presentation of biomass systems, the advantages and disadvantages along with the application constraints but the simulation of these types of mCCHP systems is beyond the scope of this dissertation.

The following section, the literature review, is a summary of the main features of mCCHP units, mentioning the weak and the strong points of every component referring to related scientific work. The thesis continues with the definition of the problem and the boundaries of the dissertation concluding with some remarks concerning the importance of the problem and some specific characteristics of his approach. The next section will be the problem definition, which is an exhaustive description of the problem and the methodology in use along with comments and remarks over the results. This section is followed by the contribution, in other words, the presentation of the results. The last part of this thesis will be the conclusion where a brief recap of the dissertation is made along with the reference of future issues to be examined or thoughts about the new trends and the potential problems that will arise in the domain in discussion.

2 Literature Review

2.1 Micro CHP and micro CCHP

Centralized combined heat and power units are at the forefront of power production during the last decades. Micro CHP and micro CCHP are also a domain of research and development during the past few years. Therefore, there is an extended scientific literature over centralized or micro CHP and CCHP configurations. The subjects discussed range from the components in use, the optimal layout to the ways of optimizing a CHP and a CCHP system and many other subjects of specific or wider concern as well. In this thesis, the author is going to refer to published scientific work that has a strong relation to the simulated cases.

Micro CCHP systems are used in order to provide electrical power and thermal energy to residential complexes. The idea behind the combined production of power and energy is to raise systems efficiency by using waste heat to produce thermal energy. Barbieri et al. in their paper show that a micro CCHP system can adequately cover the power and thermal energy demand of a building [24]. They simulate heating, cooling and power demands of two single-family dwellings with CCHP systems, based on a wide range of technologies, such as internal combustion engines, micro gas turbines, micro Rankine cycle and Sterling cycle engines and of course thermo-photovoltaic generators. The authors conclude that CCHP can cover 80% of the thermal energy demands of the buildings and 85% of the electric power demand. At the same time, there is a reduction of the consumption of primary energy from 20 to 28% depending on the prime mover technology. They also highlight the importance of the correct capacity sizing of the devices and storage units in order to achieve the maximum primary energy saving.

Throughout the years, different types of mCCHP systems have been designed and developed, with different configurations and components. A wide range of power generation units are used such as reciprocating engines, Stirling engines, microturbines, Organic Rankine cycle engines or fuel cells. Different types of thermal storages with different operational characteristics. Configurations which provide power, heating and cooling opposed to those that provide only power and heating, hybrid configurations against those that depend on only one power generation unit are a limited part of the choices that mCHP and mCCHP systems provide. Marugan et al. in their work describe the basic components of mCHP systems, focusing on their characteristics and their abilities. They also give a definition of hybrid systems, which are going, among others, to be presented in this thesis. According to the authors, a system designed to allow the operator to choose between multiple sources, is defined as a multi or hybrid mCCHP system [25].

Chua et al. has calculated that even a hybrid system with 80% of microturbine production, 10 % of PVT and 10% AFC (alkaline fuel cell), in other words with 80% conventional fuel and 20% environmental friendly resources, can achieve a 1.7 PFI (Performance Fraction Indicator) which means lower cost of thermal energy and power production, lower primary energy consumption and carbon dioxide emission [26].

Buoro et al. combine the energy demands of six different buildings- Town Hall, Theatre, Library, Primary School, Retirement Home, Municipal Archive- in order to design the optimal in terms of installation and operation cost solution [27]. The authors take into consideration all the financial aspects and the topology of the buildings, providing the exact number, capacity and location of the micro grid components. Figure 3 shows the resulting optimal layout of the four different cases that Buoro et al. examined.

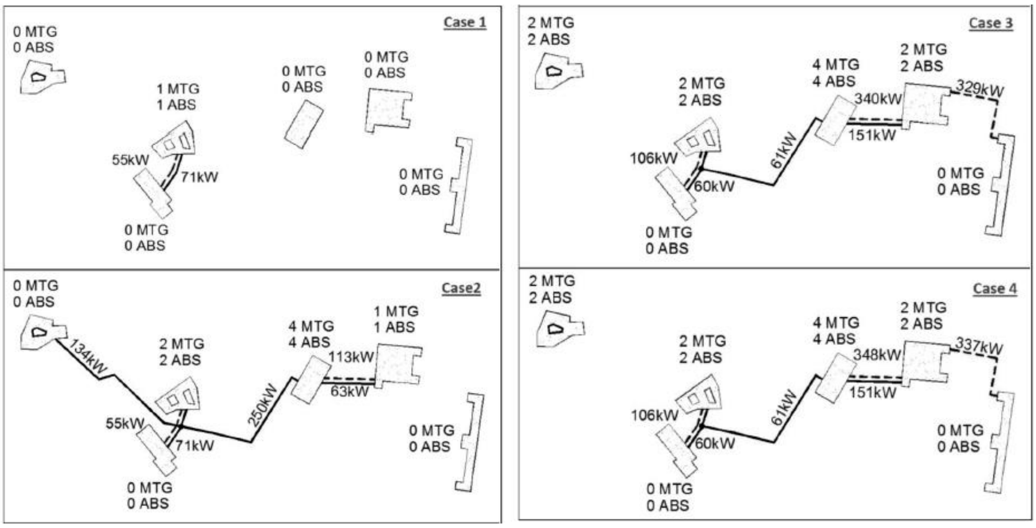

Figure 3: Optimal layout of mCCHP system

In [28] Mohammad and Besharati analyze four different design scenarios of a mCCHP system in a residential complex in Tehran. The group of buildings under review consists of seven building blocks. The first scenario is a conventional energy supply scenario, the second consists of CCHP systems that are not connected with each other. Contrary to the second scenario, the third deals with a mCCHP system, in which all the PGUs of the system are distributed within the residential complex while the last scenario includes PV panels as PGU. Gas turbines, electrical boilers, absorption and electrical chillers and PV panels are distributed to the residential sites in order to cover the energy demands of the buildings in the optimal, most effective, way both from a financial and energy efficiency perspective. Apart from covering the thermal energy demands of the group of buildings, the authors calculate for each case, the electricity produced by the mCCHP systems compared to the electrical energy procured by the central grid and the CO_2 emissions saving compared to the conventional system. Finally, they make a financial analysis of the installation and operational costs of each case, concluding in the optimal layout of each system.

Martinez et al. made a presentation of both conventional and renewable energy sources, which can power mCCHP systems. A wide spectrum of power generation units is presented with the advantages and disadvantages of each technology. Apart from diesel engines and gas turbines, the authors elaborate on the operational characteristics of micro-gas turbines, Stirling engines, Organic Rankine cycle engines, fuel cells, biomass and biofuel systems and of course the solar thermal and photovoltaic panel solutions [29]. In another study, Vokas et al. made a theoretical approach over the Hybrid photovoltaic-thermal systems [30] while Barbieri et al. among others, discussed over the optimal design of innovative mCHP systems as the thermophotovoltaic generators (TPV), which also are going to be discussed in this dissertation [31].

2.2 Components

Hybrid systems consists of a PGU (Power Generation Unit) , a device such as ICEs (Internal Combustion Engines), Stirling engine, microturbine or fuel cell technologies, along with thermal energy storage units and cooling devices. By utilizing a variety of producing, converting and disturbing technologies, users are more confident that they make use of the system to the full extent of their capabilities. This brings us closer to the highest possible efficiency of the mCCHP system in each and every possible location and under each and every possible weather conditions.

Maghanki et al. made a full review of the combined heat and power systems, presenting the current installed capacities around the world for both central and on-site power production and at the same time a wide range of potential devices that can compose a mCHP or CCHP system [33].The author shows how the global 2013 production of 330GW_e CHP capacity is distributed through countries, with Denmark, Finland and Russia being the leaders in CHP production. Moreover, Maghanki cites the share of the CHP production of the total national electrical power production of countries that produce, highlighting the successful implementation policy of CHP technologies and policies in different countries. According to his work, Germany and China have the potentiality to excel in the CHP production in the next decade (2030). In other work, Martinez et al. focus on the micro CHP systems which are based on renewable energy sources [34]. This type of energy based systems, as it was mentioned before, apart from other advantages, they are highly promoted by the latest European Union and international directives.

Especially for the solar technologies that can be used as the electrical power and heating/cooling energy production devices of a mCHP and CCHP system and the coupling of those systems with thermal storage devices, a lot of research has be done during the past years. PV (Photovoltaic) and HCPV (High Concentrated Photovoltaic) technologies are used to provide power and the hot medium respectively, in order to satisfy the heating and the cooling loads. For solar thermal and power generation, on the one hand, obviously production ceases during the nighttime and on the other, it is strongly dependent on solar radiation. Consequently, time and season dependence in the majority of PV and HCPV installations are critical factors that have a deep influence on the real-time energy production.

Much the same applies to the wind energy production which is even less predictable as the wind usually blows with no specific time pattern throughout the day. Power production depends on the wind force and it ranges from zero to the maximum device capacity. Therefore, this is the reason, along with the existence of peak loads, why energy storage will be a necessity in order to decrease the number of the central power production units, to integrate renewable energy sources to the prevailing energy mix and to support local systems as mCCHP systems or stand-alone power production installations. Additionally the use of thermal storage tanks prolongs the yearly operation time of a CHP facility and allows the power generation unit to operate more continuously [19]. Baudin et al. propose efficient ways of storing energy in renewable energy based systems, such as pumped hydro or compressed air energy storage systems, different types of batteries, flywheels and capacitors [35]. In this study are also presented the weak and the strong characteristics of each configuration.

However, the existence of a thermal storage unit transforms the optimization methods from a single point (quasi-steady) optimization process to a dynamic approach [19], making the optimization process more demanding in specification, programming and computational resources. New parameters are introduced to the simulation. Apart from the technicalities, the cost of the storage units has a deep influence on the installation costs of the system [36].

2.3 CCHP layout

Ercan and Kayakutlu proposed a model for scheduling a hybrid-trigeneration system [29]. Through a stochastic model for scheduling wind and solar sources, the authors face the issues of uncertainties in electricity prices, energy demand, and the intermittency of the output of the aforementioned renewable energy sources. The proposed configuration of the mCCHP system is shown in Figure 4.

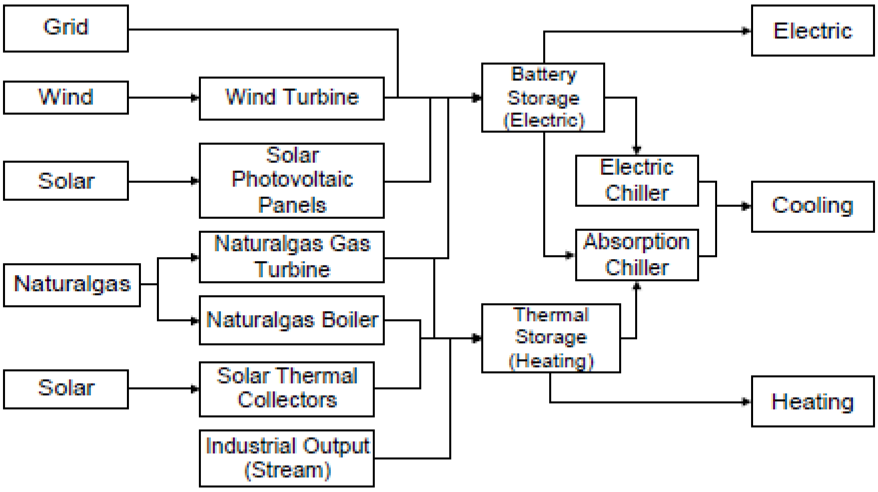

Figure 4: Hybrid trigeneration system

Apart from PV and HCPV, there is a wide range of devices that serve as power generation units and procure micro CHP systems with the needed thermal energy. Sterling engines, Internal Combustion Engines, Spark Ignition (SI) and Compression Ignition (CI) engines, microturbines (MGT), Organic Rankine Cycle engines (ORC) as well as fuel cells are widely used as power generation units of CHP systems. In order to opt for the appropriate PGU, one of the main and decisive characteristics, is the heat-to-power ratio. There are also other factors to take into consideration as the recoverable heat, the emissions and of course different indexes of efficiency such as the thermal, the electrical power and the total. As we will see in the following chart, making the best choice that serves the systems needs can improve CCHP efficiency securing the system's devices function at the most efficient operational point of their functional charts [38].

Description	SE	ICE (SI)	ICE (CI)	MGT	ORC	SOFC	PMFC
Recoverable heat		15-30% 80℃ Coolant, 15-20% 480 ℃ exhaust	15-20% 80℃ Coolant, 15-20% 480 ℃ exhaust	45-55% 315℃ Exhaust	45-65%	25-35% 260℃	25-35% 260℃
Start up	Easy	Easy	Easy	Little difficult	Easy	Easy	Easy
nth(%)	75	64	64	60	60	40	<30
nel (%)	10-20	20-40	25	15-30	~10	30-70	25-40
ntotal (%)	65-95	50-80	60-80	60-80	65-80	60-80	60-80
Power to heat ratio	0.2	0.38	0.38	0.33	N/A	1	1
Heat Input	External	External	External	External	External	Electrochemical	Electrochemical
Source of heat input	HC fuels, Waste heat, Hydrogen	HC fuels, H_2	HC fuels, H_2	HC fuels, Waste heat H_2	HC fuels, Waste heat H_2	Natural Gas	H2, enriched H2
Starting	Easier	Easier	Easier	More Difficult than ICE and SE	More Difficult than ICE and SE	Depending on demand	Depending on demand
Respond to load changes	Low	Faster	Faster	Faster	Faster	Faster	Faster
Initial investment	Low	Low	Low	900-1200 €/kW	High	High	High
Emission, NO ppm	Low	100	100	10	0	Low	Low
Units installed in the world	1000	10,000	10,000	N/A	N/A	10,000	N/A
State	Development, early market	Widespread	Widespread	Uncommon	Development, early market	Proven technology	Proven technology

Table 2: Power Generation Units

Power to thermal energy ratio is a key parameter in choosing the adequate operational strategy of a CCHP. Maximum efficiency is achieved when all the devices run at their best efficiency functional point and the demands are equal to the power and the thermal energy produced. However, in real applications, the latter is rather the exception than the rule. The randomness of load demands along with the intermittency of some energy sources, e.g. renewable energy sources, or other factors result in excessive power or thermal energy production. In case of excessive electrical power, exchanging electricity with the central electrical power grid is a traditional and efficient way to face this issue. However, when it comes to excessive thermal energy, the problem is more complicated.

According to Fang et al., there are two different ways of making full use of the excessive thermal energy of a CCHP system, an active and a passive one. Thermal storage devices are the passive and direct way to make use of the full extent of CCHP productivity. An active and indirect one is to convert this thermal energy into electrical power. An electric chiller paired with an ORC is the author's proposal. Fang et al. used a hypothetical hotel in Beijing and with their simulation they proved that the proposed configuration lead to increased efficiency of the CCHP system and improved operation against three indexes, primary energy consumption, CO_2 emissions and operational costs [38].

Apart from the aforementioned function and the ability of ORC technologies to fit in recovery applications, these types of engines are also a perfect match with HCPV and thermal collectors. Kosmadakis et al. tested different types of ORC engines and working fluids, in laboratory and in-site, highlighting the thermal efficiencies of each case [39]. Among others, the most interesting and useful conclusions are two. Firstly, based on the simulation results, the authors has shown that ORC engines with small capacity, even 3kW, have an acceptable thermal efficiency when operating at very low temperatures and secondly that ORC engines can operate efficiently even at unsteady conditions improving the performance of hybrid mCCHP systems throughout the year.

Another issue is raised by Lecompte et al. as they examined ORC behavior in a part load function when it is used for a CHP system needs is the working fluid and the temperature and operation boundaries of their function. Solar and waste heat applications, which are going to be used in this thesis also, were simulated and the primary optimization index is the specific investment cost (SIC). After simulating the system for different working fluids and a wide range of nominal and boundary temperatures, the authors opt for R152a as the working fluid, functioning at a nominal ambient temperature of 9°C. They also highlighted that there is a significant drop in the system efficiency, nearly 50%, when it operates between -9 and 35°C [40] .Bearing the above in mind, in the thesis ORC engines will be coupled with solar collectors in the respective simulations.

2.4 Thermal energy for cooling

A lot of research is in progress concerning the incorporation of cooling machines in the mCHP systems. Barbieri et al. used a lithium bromide and water absorption chiller as this type of chiller is compatible with the lower inlet water temperatures produced by solar heating systems [41]. This device is going to be used in this thesis as well, as this will be proved to be an effective match with the renewable energy sources as power generation unit configuration.

Jradi and Riffat conclude that mCCHP systems with Sterling or Organic Rankine engines as power production unit are not a viable solution if the cooling demand is too large compared to the heating one [42]. This is the reason why in this thesis, residential buildings are going to be coupled with public services and schools that have a different pattern of cooling needs. For instance, as we know, schools are closed during summer in Greece.

So, the cooling demands are not as high as the heating demands, securing the smooth function of the system throughout the whole year. The same clustering approach is also adopted by Li et al., who coupled residential and office buildings [43] and by Bracco et al. who combined the thermal energy and electrical power demand of all the buildings of University of Genoa into one smart polygeneration microgrid [44].

2.5 Optimization process

2.5.1 FTL/FEL/Base load

Evaluation of the mCCHP system is of outmost importance as the different proposed configurations should be evaluated and compared one against the others in order to achieve the optimal design that secures the lowest cost or the lowest energy consumption. There are numerous methods for CCHP systems evaluation proposed in literature such as evaluation through primary energy saving [45, 46], financial efficiency[47,48] or LCA assessments [49]. Moreover, there are indexes that incorporate costs and other financial aspects of a buildings system. The latter methods are controversial as the installation and operational costs differ from country to country as a result of different energy building policies or simply each state's inherent diversion in technology and fuel costs. Other optimization parameters, technology related, can be emission indexes and exergy [50].

In order to take into consideration all those parameters, a wide range of rates and indicators have been introduced. To name but a few, there are optimization parameters as:

- Primary energy savings ratio
- Primary energy savings
- Trigeneration primary energy savings
- Fuel energy saving ratio
- EUF (Energy Utilization Factor)
- Straight heat input or output exergy
- Exergy efficiency
- Exergy efficiency of trigeneration
- CER ratio (ratio of the amount of CO_2 emissions)
- Trigeneration CO_2 emission reduction
- Sustainability index
- Total cost rate e.t.c.

The optimization process of a mCCHP system is a two steps process. Firstly, one have to size the system, meaning to choose the suitable components/devices and their capacity. In order to reach this type of decisions the designer evaluates their case against some criteria, which include but are not limited to energy prices, climatic conditions, unit characteristics and of course electricity grid constraints. The second step is to make these units work harmonically and efficiently together. In order to identify the optimal operation mode of the mCCHP, numerous studies using different types of optimization algorithms have been published. Some of these methods are going to be presented in this dissertation. According to [51] the steps towards optimization of a CCHP system are:

1) Selection of the basic system (schematic diagrams) for the energy system

2) Optimization of equipment capacity composing each energy system

3) Optimization of the operational process of each energy system

4) Selection of the best design by comparing each local optimal solution

Before deciding on the components of a mCCHP unit and their nominal capacity, one has to choose the operational strategy of the unit. There are three major groups of strategy for the function of a CCHP.

- Following the electric load (FEL)
- Following the thermal load (FTL)
- Base load operation

In their paper Wang et al. executed a sensitivity analysis and comparison of the performance of a mCCHP system functioning in the two main operation modes, electrical demand management (or FEL) and thermal demand management (or FTL) [52]. In their work, the authors highlighted the importance of this decision over the final design and the components selection. Vice versa, the selection of the operation mode is heavily dependent on the building energy demands, the separated production system (auxiliary production system) and of course the mCCHP system itself. Concerning the comparison between EDM (Electrical Demand Management) and TDM (Thermal Demand Management) modes, the authors reach some useful conclusions. Again, among others, they propose an EDM operation strategy when the system is isolated, in other words, when the system is not connected to the centralized electrical power grid and when the excessive thermal energy is dissipated into the environment. The same operational choice is the optimal, according to the authors, when the heating/cooling load to power load ratio of the building is much higher than the heat to electricity ratio of the power generation unit of the system. Last but not least, they calculate that mCCHP system performs better during winter than summer.

2.5.2 Other optimization strategies

In the following section, conclusions and ideas over different types of optimization strategies are discussed.

Yokoyama and Matsumoto stated that simple operational strategies may not result in an economically feasible solution as the operation of cogeneration system is subjected not only to the variation of load demands but also to fuel prices [53].

Kavadias et al. proposed an electrical equivalent load following strategy where the electrical demand includes only the portion of the cooling demand that the absorption chiller cannot meet [54].

In another study the system follows a Hybrid Electric-Thermal load Strategy (HETS) [55]. Results indicated that a HETS is a good alternative for CCHP systems operation since it provides reduction of operational costs, emissions, and primary energy consumption.

Jing et al. in [56] optimized the system of a BCHP system, operating either as a FEL or a FTL system, based on LCA (life cycle assessment). Their optimization results indicated that FEL strategy provided more environmental benefits than FTL strategy.

Fang et al. divided the operation of the CCHP into different regions by one to three border surfaces estimated by the CCHP system energy requirements, using an IPC (Integrated Performance Criterion) [57].

A Building Primary Energy Ratio (BPER) parameter is used to evaluate the energy performance of CCHP systems. This parameter measures the variation of the primary energy consumption of the CCHP versus the conventional system, which allows controlling the CCHP system to operate only when primary energy is being saved [58].

A hybrid method is described by Smith and Mago which either follows the thermal or electric demands in a given time period, in order to minimize the amount of excess electrical or thermal energy produced by the CHP system. This proposed hybrid system showed higher efficiencies for the simulated building in a wide range of climatic conditions [59].

The optimization process for sizing and design of mCCHP systems is a very demanding process both in regards of programming skills and computational power. The main obstacles that one should overcome are three. First of all, is the combination of devices. In the course of time and as mCHP and mCCHP systems are getting more and more popular, numerous types and technologies are developed, each one with its specific characteristics, advantages and disadvantages. One should bear in mind that even a simple residential system needs a power generation unit (PGU), a heating and a cooling device at least, rendering optimization process complicated. Secondly, the operational efficiency of each one of the aforementioned devices is strictly depended on how the device is used. In other words, each component's efficiency is heavily dependent on the load that it functions, partial or full. Last but not least, predicting the demand of the building in electrical and thermal energy during the early stages of the buildings design, apart from a difficult task can also be misleading.

In their paper, Fabrizio et al. demonstrate the decision that a designer has to make in order to propose and optimize multi energy systems in the first stages of the building design, widely known as the concept stage [60]. According to the authors, designing the CCHP system during the concept stage can lead to the following four beneficial parameters:

- The minimization of the buildings loads
- The increasing of system efficiency
- The use of regenerative systems
- The use of renewable sources as system driving inputs

2.5.3 Optimization algorithms

For the optimization of a mCCHP system, a repetitive simulation process is usually the rule rather than the exception. Therefore, numerous methods have been developed for the optimization of the mCCHP systems, each one serving a specific purpose. Mixed integer linear programming (MILP) tools are used when we have a medium sized mCCHP unit to consider. In this kind of systems, one can assume that the relation between the input and the output of the systems components is linear, which is not the case in systems with higher capacity. So, linear programming tools are useful for the residential application and focus on the mCCHP units. Ren et al. use the aforementioned method to design the optimal lay-out for a residential application [61]. Mehleri et al. build a mathematical programming approach for the optimal design of distributed energy systems at the neighbourhood level [62]. C Brandoni and M. Renzi used the MILP method to optimize a hybrid solar micro CHP system for household application [63].

Apart from MILP optimization logic, there are also other considerations such as the maximum rectangular methodology or fuzzy logic which were proposed by researchers and are specialized in specific functions [64]. Chicco and Mancarella use Matrix modelling in order to optimize a small scale trigeneration system [65]. Using this calculation approach the authors are capable of simulating simultaneously multiple energy flows taking into consideration their characteristics, resulting in a uniform set of input and output variables. This process leads to a simplified table of results that shows the optimal configuration of the tested system. Moreover, genetic algorithms are used when we are focusing on more than one optimization parameters, meaning when a multi-objective optimization is followed. This means that with this method we can optimize parameters such as the capacity and the type of the systems in use, but also parameters as cost in relation to the operational control management and installation or emissions and different energy building design policies at the same time. Genetic algorithms became a necessity with the progress of inverters as from that point, input and output of systems devices cannot be considered as linear any more. Ooka and Komamura developed a design method for oprimization of a CCHP system using genetic algorithms. Their work incorporates the optimal function of the system’s devices, thorough consideration of the energy demand of the building along with seasonal analysis [51].

A pivotal point of concern about running the optimization process of a mCHP and a m CCHP system is the selection of the typical demand days. As acquiring and processing the whole annual weather data for a case is very costly and computationally time-consuming, scientists have worked on ways to minimize the weather data needed for the simulation without compromising significantly in the quality of the resulting optimization. Munoz et al. proposed a method to limit a full year of demand data to a few representative days reducing the needs of computational time and sources significantly. In order to avoid distorting the simulation results, the authors took into consideration parameters such as peak demands, demand duration curves, and the temporal inter-relationship between the different types of demands as power, heating and cooling. They used ten typical days and linked each and every day of the year with one of them, creating a calendar that summarized how many days of the year were attributed to each typical group.

The typical days in use have various heating, cooling or power demands, are categorized into weekdays or weekends simulating the different occupational needs and incorporate the peak cooling or heating days. Figure 5 shows the calendar of the typical days that Munoz et al. used in their optimization process [66].

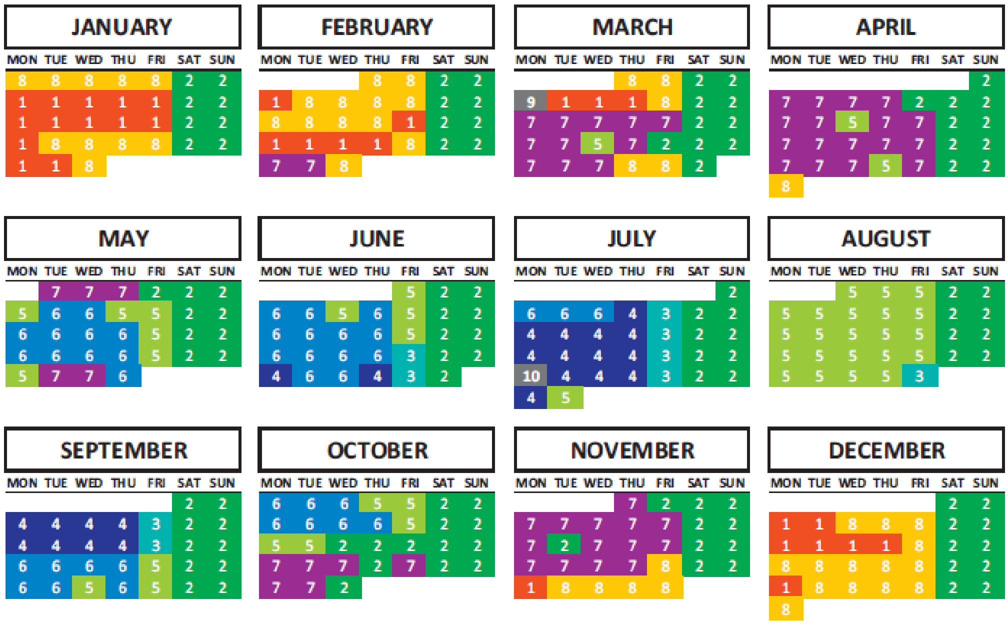

Figure 5: Calendar of Typical days

In other considerations concerning the problem of selecting representative days, Lozano et al. used 24 days, one weekday and one weekend day for each month [67]. Mavrotas et al. minimized demand data by using only twelve days, one per month, and at the same time categorize the days into seasonal groups and the hours into groups of the same power, heating and cooling demands, resulting in a very simple and flexible data group for the building's demands [68]. Casini et al. focused on power demand using extensive data of 24 typical days for the time dependent data of power consumption and the excessive power produced, that is sold to the grid, and at the same time only three typical days for the thermal demands, assuming a winter, a summer and a middle season typical day [69]. Piacetino and Cardona concluded that a number of days ranging from 24 to 30 for a CHP optimization problem, is adequate to provide reliable results [70].

2.5.4 Examples

In this section, four scientific papers will be thoroughly presented. These papers share a common objective with the author's thesis.

In specific, the first paper deals with a building that is located on different areas of China and Italy. In these different cities, different weather condition prevail, which leads to different optimal configurations of the mCCHP system in each case. In the same way, in this thesis the same group of building is located on different Greek cities resulting in different system's configurations.

The second paper compares two different types of an HVAC system, a traditional configuration which is totally depended on the central electrical power grid and contains fossil fuel boilers with a system that uses combined heat and power technologies. It highlights the advantages and disadvantages of each configuration, proposing the later as a more efficient solution concerning the primary energy consumption, costs and CO_2 emissions.

The third paper deals with PV (Photovoltaic) and HCPV (High Concentration Photovoltaic) powered mCCHP systems which are also presented in this dissertation while the last reference has to do with the smart grids, their relation with the mCHP and mCCHP systems and the benefits that smart grids bring to those systems.

i. System optimization

An example of selecting efficient components and deciding on the best configuration of micro CCHP system is the following. Barbieri et al. used a specific building G.E.L (Green Energy Laboratory) in order to evaluate different configurations of CCHP system [71]. They used a diverse selection of power generation, heating and cooling devices as they simulate different layouts and located it in 4 different cities (Venice, Rome, Shanghai and Guangzhou). System under test consisted of solar photovoltaic, solar heating cogenerators, absorption chillers, reversible ground source heat pumps and reversible air source heat pumps. Condensing boilers and electric chillers were used as auxiliary systems. Renewable energy systems, partially renewable energy systems and systems powered by natural gas or electricity are modeled. Based on the simulation results, the authors decided on which configuration stands out in regards of the primary energy consumption criteria. They opted for the primary consumption criteria as any cost criteria is heavily dependent on financial aspects (tariffs, incentive scenarios, other economic considerations) and potential local circumstances that happen in each specific country and in each specific time frame.

In order to assess the different models and propose the appropriate size and type of each technology, they used as inputs the following data:

- Characteristics of the building envelope
- Climatic conditions of the different cities (external air temperature, solar irradiation e.t.c.)
- Heating and cooling needs of the occupants

For the sensitivity analysis, they used genetic algorithms in MATLAB. All the devices were able to modulate between their nominal and minimum load ensuring that for every hour of the year, power, heating and cooling demand is satisfied by the CCHP system. Both nominal and minimum load data along with the efficiency rates of the devices were extracted from official manufacturer manuals of the machines or from scientific literature textbooks.

The optimal outcome of four different configuration types is formulated in the following simulations:

Simulation 1: A system that cannot exchange electrical power with the centralized grid (stand-alone system) but using all the range of the aforementioned devices. The best case scenario was observed in Venice. The authors measured a 21.2 % primary energy consumption reduction of the CCHP system in comparison to the traditional system.

Simulation 2: In Rome, using a system that interfaces with the centralized power grid (annual energy balance was negative or at least zero), a reduction of 68.2 % of the primary energy consumption was calculated. Moreover, the authors predicted an even greater efficiency of the system in case of a non-programmable renewable energy sources exploitation.

Simulation 3: In this case, the authors examined a stand-alone system but heat pumps were excluded from it. A GEL building in Shanghai consumed the less amount of primary energy with a 9% reduction from the traditional system (baseline).

Simulation 4: A pair of a CHP and an absorption chiller, using only solar PV and solar thermal sources that has access to the centralized power grid, in Venice, had 20.9% better performance than the baseline system concerning the primary power consumption.

Some useful remarks and lessons learnt from this paper could be the following:

- Thermal solar heating system works throughout the year but its production has a great variation from very low in winter until high production in summer time.
- In Beijing, the coldest city, the heat pumps have the greatest size and contribution
- In Venice, the same amount of electric energy with Rome is produced with less active PV panel's area because of the higher monthly mean radiation.
- In Guangzhou, the hottest city of the four, the reversible heat pump is used only for cooling purposes. For heating purposes, the CCHP system advantages other means of heating energy production.
- The reversible air source heat pump is working in general only to satisfy the peak demand, meaning that it is a peak saving device which works for limited time.
- As the solar thermal system is a non-programmable system and the capacity of the storage tank is finite, in order to minimize the dissipation of thermal energy, throughout the mid-season, the device satisfies the hot water demand.
- For all the cases, the reversible ground heat pump produces the maximum amount of energy because of its highest efficiency.

ii. CCHP and traditional cooling and heating systems

The differences between a traditional thermal and power system and a CHP or a CCHP configuration has initiate the research and development of the domain. These operational advantages of combined heat and power production unit against the former solutions are described in numerous scientific papers. Bracco et al. used a four type building group configuration in order to assess the economical, energetic and environmental advantages of using CHP in the place of the traditional systems [72]. As it has already been noted, traditional systems are assumed those which use boilers to satisfy thermal loads and buy electricity from the grid to meet the power demands. The authors examined a group of residential buildings (residential complex), a school, a swimming pool and the city hall of Arenzano a city of the Italian North. They used a mixed-integer linear programming model to create a multi-objective optimization function. In each building only a number of CHP and boilers can be installed, all fed by natural gas. Buildings can exchange thermal energy but there is no possibility of exchanging electricity between them.

In order to run the simulation, the authors gathered and used data such as the hourly electrical and thermal loads of buildings, their geographical location resulting in different local climatic data, technical performance data related to cogeneration gas turbines, internal combustion engines, boilers and pipelines, installation and maintenance costs, fuel and electricity prices and technical constraints related to the system devices. A partitional clustering algorithm that they used, help them to reduce the computational time by using a representative day for each season (winter, spring, summer, autumn) to replace the extent of the overall data. Therefore, four typical days were used and the operation followed the thermal load strategy.

Simulation and optimization of the problem resulted in the design of the most efficient heat distribution network compared to the traditional centralized system. The comparison between them, the optimized distributed generation system and the separate and centralized production scenario lead to a decrease of 41.5 % in primary energy consumption, of 32.5% in the CO_2 emissions and of 45% for the total costs (installation, maintenance and functional costs).

In order to satisfy the thermal loads of the building, which are considerably higher than the electrical loads, a lot of electrical energy is produced and enters the grid. Global efficiency of the system is equal to 84% as energy losses from the power plants and the heat distribution represent the 16% of the primary energy input.

iii. CCHP powered by PV and HCPV

Brandoni et al. developed a linear program in order to find the optimal size of a multi-system CCHP [73]. Electricity needs were satisfied by solar PV, a mCCHP unit or the electricity grid while the thermal needs by PV and HCPV systems, the mCCHP unit or a boiler. A thermal storage system was also included in the system. An absorption chiller or a vapor compression chiller transformed thermal energy from the aforementioned systems to cool air for summer needs.

Simulation results showed an energy saving of 16.7% over the traditional system. In all simulations the compression chiller was the most effective solution concerning the cooling loads. The resulting solar capacity was maximized, leading to an electrical power production of the peak load demands of the building. Interestingly, the mCCHP unit coupled with solar technologies had to be of a very small electrical power capacity compared to the solar energy power production installation. Therefore, the authors suggested that a better configuration of the system demands a higher electrical power load and consequently they proposed that maximum efficiency will be reached if more dwellings were combined and served by one system. Their analysis proposed that a ten dwelling group will maximize the systems efficiency. The same was the conclusion of Ooka et al. [74] and Cho et al. [75] who reported that for a residential building CCHP saves energy unless the required heating load falls below 150 kW. The highest overall efficiencies occur during winter, when heating demand is high. All the aforementioned papers proposed that a wider mCCHP system will serve the occupants better, given that the electrical grid constraints were lifted. Finally, they highlighted the importance of improving the electrical grid infrastructure, the development of different innovative management techniques and the manufacturing of more efficient thermal and electricity storage systems.

iv. Smart grid

Bracco et al. used the Smart Polygeneration Microgrid operating in the University of Genoa in order to [76]:

- Predict the production of renewable energy sources using forecasting tools
- Evaluate methods for the optimal operation of storage systems and of dispatchable sources and introduce a proactive day ahead production schedule.
- Introduce a flow control of electricity with the external grid.
- Create a central database of different types of energy measurements (forecasting, researchers)
- Test different ways of integrating renewable energy sources such as smart power converters.

The optimized scenario proposes, scheduling of both boilers and microturbines. As a result, a 28% reduction in operational costs, 22% reduction in CO_2 emissions and 20% reduction in the consumption of primary energy were noted. This scenario assumed a day-ahead estimation of both thermal and electrical demands. Photovoltaic generation was available and was also calculated in a daily basis. The simulation showed 85% of self-consumed electrical energy while 15% is sold to the grid. Moreover, the electrical power mix came 47% from the one CHP unit and 34% from the other while the rest 19% of the electrical energy was procured by the PV panels. Concerning thermal energy generation, 37% derived from the boiler, 30% and 32% from the CHP respectively.

3 Problem Definition

In this section, the significant parameters and characteristics on which the simulation of the mCCHP systems under review is based, are highlighted. With the below mentioned order, we get a deeper insight of the following issues:

- Selection of building typology and date of construction
- Heating, cooling, domestic hot water and electricity power demand data extraction
- Calculation of Space heating, cooling and domestic hot water demands
- System components
- Simulation scenarios

3.1 Selection of building typology and construction date

Bearing in mind that from the 4.1 million buildings in Greece, 2.9 million are strictly residential buildings [77], a representative selection of the Greek building stock is attempted. A parameter, that plays a significant role in the selection, apart from the use, is the construction date of the buildings and the regulations that were in force during construction time. In other words, as almost 71% of the Greek residential buildings are constructed in 1981 or earlier [78], in order to get a view of the Greek building stock, a selection of buildings with both later and earlier than 1981, construction date should be followed. The reason why, the year of 1981 is considered as a significant milestone in the Greek construction sector is the implementation of the first Hellenic building thermal insulation regulation (HBTIR) [79]. The improvement that this implementation brought to the energy performance of the newly constructed residential buildings is immense and is clearly depicted in the following calculations.

Another milestone in the building construction regulation in Greece, was the integration of the European Directive on the Energy Performance of Buildings (EPBD) by KENAK in 2010 [10]. According to this regulation, higher standards of energy performance have to be achieved by a building, so as an Energy Performance Certificate (EPC) to be issued. The Energy Conservation Measures (ECMs), which the directive proposes, lead not only to better living conditions but also to minimal energy consumption and costs. This will be translated, in order to fit our cause, to minimal electrical power, heating and cooling demands of the buildings. Consequently, this transition from the buildings of 1981 and earlier, to 2010 and later constructions, will be highlighted and taken into consideration in the building selection of this dissertation.

As a result, these different versions of the Greek building legislation, have a deep impact on the energy performance of the newly constructed buildings of each year. In other words, as regulations and directives are getting more and more challenging in their energy efficiency demand, new buildings are getting more and more energy efficient. On the contrary, buildings constructed earlier, are more energy demanding in order to satisfy their energy needs. Therefore, a selection of a single family house building constructed before 1981, a single family house building constructed after 1981 but before 2010, and a multifamily house building constructed after 2010, seems to cover to a satisfying extend the range of the current Greek building stock .

Even if, it seems logical that new combined heat and power technologies will be introduced at higher rates to new building constructions compared to the implementation of those technologies in former constructions, the author does not exclude this group. Especially, concerning buildings constructed before 1981, it seems unlikely that an investment into a cutting edge technology such as a combined heat and power system will be preferred over less expensive and, in the end, more efficient refurbishment measures. However, so as not to eliminate a significant part of the Greek building stock, the author includes a single family house building of that age in the simulation. The single family house building constructed between 1981 and 2010 represents the major part of the Greek building stock in the years to come. On the other hand, the multi-family house building of later construction date represents the construction trend, as combined heat and power technologies will be widely used in the next few years, imposed by current and new international regulations and directives but also encouraged by financial state incentives as well.

3.2 Data extraction

After the selection of buildings, the focus will be on the calculation of the heating, cooling and electrical power demands. This calculation process is based on Episcope [80], a European Union project, which aims to provide a rough estimation of the energy demands of a wide range of building topologies located on the different countries of the European Union. Episcope project is heavily related to the Tabula project [80], which is also a European Union originated project. These two projects provide researchers with a decent initial estimation of the heating and cooling loads of buildings, setting a solid foundation and a starting point for further calculations or simulations.

To begin with Tabula project, it consists of a selection of building topologies that represent the building stock of each country-member of the European Union. Compared against a wide range of construction criteria, the most common types of buildings within a country's building stock are categorized and create the Tabula project's groups of topologies. The aim of this project and its ultimate goal, is to attribute the greatest part of the building stock of a country to a rigidly specified building category. As it is mentioned earlier, the parameters-criteria against which each building is examined are diverse. The categories are designed to include the common types of a country's building stock. Buildings as single family houses or multifamily houses and so on, are distinguished between each other and grouped together based on their type, size and location, construction methods and the materials used. This segregation leads to a significantly different energy performance of each group.

For example, and as far as Greece is concerned, there are 24 main topologies included in the Greek publication of Tabula. The decisive factors that lead to these 24 different types are:

1) Construction date. Buildings are separated in three different time periods. Buildings constructed before 1981, those constructed between 1981 and 2000, and those constructed after 2000. These decisive dates are connected to the evolution of the building legislation code in Greece and in specific, the introduction of insulation in the construction code. Therefore, buildings constructed before 1981 are in general uninsulated and belong to the first category, those constructed from 1981 to 2000 follow the first HBTIR legislation and are partially or fully insulated.

The last category consists of the buildings constructed after 2000 and following the latest and more demanding edition of the HBTIR code are fully insulated.

2) Building size. Buildings are separated in two different categories , the Single Family House buildings, which consist of one or two floors and the Multi Family House buildings which are higher (three floors or more), with the distinctive example of the widespread building typology in Greek cities, known as 'Polykatoikia'.

3) Location. The third decisive factor is the location. Greece territory is separated into four different climatic zones. From south to north, zone A includes Crete, the majority of Aegean islands and the southern area of Peloponnese, zone B includes Athens and the middle section of the continental Greece, zone C includes Thessaloniki and the northern Greece while zone D includes some areas with the harshest winter in Greek territory, in other words areas such as Kastoria and Florina. This zone enjoys the mildest summer and the harsher winter in Greece. The difference between these zones becomes more plausible if one takes into account the HDD (heating Degree Days) of each zone. On this account, zone A, which contains Irakleio, ranges from 601 to 1100HDD, zone B, from 1101 to 1600 HDD, is the climatic zone of the capital of Greece, Athens, zone C, with 1601 to 2200 HDD includes Thessaloniki, and finally in the zone D, 2201 to 2620 HDD, belongs Kastoria. In the following figure there is a colored map representing the Greek climatic zones.

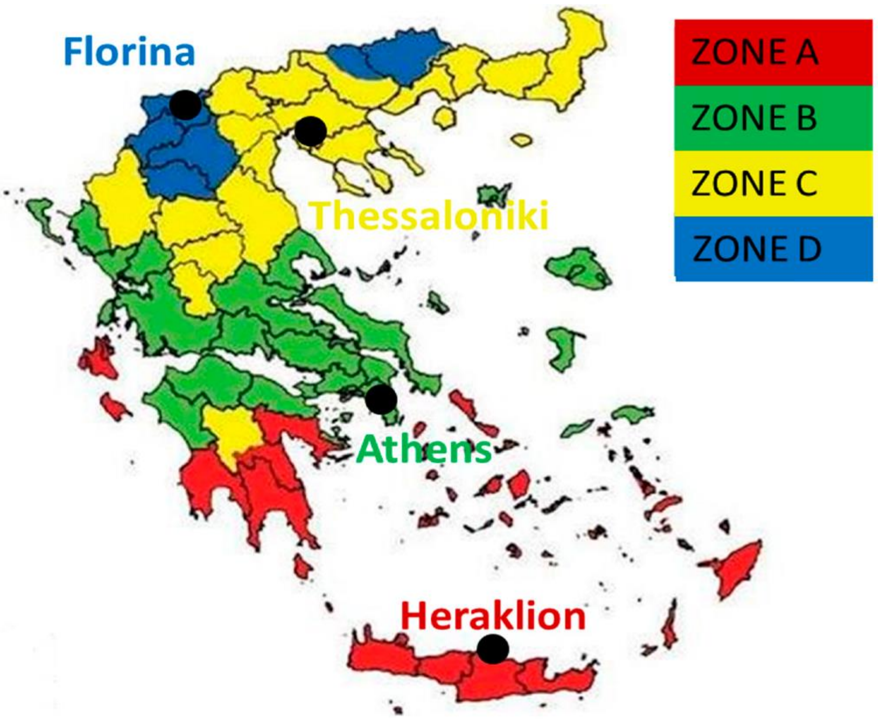

Figure 6: Greek Climatic zones

On the other hand, Episcope is a multinational (within the European Union borders) project, with the aim of calculating the energy efficiency of the different Tabula exemplary building topologies by using accredited simulation tools. The result of this process is the creation of a database that contains preliminary simulation results of the energy efficiency for a great part of the building stock within the European Union. However, apart from the aforementioned categories, there are more sub-categories that can increase the precision of the calculation process such as general features, i.e. the area or the number of the floors, data concerning the envelope area or the volume of the building itself, technical characteristics of the envelope construction or even performance parameters of the respective heating system. Concluding, Episcope and Tabula databases can provide one with a solid base in order to calculate and estimate the heating and cooling energy demands of a building at a national level in the European Union. In this dissertation, extensive use of these two databases is made in order to calculate the heating, cooling and hot domestic water demand of the buildings under review.

As far the electrical energy is concerned, the calculation process is based on published literature work and the database provided by ELSTAT, which is the official Greek statistical agency.

3.3 Calculation of power and energy demands

In order to design and size a mCCHP system, the first and a main concern, is the calculation the thermal (both cooling and heating), the domestic hot water (DHW) and the electrical energy demands. In this dissertation, a group of buildings, which consists of a school, a single family house building with construction date before 1981 (SFH1), a single family house building constructed after 1981 (SFH2) and a group of apartments, a multifamily house building, known in Greece as Polykatoikia (MFH) are investigated. These types of buildings have different energy demands as they are different in shape, operational and occupation characteristics and of course indoor air quality specifications. Data from published literature and from the Episcope and Tabula European Union projects will be used for the calculation of the thermal and electrical energy demands. However, this data will be customized in order to fit in the needs of this dissertation.

3.3.1 School Unit

In order to calculate the thermal energy and electrical power demands of an indicative school unit on the four aforementioned locations, published literature and the simulation works that have already been done are used. Daskalaki and Serpetzoglou calculated the energy demands of schools located on the four different climatic zones of Greece. The shape and the material of the building envelope, its age along with the occupational parameters are taken under consideration. Based on this work, the following tables show the thermal energy and the electrical power needs used in this dissertation. However, the following assumptions are made, some of which are imposed in all cases (locations) and demands (heating, cooling, DHW energy and electrical power) and others are imposed partially in specific cases.

- A 1300 m^2 building is considered as the school unit used in this dissertation.
- Electrical energy demands contain lighting, which has a seasonal fluctuation, as it will be shown later on, and the other electricity powered devices that are used equally throughout the year, such as personal computers, projectors, coffee machines etc.
- The total of the electrical energy demand of the prototyped school is assumed equal for all the locations, Iraklio, Athens, Thessaloniki and Kastoria.
- Schools in Greece are closed approximately from the 10^{th} of June until the 10^{th} of September. At the same time, there are two major holiday periods, one during

the winter, containing Christmas and New Year's Eve, and one during the spring with its specific date changing from year to year. It is assumed that the school operates throughout the year with the exception of the summer months, June, July and August.

- The operational hours for the Greek schools are assumed from 8:00 am until 2:00 pm. Schools are closed at weekends.
- For the calculation of the electrical energy demands a weighting factor was used to differentiate the demands of the winter months from the spring and autumn months. The idea behind imposing this factor, is from the one hand that there is a seasonal fluctuation on the time of sunrise and, on the other hand, there is a seasonal difference in the number of the sunny days of the month compared to the days with an outcast sky. A sunny day and the early spring and autumn sunrise mean limited use of the lights, decreasing the electrical power need of the building.

Taking all the above into consideration, the annual electrical energy demand of a school unit located on the four specified cities is the same and equals to 17,500 kWh.

Concerning the thermal energy demand for heating purposes, the calculations are also based on literature. Giannakopoulos and Psiloglu calculate the thermal energy needs taking into consideration the same parameters as in the electrical energy calculation. For the needs of this dissertation, the following assumptions are made:

- The same 1300 m^2 school building is considered.
- From April until September no heating is required in none of the four locations.
- The total thermal energy for heating demands for each location is based on the calculations in [82].
- In Athens and Iraklio, because of the milder weather conditions, heating demand is limited to the period between November and mid-April. On the contrary, the heavier winter of Thessaloniki and Kastoria, account for the function of the school's heating system from mid- October to the end of April. These timeframes are also referred by the official Greek national building code as the official simulation process proposed for the calculation of a building's heating demand. According, to TEE-KENAK, which is the calculation tool developed by the National Observatory of Athens for Technical Chamber of Greece (TEE), "The heating

period for A and B climatic zones in Greece is from November to mid-April and for C and D climatic zones from mid-October to April”

Taking all the above into consideration, Table 3 shows the monthly and annual thermal energy for heating purposes for the prototype school unit located in the four specific areas.

Heating Energy Load (School unit)									
kWh	Jan.	Feb.	Mar.	Apr.	May-Sept.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	8408	8058	7007	4204	0	2102	5605	7007	42391
Athens (B)	11246	10778	9372	5623	0	2812	7498	9372	56701
Thessaloniki (C)	21221	20337	17684	10610	0	5305	14147	17684	106988
Kastoria (D)	31018	29725	25848	15509	0	7754	20678	25848	156380

Table 3: Heating Energy Load (School unit)

Schools are assumed to be closed during the summer months. During the end of May and in the beginning of September, high temperatures are frequently observed in Greece but cooling devices are rarely used at that time of the year, especially when it comes to a school building. The rule is that school buildings in Greece do not even have a cooling system let alone use one. Therefore, the thermal energy cooling demand of the school unit for each and every location is considered 0 kWh.

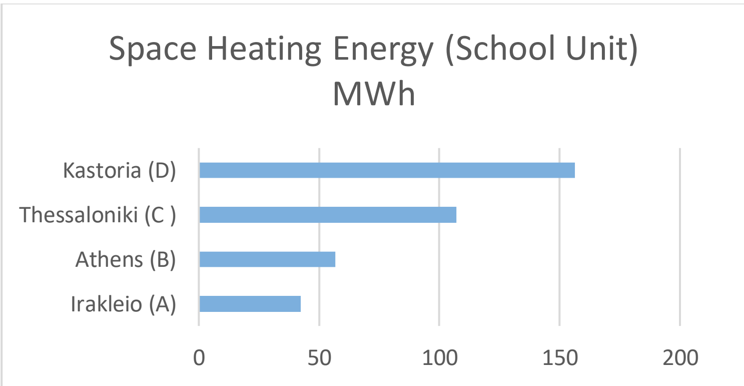

Figure 7: Space heating energy, School Unit

3.3.2 Single family house building 1 (SF1)

As it has already been mentioned, in 1981, the construction legislation in Greece undergoes a major change. In that time, thermal insulation is firstly introduced to the Greek building code. From that date on, a building in order to get certification has to be thermally insulated, based on the Hellenic Building Thermal Insulation Regulation (HBTIR). With this significant step, building stock in Greece, moves towards a better energy efficiency as the introduction of the new legislation lead to the higher thermal insulation of the newly constructed buildings. However, Greek building stock is changing in slow pace, especially during the last couple of decades, as the financial crisis in Greece stroke the building construction domain. Building construction rate has dropped and this is the reason why old buildings of 40-50 years remain a significant part of the Greek building stock. Consequently, this is the reason why a single family house building of that age is included in the test cases.

In specific, the area of this building is 85 m^2. It is constructed before 1981, matching the aforementioned description and has no thermal insulation, resulting in its poor thermal energy efficiency. It is located, for the needs of this dissertation, on the four aforementioned places, Irakleio, Athens, Thessaloniki and Kastoria, cities that represent the four Greek climatic zones, A,B,C and D respectively. The estimation of the thermal loads is based on the Tabula and Episcope database and for the electrical energy demand from the database of the Hellenic Statistical Agency (ELSTAT) [83]. There are some assumptions and modifications, which are mentioned in the following section and lead to the final estimation of the building thermal energy and electrical power loads.

At this point, it should be highlighted that the thermal loads of a building are highly dependable on parameters that are not taken into consideration in this dissertation. Operational patterns, occupancy, construction materials, orientation of the building, region's micro climate and wind patterns, the type of the HVAC system, even the proper or not maintenance of the buildings envelope or the incorporated thermal systems can lead to considerable differences in the energy efficiency of the building. However, taking no account of all these parameters will not affect the dissertation claims as its aim is not the accurate calculation of the thermal and electrical energy loads but the presentation of different types of combined heat and power systems that can serve the building's needs. In other words, ignoring the aforementioned parameters and introducing some assumptions that seem logical in the eyes of the author will not affect the precision of the final results or the further discussion over the configurations of mCCHP proposed and the difference in the primary energy consumption between a modern combined heat and power system configuration and more traditional approach.

In [82] Giannakopoulos and Psiloglou show the annual, seasonal and daily trends of electrical power consumption of households in Athens. An annual increase in the energy consumption of the households is observed throughout the years, due to economic, social and demographic factors, however, this observation is beyond the scope of this dissertation. In this dissertation, the focus will be on the seasonal and daily fluctuations of the heating, cooling and electrical power demands of the household. Among the most important factors of this fluctuation are (the list is extensive but not exhaustive):

- Weather fluctuations and especially the ambient air temperature
- Relative humidity, clearness index and wind speed
- Economic factors as energy prices, income and energy demand index
- Weekends compared to weekdays have significantly lower energy consumption values
- August consumption is lower as the majority of Athens population is on vacation. This decrease is observed mainly in the electrical power consumption.
- December is also a month with a high, relatively, energy consumption due to the increased energy requirements during the festive Christmas and New Year's Eve periods.
- During winter, maximum energy consumption reflects needs for home entertainment as most people stay indoor due to the low outdoor temperature. The exact opposite to the summer months, when the majority of people spent afternoon and evenings out and return late at home.
- ELSTAT clusters the electrical power consumption based on the population. In greater cities, consumption tends to be slightly higher.

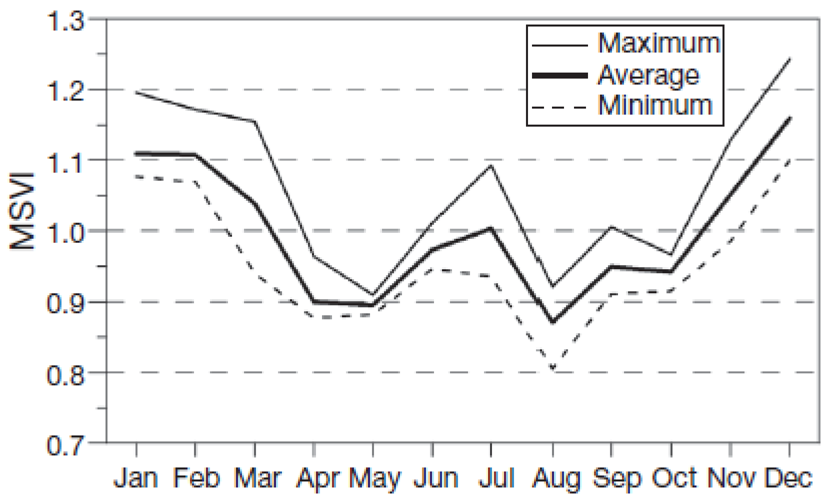

Figure 8: Mean monthly seasonal variation index (MSVI) of electricity consumption (1997-2001)

Based on the above assumptions, ELSTAT database and the Monthly Seasonal Variation Index (MSVI) are used to calculate the electricity demand of SFH1. The MSVI that is used for the calculations is specified on Table 4 resulting in the electrical energy demand of the building, showed on Table 5.

MSVI coefficient											
Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1.1	1.1	1.05	0.9	0.9	0.95	1	0.875	0.95	0.95	1.05	1.175

Table 4: MSVI coefficient

Electricity Consumption (SFH1)									
kWh	Jan.	Feb.	Mar.	Apr.	May	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	353	353	337	289	289	305	337	377	3852
Athens (B)	376	376	359	308	308	325	359	402	4104
Thessaloniki (C)	376	376	359	308	308	325	359	402	4104
Kastoria (D)	353	353	337	289	289	305	337	377	3852

Table 5: Electricity Consumption (SFH1)

The calculation of cooling, heating loads and the demand for DHW for the SFH1 are based on the estimations made in Episcope. Of course, the calculations in this dissertation are only indicative and present only an estimation of the cooling, heating and DHW demand of an average house in the respective climatic zones. According to KENAK, heating season for Greek climatic zones A and B is from November until the mid-April whereas for climatic zones C, D from October until the end of April. Cooling season is limited to summer months, from June to August. July is considered to be the month with the highest cooling loads as during July are expected the highest temperatures. On the other side, in

June and August lower temperatures and less days of excessive cooling demand are usually observed. This is the reason why cooling demand of July is assumed higher than the thermal demand of the other two summer months. May and September are the two months that heating and cooling are not required. At the same time, DHW is used throughout the year, with higher consumption during winter and lower during the summer time, because of the higher ambient temperature along with the higher temperature of the distributed tap water during summer. On Table 6, one can see the total thermal demands of space heating and cooling, along with the DHW demand of SFH1 in all four locations.

Single Family House (SFH1)													
Space Heating Load													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot.
Irakleio (A)	2704	2592	2254	1352	0	0	0	0	0	676	1803	2254	13635
Athens (B)	2858	2739	2381	1429	0	0	0	0	0	714	1905	2381	14407
Thessaloniki (C)	5470	5242	4558	2735	0	0	0	0	0	1367	3647	4558	27577
Kastoria (D)	7141	6844	5951	3571	0	0	0	0	0	1785	4761	5951	36003
Space Cooling Load													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot.
Irakleio (A)	0	0	0	0	0	1057	1526	1409	0	0	0	0	3992
Athens (B)	0	0	0	0	0	990	1430	1320	0	0	0	0	3740
Thessaloniki (C)	0	0	0	0	0	630	910	840	0	0	0	0	2380
Kastoria (D)	0	0	0	0	0	496	716	661	0	0	0	0	1872
Domestic Hot Water Demand													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot.
Irakleio (A)	441	441	441	441	441	147	147	147	441	441	441	441	4410
Athens (B)	501	501	501	501	501	167	167	167	501	501	501	501	5010
Thessaloniki (C)	546	546	546	546	546	232	232	232	546	546	546	546	5610
Kastoria (D)	696	696	696	696	696	232	232	232	696	696	696	696	6960

Table 6: Single Family House (SFH1)

3.3.3 Single family house building 2 (SF2)

The second single family house building is a 125m^2 area residential building constructed after 1981. The only difference with SFH1 is that SFH2 follows the basic directives of the HBTIR code. According to this regulation, and in order to attain a better thermal efficiency behavior, insulation is applied on the envelope of the building. This layer of insulation along with the modern construction materials and the new building techniques lead to a higher energy efficiency compared to the previous case.

Electricity consumption of SFH2 is considered to be the same as SFH1. As both these buildings are not heated or cooled by an electrical power driven device, electricity consumption is due to other occupational activities, such as lighting, electrical devices as TV set, PCs, oven e.t.c. The number of the occupants is considered to be the same in both cases, even if in the latter case, the building is larger than in previous one. At the same time, electrical energy consumption patterns are assumed to be the same, leading us to exactly the same electricity consumption for both cases. Once more, emphasis should be laid on the fact that, electricity consumption is assumed to be greater in cities than in the provincial areas as the official Greek statistical agency estimation dictates. On this occasion, it should be also highlighted that this estimation is an outcome of an official statistical research that the Greek statistic agency has conducted and not a theoretical calculation or a computational simulation. Therefore, Table 7 shows the electricity demand of SFH2 for the four aforementioned locations are depicted.

Electricity Consumption (SFH2)													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	353	353	337	289	289	305	321	281	305	305	337	377	3852
Athens (B)	376	376	359	308	308	325	342	299	325	325	359	402	4104
Thessaloniki (C)	376	376	359	308	308	325	342	299	325	325	359	402	4104
Kastoria (D)	353	353	337	289	289	305	321	281	305	305	337	377	3852

Table 7: Electricity Consumption (SFH2)

After a brief review of the resulting demands of the second building, it is easily understood how much different -better- is the thermal behavior of this building compared to the SFH1, thanks to the insulation layer applied to the building's envelope. In this case, one would expect that a larger building, with greater volume and more external wall area would demand more thermal energy to achieve the same conditions for the same number of people with the same occupational pattern. On the contrary, SFH2, which is assumed to be constructed after 1981, despite the fact that is larger shows better thermal efficiency and a lower, in absolute number, total thermal load than SFH1. Taking this result into consideration and bearing in mind that Episcope and Tabula calculations and specifications are based on a statistical research and they are not theoretical calculations or computational simulations, the difference between an insulated building and a non-insulated building becomes more than plausible. On Table 8 are shown the thermal demand for heating, cooling and DHW of SFH2.

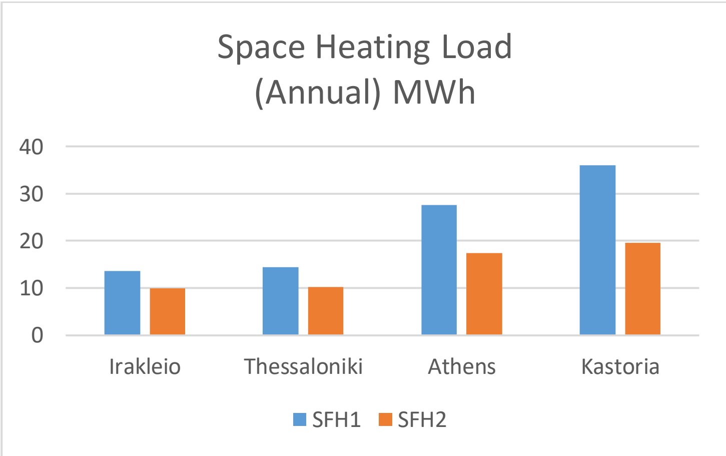

Figure 9: Annual Space Heating Demand

Single Family House 2 (SFH2)													
Space Heating Load													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	1976	1894	1647	988	0	0	0	0	0	494	1317	1647	9963
Athens (B)	2026	1942	1688	1013	0	0	0	0	0	507	1351	1688	10215
Thessaloniki (C)	3448	3305	2874	1724	0	0	0	0	0	862	2299	2874	17386
Kastoria (D)	3889	3727	3241	1945	0	0	0	0	0	972	2593	3241	19608
Space Cooling Load													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	0	0	0	0	0	1059	1529	1412	0	0	0	0	4000
Athens (B)	0	0	0	0	0	926	1338	1235	0	0	0	0	3500
Thessaloniki (C)	0	0	0	0	0	596	860	794	0	0	0	0	2250
Kastoria (D)	0	0	0	0	0	430	621	574	0	0	0	0	1625
Domestic Hot Water Demand													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	475	475	475	475	475	159	159	159	475	475	475	475	4752
Athens (B)	501	501	501	501	501	171	171	171	501	501	501	501	5022
Thessaloniki (C)	687	687	687	687	687	229	229	229	687	687	687	687	6870
Kastoria (D)	725	725	725	725	725	242	242	242	725	725	725	725	7251

Table 8: Single Family House 2 (SFH2)

3.3.4 Multifamily House building (MFH)

This building is a three-story residential building of 220 m^2 with ten apartments. It is directly chosen from the Tabula project catalogue, so the thermal load calculations are based on the Episcope project. The same assumptions and restrictions with the previous cases are imposed.

Concerning the electrical energy demand, taking into consideration that the MFH contains ten apartments, Table 9 summarizes the electricity demand of the building. The calculations are based on ELSTAT, the official Greek statistic agency and the author has applied the same seasonal modifications and the same urban and rural distinction as in previous cases.

Electricity Consumption (MFH)													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	3531	3531	3371	2889	2889	3050	3210	2809	3050	3050	3371	3772	38520
Athens (B)	3762	3762	3591	3078	3078	3249	3420	2993	3249	3249	3591	4019	41040
Thessaloniki (C)	3762	3762	3591	3078	3078	3249	3420	2993	3249	3249	3591	4019	41040
Kastoria (D)	3531	3531	3371	2889	2889	3050	3210	2809	3050	3050	3371	3772	38520

Table 9: Electricity Consumption (MFH)

Following the same assumptions and based on Tabula database and the Episcope calculations, Table 10 shows the thermal energy demand for space heating, space cooling and DHW of the multi-family house located on the four aforementioned locations.

Multi-Family house (MFH)													
Space Heating Load													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	11226	10758	9355	5613	0	0	0	0	0	2807	7484	9355	56599
Athens (B)	12811	12277	10676	6406	0	0	0	0	0	3203	8541	10676	64589
Thessaloniki (C)	14513	13908	12094	7257	0	0	0	0	0	3628	9675	12094	73170
Kastoria (D)	15335	14696	12779	7667	0	0	0	0	0	3834	10223	12779	77312
Space Cooling Load													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	0	0	0	0	0	7600	10978	10134	0	0	0	0	28712
Athens (B)	0	0	0	0	0	6755	9758	9007	0	0	0	0	25520
Thessaloniki (C)	0	0	0	0	0	6115	8832	8153	0	0	0	0	23100
Kastoria (D)	0	0	0	0	0	4964	7171	6619	0	0	0	0	18754
Domestic Hot Water Demand													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	4180	4180	4180	4180	4180	1394	1394	1394	4180	4180	4180	4180	41802
Athens (B)	4510	4510	4510	4510	4510	1504	1504	1504	4510	4510	4510	4510	45102
Thessaloniki (C)	6050	6050	6050	6050	6050	2017	2017	2017	6050	6050	6050	6050	60501
Kastoria (D)	6380	6380	6380	6380	6380	2126	2126	2126	6380	6380	6380	6380	63798

Table 10: Multi-Family house (MFH)

3.3.5 Total energy and power load

The following tables (11-15) contain the aggregated results for thermal energy load and electrical energy demand of the group of buildings for all the aforementioned locations.

Electricity demand Total (Group of Buildings)													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Irakleio (A)	6487	6487.2	5745	5167	5167	3659	3852	3371	5359	5359.4	6294.6	6776	63724
Athens (B)	6764	6764.4	6009	5394	5394	3899	4104	3591	5599	5598.8	6559.2	7072	66748
Thessaloniki (C)	6764	6764.4	6009	5394	5394	3899	4104	3591	5599	5598.8	6559.2	7072	66748
Kastoria (D)	6487	6487.2	5745	5167	5167	3659	3852	3371	5359	5359.4	6294.6	6776	63724
Tot.	26503	26503	23508	21121	21121	15116	15912	13923	21916	21916	25708	27697	260944

Table 11: Electricity demand Total (Group of Buildings)

Thermal Energy Load Irakleio (Climatic zone A)													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Space Heating	28091	23094	14826	8705	0	0	0	0	0	3977	18455	25440	122587
Space Cooling	0	0	0	0	0	9716	14034	12954	0	0	0	0	36704
DHW	5096	5096	5096	5096	5096	1700	1700	1700	5096	5096	5096	5096	50964
Tot.	33187	28190	19922	13801	5096	11416	15734	14654	5096	9073	23551	30536	210255

Table 12: Thermal Energy Load Irakleio (Climatic zone A)

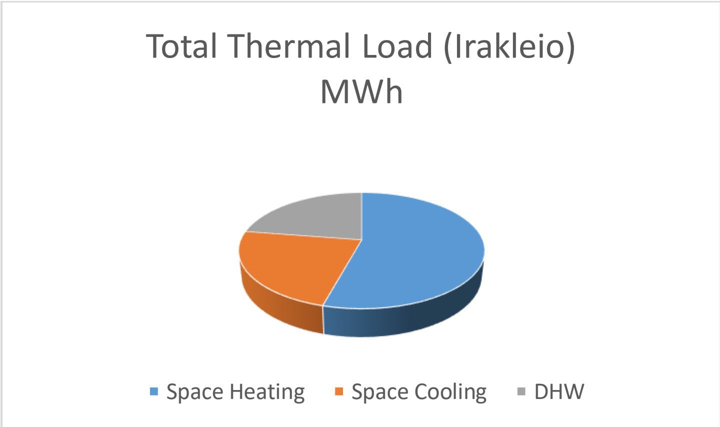

Figure 10: Total thermal load (Irakleio)

Thermal Energy Load Athens (Climatic zone B)													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Space Heating	28941	27735	24118	14471	0	0	0	0	0	7235	19294	24118	145911
Space Cooling	0	0	0	0	0	8672	12526	11562	0	0	0	0	32760
DHW	5512	5512	5512	5512	5512	1842	1842	1842	5512	5512	5512	5512	55134
Tot.	34453	33247	29630	19983	5512	10514	14368	13404	5512	12747	24806	29630	233805

Table 13: Thermal Energy Load Athens (Climatic zone B)

Thermal Energy Load Thessaloniki (Climatic zone C)													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Space Heating	44652	42792	37210	22326	0	0	0	0	0	11163	29768	37210	225121
Space Cooling	0	0	0	0	0	7340	10603	9787	0	0	0	0	27730
DHW	7283	7283	7283	7283	7283	2478	2478	2478	7283	7283	7283	7283	72981
Tot.	51935	50075	44493	29609	7283	9818	13081	12265	7283	18446	37051	44493	325832

Table 14: Thermal Energy Load Thessaloniki (Climatic zone C)

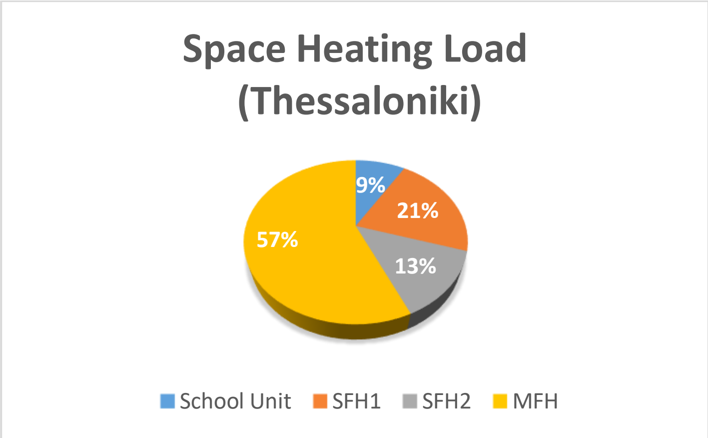

Figure 11: Space heating load (Thessaloniki)

Thermal Energy Load Kastoria (Climatic zone D)													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Space Heating	57382	54991	47819	28691	0	0	0	0	0	14346	38255	47819	289303
Space Cooling	0	0	0	0	0	5890	8508	7853	0	0	0	0	22251
DHW	7801	7801	7801	7801	7801	2600	2600	2600	7801	7801	7801	7801	78009
Tot.	65183	62792	55620	36492	7801	8490	11108	10453	7801	22147	46056	55620	389563

Table 15: Thermal Energy Load Kastoria (Climatic zone D)

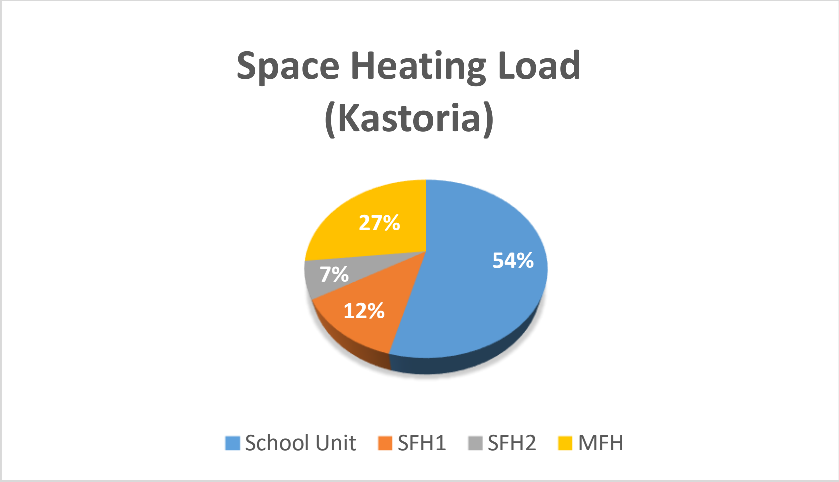

Figure 12: Space heating load (Kastoria)

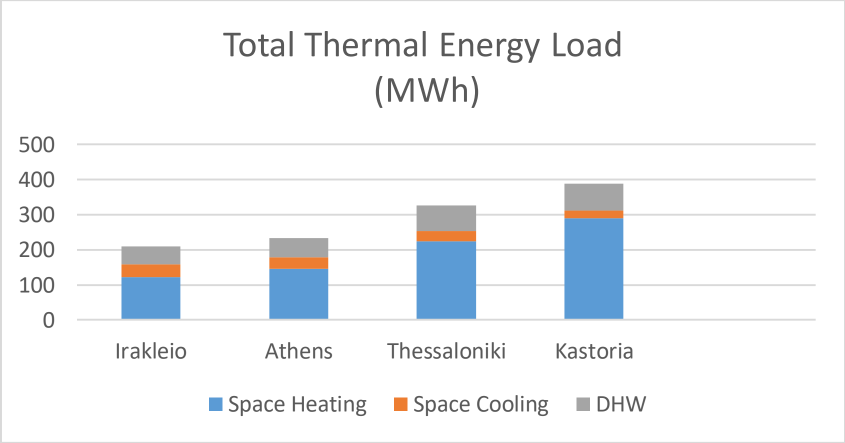

Figure 13: Total thermal energy load

3.4 System Components

In this section, there is a brief description of the devices that compose the different mCCHP systems that are examined in this dissertation.

A system designed to allow the operator to choose between multiple sources is referred to as a multi energy system or hybrid energy system [84]. This type of systems consists of a PGU (Power Generation Unit), in other words a mCHP (micro Combined Heat and Power) device such as ICEs (Internal Combustion Engines), Organic Rankine cycle engines (ORC), Stirling engines, micro turbines or fuel cells, along with thermal energy storage units and cooling devices. The use of different types of generation devices concerning both electricity and thermal energy is a way to increase the general efficiency of the system by bypassing the limitations and the inherent setbacks of each technology. In other words, by utilizing a variety of producing, converting and disturbing technologies, one is more confident that they use the devices to the full extent of their capabilities which can bring the highest possible efficiency to the system.

PGU (Power Generation Unit)

In this section there is a brief description of each power generation unit and commendation over the advantages and the weaknesses of each system, the range of application and their efficiency. Obviously, there are much more solutions, devices that can produce the hot medium needed for a mCCHP, but this discussion is beyond the scope of this dissertation.

<u>Internal Combustion Engines</u> are the most common type of mCCHP's generation unit. Their function is well known as they have the same configuration with those which are used in the automotive industry. As fuel, they use fossil fuels such as natural gas and oil but also biomass or biogas. Natural gas is the prevalent fuel. It is widely available and easily transported which makes it also more cost effective. At the same time, it is better than the other available fossil fuels, especially for building applications as it is the cleanest fossil fuel with no production of ash and odors. Therefore, natural gas has been proved to have the lower environmental impact among the fossil fuels. On the other hand, biomass and biofuels are considered as alternative fuels for the CCHP. Biofuels are alterna-

tive and sustainable fuels produced by feedstock derive from wood and agricultural products, solid waste and landfill gas or biogas. They provide a cleaner solution as their greenhouse gases emissions are lower. At the same time, they are a safer choice as they are independent from the unstable fossil fuel market. Natural gas and biogas PGU will be examined within this dissertation.

Rankine engine - Organic Rankine cycle engine have the advantage of utilizing heat from low temperature sources such as biomass combustion, waste heat and solar energy. This lower working temperatures and pressures, render Rankine engines very durable. Moreover, they have safe and simple function resulting in their cost effectiveness. These are some reasons why they constitute one of the best solutions for domestic and building applications. Rankine engines are divided in two categories depending on the working fluid, the steam Rankine engines, working with water as the medium, and the organic Rankine engines which use organic working fluid. For all the aforementioned reasons Rankine engines will be studied throughout this work.

Thermo-photovoltaic generators - hybrid photovoltaic cells are photovoltaic panels that absorb the solar radiation, specifically the infrared radiation. They convert the radiation absorbed not only to electrical power but also to thermal energy. In other words, the radiation that is not turned into electricity is not wasted but is converted to heat. Apart from the thermal energy production, this process cools off the photovoltaic cells, resulting in their better function, meaning their higher efficiency. All the aforementioned functions lead to the hybrid photovoltaic panel high electrical and thermal efficiency. Around 15-20 % is calculated the typical electrical efficiency of thermos photovoltaic panels and the total efficiency of the CHP unit rises to almost 90% [31, 32].

Solar thermal collectors are used as a renewable energy solution for the power production unit of a mCCHP. In this dissertation, flat plate and high concentration solar collectors are used to create the rooftop arrays presented in the following cases. For the calculation of their productivity, their function is assumed to last from 8 am to 4 pm (core daylight hours). This is the period of the day that in most locations, the solar incidence angle on the titled collector surface is <70º[85]. The rooftop solar installation is south-oriented and the inclination is based on the geographical latitude of each area. According to KENAK and for the best efficiency throughout the year, solar thermal collector's inclination should be within a range of ± 5º from the geographical latitude of the location that they are installed. Their total efficiency, apart from the ambient temperature and the beam irradiation which are not design characteristics, depends on the material used and the technology applied during their manufacturing. These two later parameters are introduced to the calculation of the solar collector efficiency by the coefficients of zero-loss optical efficiency and of the heat loss. The specific values of the aforementioned coefficients will be referred in the respective case.

During cooling demand periods, conversion cooling devices are used for the transition between the thermal energy produced by power generation unit and the final cooling air. In the following section we are going to have a deeper insight into the CCHP components.

Cooling devices

In this section, some indicative cooling devices that are used in the mCCHP systems are going to be reviewed. This list is far from exhaustive as there are numerous devices that can be used. Nowadays a lot of research and development is devoted to the search of an improved matching of cooling devices with mCCHP systems. Therefore, a wide range of existing and innovative ideas are tested in order to bring CCHP systems at the same efficiency level for cooling as they have for heating and electrical power production. However, before the author proceeds with the presentation of the cooling devices in use in this dissertation, a significant remark should be made. In [66] Munoz et al. concluded that mCCHP systems with Sterling or Organic Rankine engines as power production unit are not a viable solution if the cooling demand is too large compared to the heating one. This is the rational behind coupling residential buildings with public services (as school units) as public services usually have a different pattern of cooling needs. For instance, schools in Greece are closed during summer and their cooling demands are not as high as the heating demands, securing the smooth function of the system throughout the whole year. This is one of the criteria for the building selection of the cases. Following this remark, a brief presentation of the cooling devices in use is made.

<u>Absorption chiller</u> with silica-gel and water as working fluids uses hot water of 60-85℃ and produces chilled water of 7-15℃. The device COP is 0.3-0.7. Absorption silica-gel chiller is installed in small scale applications as residential and light-commercial buildings. Absorption chillers should be paired with a cooling tower as well. Cooling towers are used to reject the excessive heat to the environment. Thus, their efficiency and consequently, general efficiency of the system depends on the ambient temperature, which is also heavily dependable on the location of the CCHP system [86].

Liquid desiccant chiller needs 60-90°C hot water and provides dehumidified cold air 18-26°C with an efficiency (COP) of 0.2-1.2. Liquid desiccant cooling can be used to provide thermal control and humidity control in residential buildings [87].

Absorption chillers are preferred and will be used for the cases in this dissertation as their hot water inlet temperature requirement fits the thermal production of the PGU in use.

Auxiliary units

As auxiliary units, electrical boiler as far the thermal load is concerned and the connection to the central electrical power grid for the electricity demand are chosen for the needs of this dissertation.

In case that the system under review is connected to the central electrical power grid, the annual balance of the exchange between the CCHP system and the central power grid will be calculated. These auxiliary devices are the safety net that secures a continuous operation of the system in case of unit's failure or during maintenance periods.

Concerning thermal energy production, electrical boiler is used to confront the mCCHP system shortcoming. These devices match the design's general directives and objectives and are characterized by high efficiency, quiet function and simple operation which usually match the residential building system requirements.

Thermal energy storage

Energy storage devices are vital in order to smooth the fluctuated function of renewable energy sources. This is a vital perquisite, in order for renewable energy based power generation units to be used in mCCHP systems. Apart from the biomass and biogas which are considered to be alternative fuel sources, solar energy and wind energy are not constantly available. For solar thermal and power generation, on the one hand, it is obvious that thermal energy production ceases during the nighttime. On the other hand, their production is strongly dependent on solar radiation which is not constant. Consequently, time and seasonal dependence in the majority of solar and hybrid photovoltaic installations are critical factors that have a deep influence on the real-time energy production. Much the same applies to the wind energy production, which is even less predictable as the wind usually blows with no specific time pattern throughout the day. Power production of this type of generation units depends on the wind force and it ranges from zero to the maximum device capacity (this type of systems will not be reviewed within this dissertation). Therefore, this is the reason, along with the confrontation of peak loads, why energy storage is a necessity for the following:

- Decrease of the number of central power production units
- Integration of renewable energy sources
- Support local systems as micro CCHP systems or stand-alone power production installations.

Types of energy storage (chemical and physical storage) for thermal energy and electrical power use:

1. Batteries and electrochemical capacitors
2. Pumped hydroelectric storage, flywheel storage, comprised energy storage (CAES) and superconducting magnetic storage (SMES)
3. Thermal storage tank for cooling and heating applications
4. Hot water tank to supply hot water for sanitary use
5. Electrical grid
6. Plug-in electrical vehicles as charging and discharging storage of the system

Concluding, micro CHP and micro CCHP systems with storage devices have the advantage of better energy management and of using of devices with greater efficiency. On the other hand thermal and power storage increase the installation costs. Moreover, they are not always easy to be incorporated to the system, especially when designers deal with renovation of existing buildings. Last but not least, there are some scientific and technical issues to be confronted before storage systems become an efficient integral part of mCCHP systems, issues that in general pertain the limitations in charging and discharging cycles, costs and materials and the effective management of this type of system.

3.5 Scenarios

Throughout this dissertation, different configurations of mCCHP systems, indicative of the prevalent installations and future applications will be discussed. Different mCCHP models that are usually installed today will be compared with modern trends, highlighting the advantages and disadvantages of each configuration and concluding in the application that each type of mCCHP system is suitable for. In order to do so, the following cases are going to be reviewed. The aforementioned group of building will be located on four different cities (Irakleio, Athens, Thessaloniki, Kastoria), meaning in four different climatic conditions. Of course, occupational needs and operational patterns will remain the same throughout the dissertation for each building, giving the opportunity to compare them and draw some interesting conclusions.

The four different scenarios that will be created and used for each case study are the following:

a) The first scenario represents a usual configuration, a natural gas powered mCCHP. This means that a natural gas PGU will produce the thermal energy and the electricity needed. The basic concern of the system is to meet the thermal demands; therefore, the system follows a TDM (Thermal Demand Management) operational strategy. The central electrical power grid will receive the excessive power that the system produces and at the same time cover the electricity needs in case that the mCCHP cannot satisfy it. DHW demand is included in the total thermal energy demand. An electric boiler will be used as an auxiliary unit concerning the thermal energy demand.

b) For the second scenario, alternative fuel sources will be used. Biogas driven turbines will replace the natural gas PGU. However, having always in mind that our assessment is limited to an energetic evaluation, excluding costs or emission assessments, there will be not much of a difference between this model and the previous one. The only difference derives from the substitution of the fuel in use, from natural gas to biomass along with the efficiency and heating conversion rates of the devices. The operational strategy remains the same, TDM, as the mCCHP system will be used to satisfy the thermal needs and produce electrical energy. At the same time electricity will be exchanged between the mCCHP system and the central electrical power grid in cases of the systems over and under achievement. Again, DHW production is included in the thermal load calculation and a boiler is used as an auxiliary unit. The differences between the first two models concerning the costs of installation, fuel and operation costs along with the environmental footprint of the models are beyond the scope of this dissertation.

c) As a PGU for the third scenario, a renewable source, solar radiation is used. In specific, flat plate and high concentrated solar collectors in a rooftop array format, are used to produce the thermal energy needed for the group of buildings. The mCCHP system is connected to the central electrical power grid as the total thermal energy production, as it will be shortly shown, is not enough to cover thermal energy needs along with the electrical power demand. An Organic Rankine engine is used during the months of positive thermal energy balance, especially during the summer months, in order to produce electrical power from the excessive thermal energy production. Of course, the missing electrical energy is procured by the centralized electrical power grid. The system follows the TDM operation strategy, which means that the first priority for the system is the coverage of the thermal energy demand and secondly the electrical power demand. In order for the mCCHP system to take advantage of the excessive thermal energy production and not simply dissipate it into the environment, there is a hot water tank (thermal energy storage). This tank keeps a thermal energy reserve, capable of covering the thermal energy needs during the hours that there is no solar irradiation, which means no energy production by the mCCHP system. This reserve, of course, cannot be transferred from one month to another and this is the reason why, even if the system produces annually more thermal energy than the annual thermal energy demand, there are still months that the auxiliary unit, such as an electrical boiler, needs to produce the thermal energy missing.

d) The fourth scenario deals again with renewable energy sources and, in specific, solar energy. In this model, mCCHP uses as a PGU hybrid photovoltaic panels. This solar energy technology combines the electrical power production of photovoltaic panels with the thermal energy production of solar thermal collectors. The system is connected to the centralized electrical power grid and therefore, the excessive along with the missing electricity, compared to the needs of the system, is provided to and by (respectively) the centralized electrical power grid. TDM

(Thermal Demand Management) operation strategy is applied. The DHW energy needs are included in the calculations of thermal energy. A boiler plays the role of the auxiliary unit and uses the surplus of the electrical power production to cover a part of the thermal energy demand. In this scenario, HCPV and solar thermal panels are installed on the roof of the buildings and therefore, their productive area is limited by the building dimensions.

4 Contribution

4.1 Case 1

Location: Irakleio

Climatic zone: A

Scenario: 2

Power Generation Unit: Biogas CCHP

Cooling Device: Absorption chiller

Max hourly electricity demand: 18.53 kWh

Max hourly thermal energy demand: 96.73 kWh (typical day of January)

Connection to the centralized electrical power grid: YES

In this first case, a mCCHP system is located on Irakleio. Irakleio belongs to the first Greek climatic zone, in which mild winters and hot and humid summers are common. The installed mCCHP system is going to cover the thermal energy and the electrical power demands of the group of buildings. Biogas engines will be installed as PGU of the mCCHP system and this selection is based on two reasons. Firstly, in the rural area of Crete, livestock farming and agriculture are a common occupation for the residents, which can be, among others, translated into a large quantity of biogas. This side product of these activities can be used to power the biogas engines of the mCCHP system. The second reason, and an excluding factor at the same time, is that in the broader area of Irakleio and, in general Crete, has no natural gas infrastructure. Therefore, the solution of natural gas engines should be eliminated.

Absorption chiller will be installed in the buildings to satisfy the cooling loads. This solution will be used throughout all the cases as absorption chiller is an efficient and compatible solution for residential use. It can be coupled with all the types of PGUs that will be used throughout this dissertation. As an auxiliary unit, concerning the thermal energy demand, an electric boiler will be used in case of the PGU’s break-down, the potential maintenance time or the unlikely event of extreme and unpredictable peak thermal demands. Excessive electrical power production or demand will be dealt instantly by feeding to or drawing electricity from the central electrical power grid.

In Figure 14, there is a representation of the buildings topology and the installation of the mCCHP system. It is only an indicative image, as in this dissertation the focus is only on the primary energy consumption and not on the financial aspect of the configuration, which includes installation costs, materials and pipelines along with the cost of moving thermal energy and electricity from the point of production to the point of consumption. Therefore, in case of taking into consideration the cost of the pipelines, the installation and operational costs of the components, the optimal solution could have been significantly different. In this case, the relative position of the buildings and the components would matter, resulting in different set up and in some cases in a totally different configuration. Concluding, in Figure 14, one can only see an indicative proposal for the installation of the components of the mCCHP system.

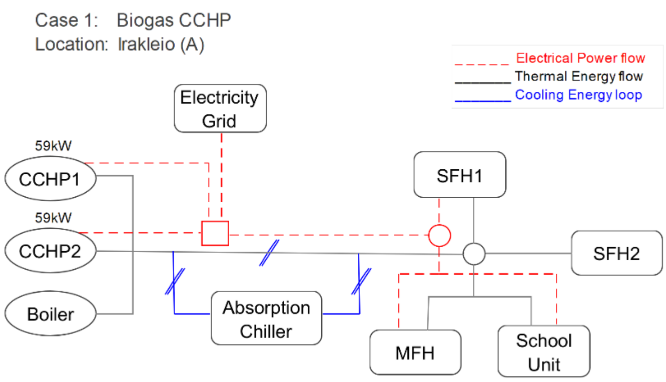

Figure 14: Micro CCHP system, Irakleio

The total electricity needs for the group of the buildings as it has previously calculated is 63,724 kWh. This number is the annual consumption of electricity which is calculated under the aforementioned assumptions. In order to assure that the proposed power generation unit produces enough electrical power to cover 100% the demand, the author uses an hourly estimation of the electricity needs. The worst case scenario occurs in December (typical day of December) between 1pm and 2pm. At this period of time, the group of the buildings have a total electrical consumption of 18.53 kWh. This is the worst case scenario that the mCCHP system needs to overpass. At the same time, the mCCHP system needs to cover the annual electrical power demand of the buildings, which is 63,724 kWh.

However, in order to size the PGU of the system, the author uses the typical day of January, as during the first month of the year the thermal energy demand reaches its peak. As it has already been noted, the mCCHP system follows a TDM operational strategy and this is the reason why the PGU is sized over the thermal energy demand of the group of buildings. Nonetheless, as it will be shown later on, the electrical power production of the system is higher than the electrical power peak and the total electricity production over-passes the total annual consumption.

In this case two engines of nominal capacity of 59 kWh thermal energy and 30 kWh electricity are chosen. These engines are real commercial products and their technical characteristics taken from their official specification data.

Electrical efficiency rate of CHP engines depends heavily on the load of the engine. In other words, the heavier the thermal energy load of the engine is, the higher the electrical efficiency becomes. This is the reason why two engines are preferred to cover the total demand, compared to a solution of a single PGU biogas engine. The later solution would include a 'heavier' engine, with higher nominal capacity rate, that would function in extremely low loads during the majority of the time and this would be translated in lower efficiency rates. There are, of course, peak hours that the single engine would have high load, but in this occasion peak hours are a very slim percentage of the total function of the unit. Therefore, the prevailing solution dictates two engines with cascade function that are scheduled to run in series. The first one covers the load to the full extent of its capacity and should there is a need for more thermal energy, the second engine would cover the remaining demand. This operational strategy would result in higher electrical production efficiency which leads to minimal dependence on the central electrical power grid. However, it should be noted, that there may be several financial aspects, that are connected with installation and operational costs that could lead to a solution of single or at the other extreme, a solution of triple power production units' configuration, but this would exceed the purpose of this thesis.

In <u>Table 16</u> there are the diverse efficiency rates of the engines for the respective load percentages.

Electricity Production of biogas CHP at different loads				
kWh	25%	50%	75%	100%
Engine 1	25.8	28.6	29.5	30
Engine 2	64.6	71.6	73.7	75
Engine 3	91.3	101.2	104.2	106

Table 16: Electricity production of biogas CHP at different loads

CHP biogas Engines – Power Generation Unit							
Biogas	Electrical output in kWh	Heat output in kWh	Electrical/Heat ratio	Electrical efficiency	Heat efficiency	Total efficiency	Energy Input in kWh
Engine 1	30	59	0.51	30.9	60.7	91.6	97.1
Engine 2	75	104	0.72	36.8	49.8	86.8	209
Engine 3	106	143	0.74	36.4	49.2	85.8	291

Table 17: CHP biogas Engines – Power Generation Unit

Concluding, the author uses two CHP engines as the power generation units of the CCHP system, as it is already outlined, two CHP engines of type engine 1. The total of the nominal electricity production capacity (60 kWh) is well above the total peak (18.53 kWh) hourly electricity consumption. This is well expected as the total demand of the group of buildings for electrical power is easier to be covered than its thermal energy needs.

On the other hand, the annual balance between the mCCHP system's electrical energy production (111,000 kWh) and the buildings consumption (63,724 kWh) is positive from the buildings administrator point of view. Therefore, there is plenty of excessive energy (47,243 kWh) that will be fed into the central electrical power grid. In the unlikely event that electrical power consumption of the buildings is higher than the total nominal capacity of the engines or the CHP engines are shut down for maintenance or due to a mechanical malfunction of the system, the extra power needed is provided from the central electrical power grid. The total electrical energy balance of the system, which is going to be positive from the mCCHP system point of view is presented on Table 18.

Total Electricity Production													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Prod.	16300	13846	9785	6778	2503	7628	10682	9921	2503	4456	11567	14998	110967
Cons.	6487	6487	5745	5167	5167	3659	3852	3371	5359	5359	6295	6776	63724
Balance	9813	7358	4040	1612	-2664	3968	6830	6551	-2856	-903	5273	8222	47243

Table 18: Total Electricity production

In this case thermal energy is produced by two, cascading in their function, biogas CHPs. In the previous sections, the total thermal demand of the group of buildings was calculated. The total nominal thermal energy capacity of the engines is 118kWh, as they are identical and have a nominal thermal capacity of 59kWh each. Concerning the thermal demands, as the author has previously shown, the worst case scenario, in other words the highest hourly thermal energy demand occurs during January, with almost 97 kWh needed.

Apart from covering the peak hourly thermal energy demand, mCCHP system should cover the thermal energy load in total. As one can see, the total thermal energy demand for the typical day of January, which is the worst case scenario, is 1,106 kWh. In case of a full load function of the two CHP biogas engines, the total thermal energy production is 2,834 kWh, which means that according to their nominal energy production, the engines are capable of covering the worst daily demand of year. Therefore, it is obvious that the mCCHP system can cover the monthly and annual thermal energy demand of the group of buildings. This means that the mCCHP system can cover the energy demands for cooling during summer, heating during winter and the demand for DHW throughout the year for the buildings in test. In the unlike occasion of greater peak demand, the electric boiler would, as an auxiliary unit, provide the energy surplus needed.

As it has already been mentioned, the function of the engines will be cascading. In other words, the first engine covers the first 59kWh of energy demands and in case of higher demand the second engine would start to run in order to cover the rest. Therefore, the first engine would have high load function in general, resulting in higher efficiency while the second would normally run part load and suffer from lower efficiency. Based on this percentage of loading, the calculation of the electricity production of the mCCHP system is made. On the following tables (19, 20), the exact information over the mCCHP system function is given. Table 19 shows the exact functional loads on the CHP biogas engine throughout the typical day of January and Table 20 shows how electricity production is distributed throughout the day.

Biogas CHP Function Load							
Time	Capacity 1 in kWh	Load Engine 1	Primary Energy Cons. 1 in kWh	Capacity 2 in kWh	Load Engine 2	Primary Energy Cons. 2 in kWh	Boiler Load
00:00	59	0.36	34.90	59	0	0	0
01:00	59	0.36	34.90	59	0	0	0
02:00	59	0.18	17.45	59	0	0	0
03:00	59	0.18	17.45	59	0	0	0
04:00	59	0.18	17.45	59	0	0	0
05:00	59	0.18	17.45	59	0	0	0
06:00	59	0.36	34.90	59	0	0	0
07:00	59	1.00	97.10	59	0.64	62.11	0
08:00	59	1.00	97.10	59	0.46	44.65	0
09:00	59	1.00	97.10	59	0.22	21.36	0
10:00	59	1.00	97.10	59	0.04	3.91	0
11:00	59	1.00	97.10	59	0.04	3.91	0
12:00	59	1.00	97.10	59	0.04	3.91	0
13:00	59	1.00	97.10	59	0.04	3.91	0
14:00	59	1.00	97.10	59	0.28	27.20	0
15:00	59	0.36	34.90	59	0	0	0
16:00	59	0.36	34.90	59	0	0	0
17:00	59	0.60	58.20	59	0	0	0
18:00	59	0.78	75.65	59	0	0	0
19:00	59	1.00	97.10	59	0.02	1.85	0
20:00	59	1.00	97.10	59	0.62	60.04	0
21:00	59	1.00	97.10	59	0.20	19.30	0
22:00	59	0.72	69.81	59	0	0	0
23:00	59	0.54	52.35	59	0	0	0
Total			1568.43			252.13	

Table 19: Biogas CHP Function Load

On Table 19, the total primary energy that is consumed during the mCCHP function is highlighted. The first engine consumes 1,568 kWh of primary energy and the second 252 kWh. The total of 1,820 kWh is procured by the biogas, which is the fuel source of the system. On the same table, the function rate of each engine is noted. These values are necessary for the calculation of the total electrical power production.

On Table 20, the electricity production is shown.

Electricity Production									
Time	El. Capacity Engine 1 in kWh	Load Engine 1	El. Efficiency	Electricity Prod. 1 in kWh	El. Capacity Engine in kWh	Load Engine 2	El. Efficiency	Electricity Prod. 2 in kWh	Total Electricity Prod.
00:00	30	0.36	0.86	9.29	30	0	0	0	9.29
01:00	30	0.36	0.86	9.29	30	0	0	0	9.29
02:00	30	0.18	0.86	4.65	30	0	0	0	4.65
03:00	30	0.18	0.86	4.65	30	0	0	0	4.65
04:00	30	0.18	0.86	4.65	30	0	0	0	4.65
05:00	30	0.18	0.86	4.65	30	0	0	0	4.65
06:00	30	0.36	0.86	9.29	30	0	0	0	9.29
07:00	30	1	1	30	30	0.64	0.98	18.86	48.86
08:00	30	1	1	30	30	0.46	0.95	13.17	43.17
09:00	30	1	1	30	30	0.22	0.86	5.68	35.68
10:00	30	1	1	30	30	0.04	0.86	1.04	31.04
11:00	30	1	1	30	30	0.04	0.86	1.04	31.04
12:00	30	1	1	30	30	0.04	0.86	1.04	31.04
13:00	30	1	1	30	30	0.04	0.86	1.04	31.04
14:00	30	1	1	30	30	0.28	0.86	7.24	37.24
15:00	30	0.36	0.82	8.80	30	0	0	0	8.80
16:00	30	0.36	0.82	8.80	30	0	0	0	8.80
17:00	30	0.60	0.95	17.17	30	0	0	0	17.17
18:00	30	0.78	0.98	22.98	30	0	0	0	22.98
19:00	30	1	1	30	30	0.02	0.86	0.49	30.49
20:00	30	1	1	30	30	0.62	0.95	17.71	47.71
21:00	30	1	1	30	30	0.20	0.86	5.14	35.14
22:00	30	0.72	0.98	21.20	30	0	0	0	21.20
23:00	30	0.54	0.95	15.44	30	0	0	0	15.44
									543.31

Table 20: Electricity production

Following the same methodology, the electrical energy production of the typical day of each month is calculated. On Table 21, one can see the monthly electrical energy production along with the total annual production and the electrical energy balance of the system.

Total Electricity Production													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Prod.	16300	13846	9785	6778	2503	7628	10682	9921	2503	4456	11567	14998	110967
Cons.	6487	6487	5745	5167	5167	3659	3852	3371	5359	5359	6295	6776	63724
Balance	9813	7358	4040	1612	-2664	3968	6830	6551	-2856	-903	5273	8222	47243

Table 21: Total Electricity production

During three (May, September and October) of the twelve months of the year, the electrical energy production of the mCCHP system is not enough to cover the monthly demand of the group of buildings. This fact can be easily explained, as for May, September and October, no thermal energy demand for cooling or heating purposes was assigned by the calculation method. Therefore, the mCCHP engines, produce thermal energy to cover only the DHW demand of the buildings, meaning that they have not much of thermal energy load to produce. Therefore, their low thermal load function (actually, during the aforementioned months, only one CHP engine works) is translated into low electrical energy production. The negative balance of the system, concerning electricity, in other words the missing electrical energy is delivered to the system by the centralized electrical power grid. However, the annual production of the mCCHP system does overcome the buildings demand by 47,243 kWh. So, even if, during three months of the year, the mCCHP system falls short and consumes energy from the grid the total annual balance, is clearly in advantage of the consumer. Concluding, it is up to the metering regime (feed-in, tariff e.tc.) how much the financial gain for the buildings' administrator will be.

4.2 Case 2

Location: Kastoria

Climatic zone: D

Scenario: 2

Power Generation Unit: Biogas CCHP

Cooling Device: Absorption Chiller

Max hourly electricity demand: 18.5 kWh

Max hourly thermal energy demand: 195.7 kWh (typical day of January)

Connection to the centralized electrical power grid: YES

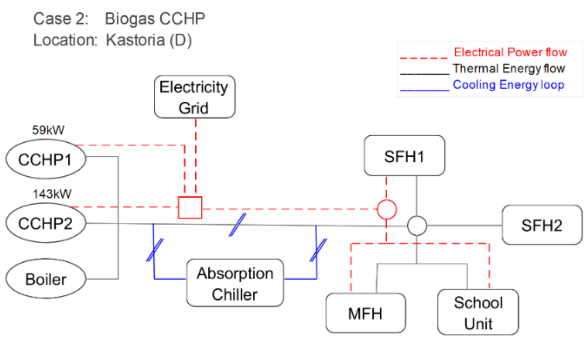

Figure 15: Micro CCHP system, Kastoria

In this case, the mCCHP system is located in Kastoria. This system consists of two biogas CHP engines, working as PGUs and an absorption chiller as cooling device. The system is connected to the centralized electrical power grid and a boiler is installed as an auxiliary unit for the thermal energy demand. The system has the same design configuration with the first case but with biogas CHP engines of a different capacity. Kastoria belongs to the fourth climatic zone of Greece, which means that the winter is harsher and summer is milder than the other climatic zones. Therefore, the peak thermal energy demand in this case is higher and PGUs with greater nominal capacity are required.

In specific, two biogas engines, available in the market, are installed, one with nominal thermal capacity of 59kWh and one of 143kWh. These engines, in full load, have an hourly consumption of 97kWh and 291 kWh of primary energy, respectively. Their electrical production is 30kWh for the first and 106 kWh for the second engine. The nominal capacity of the devices is chosen in order to meet the greatest hourly thermal energy demand, which occurs in January at 7 am.

Biogas CHP Function Load							
Time	Capacity 1 in kWh	Load Engine 1	Primary Energy Cons. 1 in kWh	Capacity 2 in kWh	Load Engine 2	Primary Energy Cons. 2 in kWh	Boiler Load
00:00	59	0.60	57.85	143	0	0	0
01:00	59	0.60	57.85	143	0	0	0
02:00	59	0.30	28.93	143	0	0	0
03:00	59	0.30	28.93	143	0	0	0
04:00	59	0.30	28.93	143	0	0	0
05:00	59	0.30	28.93	143	0	0	0
06:00	59	0.60	57.85	143	0	0	0
07:00	59	1	97	143	0.96	278.23	0
08:00	59	1	97	143	0.83	242.46	0
09:00	59	1	97	143	0.74	214.47	0
10:00	59	1	97	143	0.61	178.70	0
11:00	59	1	97	143	0.61	178.70	0
12:00	59	1	97	143	0.61	178.70	0
13:00	59	1	97	143	0.61	178.70	0
14:00	59	1	97	143	0.71	206.69	0
15:00	59	0.60	57.85	143	0	0	0
16:00	59	0.60	57.85	143	0	0	0
17:00	59	0.83	80.49	143	0	0	0
18:00	59	1	97	143	0.05	15.23	0
19:00	59	1	97	143	0.15	43.22	0
20:00	59	1	97	143	0.49	142.75	0
21:00	59	1	97	143	0.27	78.99	0
22:00	59	1	97	143	0.08	23.01	0
23:00	59	0.89	86.78	143	0	0	0
			1834.54			1959.86	

Table 22: Biogas CHP Function Load

On Table 22, the hourly load values of each engine, the hourly thermal load of the group of buildings and the calculation of the daily primary energy consumption are presented. Moreover, in the last column, there is the contribution of the boiler, which is 0 kWh. This means that the combination of the power production engines can satisfy the thermal load of the buildings not only to an annual or monthly extent but also during every single hour of the year. The integration of a boiler to the system becomes a proactive action for safety reasons and instances, such as engines' breakdown or the shutdown periods due to maintenance reason. Finally, the boiler is used in the unlikely occasion of a peak load that cannot be covered by the CHP engines.

Based on the thermal energy results and the functional rates of the engines, follows the calculation of the electrical energy production. This system, as the previous one in case 1, follows a TDM operational strategy, meaning that the function of the electrical power production units follows the thermal energy demand. Keeping the above in mind, Table 23 shows the electricity production of the system. This production is the electrical energy production of the month January which is the month with the greatest thermal demand and contains the hourly peak value. It is worth to highlight that the month with the greatest electrical energy demand is the December. As, it will be shown later, the mCCHP system covers this demand, but fails to cover the demand of other months.

Electricity Production									
Time	El. Capacity Engine 1 in kWh	Load Engine 1	El. Efficiency	Electricity Prod. 1 in kWh	El. Capacity Engine in kWh	Load Engine 2	El. Efficiency	Electricity Prod. 2 in kWh	Total Electricity Prod.
00:00	30	0.60	0.95	17.07	106	0	0	0	17.07
01:00	30	0.60	0.95	17.07	106	0	0	0	17.07
02:00	30	0.30	0.86	7.70	106	0	0	0	7.70
03:00	30	0.30	0.86	7.70	106	0	0	0	7.70
04:00	30	0.30	0.86	7.70	106	0	0	0	7.70
05:00	30	0.30	0.86	7.70	106	0	0	0	7.70
06:00	30	0.60	0.95	17.07	106	0	0	0	17.07
07:00	30	1	1	30	106	0.96	0.98	99.63	129.63
08:00	30	1	1	30	106	0.83	0.98	86.82	116.82
09:00	30	1	1	30	106	0.74	0.98	76.80	106.80
10:00	30	1	1	30	106	0.61	0.95	62.15	92.15
11:00	30	1	1	30	106	0.61	0.95	62.15	92.15
12:00	30	1	1	30	106	0.61	0.95	62.15	92.15
13:00	30	1	1	30	106	0.61	0.98	63.99	93.99
14:00	30	1	1	30	106	0.71	0.98	74.01	104.01
15:00	30	0.60	0.95	17.07	106	0	0	0	17.07
16:00	30	0.60	0.95	17.07	106	0	0	0	17.07
17:00	30	0.83	0.98	24.45	106	0	0	0	24.45
18:00	30	1	1	30	106	0.05	0.86	4.78	34.78
19:00	30	1	1	30	106	0.15	0.86	13.56	43.56
20:00	30	1	1	30	106	0.49	0.95	49.65	79.65
21:00	30	1	1	30	106	0.27	0.86	24.79	54.79
22:00	30	1	1	30	106	0.08	0.86	7.22	37.22
23:00	30	0.89	0.98	26.36	106	0	0	0	26.36
									1244.62

Table 23: Electricity production

Based on the same methodology and as the power generation units work following the thermal energy demand of the buildings, the electricity production for the typical day of each month and therefore, the monthly and annual production of the mCCHP system are calculated. Table 24 shows the electrical energy production per month, the respective electricity consumption of the buildings and the monthly balance of the system. As one can see, the system fails to cover the electrical energy demand in the months of May and September. This is a much anticipated result as during these months, there is no heating and cooling load, and therefore, the power production engines cover only the DHW thermal energy demand. Once again, low thermal energy production in this case leads to low electricity production. During the aforementioned months, the low electrical energy production is backed up from the centralized electrical power grid. However, in total the annual production is higher than the annual consumption, resulting in a positive energy balance, from the consumer's perspective. From their financial perspective, the administrator of the group of buildings in the present instance, will benefit depending on the exchanging power financial regime with the centralized electrical power grid (feed-in, tariff or any other).

Total Electricity Production													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug	Sep.	Oct.	Nov.	Dec.	Tot.
Prod.	37320	35460	30870	18960	3420	3720	4860	4590	3420	10380	24780	30870	208650
Cons.	6487	6487	5745	5167	5166.8	3659	3852	3371	5359.4	5359	6295	6776	63724
Bal-ance	30833	28973	25125	13793	-1747	60.6	1008	1220	-1939	5021	18485	24094	144926

Table 24: Total Electricity Production

Concluding the mCCHP system apart from covering the thermal energy and electrical energy demand of the four buildings, it produces an annual surplus of 144,926 kWh. The system, as it works only when there is thermal energy load, has no storage of thermal energy and no excessive production or missing thermal energy demand.

4.3 Case 3

Location: Athens

Climatic zone: B

Scenario: 1

Power Generation Unit: Natural gas CCHP

Cooling Device: Absorption chiller

Max hourly electricity demand: 19 kWh

Max hourly thermal energy demand: 105 kWh (typical day of January)

Connection to the centralized electrical power grid: YES

In case 3 the mCCHP system is located on Athens, the capital of Greece. Athens belongs to the Greek climatic zone B. The winter in this climatic zone is mild and the summer is rather hot. As Athens is a modern city complex, there is natural gas infrastructure. Therefore, in this case a natural gas powered mCCHP system is reviewed. The thermal energy peak of the group of buildings occurs during January and therefore, the typical January day is going to be reviewed. Concerning electricity, the peak demand occurs in December. There will be a full annual review of the consumption and the production of both the thermal and electrical energy.

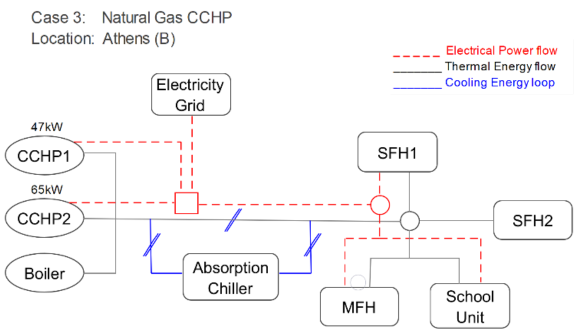

Figure 16: Micro CCHP system, Athens

In this case, the author opts for natural gas PGUs. The selected engines, are commercial products and their technical coefficients are taken from the official specification papers of the products. The engines have a 47 kWh and a 65kWh nominal thermal energy capacity and consume 71 kWh and 101 kWh of primary energy per hour, on full load. The electrical capacity of the PGU units are 20 kWh for the first and 30 kWh for the second engine. The electrical efficiency of the engines depends on the load coefficient in a relation that is defined on Table 25.

Electricity production of natural gas CHP at different loads				
kWh	25%	50%	75%	100%
Engine 1	17.2	19.1	19.7	20
engine 2	25.8	28.6	29.5	30
engine 3	43.1	47.7	49.2	50

Table 25: Electricity production of natural gas CHP at different loads

The following tables (26-28), present the thermal and electrical energy production of the mCCHP system. The rationale behind the calculations is the same as in the previous cases.

Natural Gas CHP Function Load							
Time	Capacity 1 in kWh	Load Engine 1	Primary Energy Cons. 1 in kWh	Capacity 2 in kWh	Load Engine 2	Primary Energy Cons. 2 in kWh	Boiler Load
00:00	47.2	0.50	35.39	65.4	0.00	0.00	0
01:00	47.2	0.50	35.39	65.4	0.00	0.00	0
02:00	47.2	0.25	17.69	65.4	0.00	0.00	0
03:00	47.2	0.25	17.69	65.4	0.00	0.00	0
04:00	47.2	0.25	17.69	65.4	0.00	0.00	0
05:00	47.2	0.25	17.69	65.4	0.00	0.00	0
06:00	47.2	0.50	35.39	65.4	0.00	0.00	0
07:00	47.2	1	70.80	65.4	0.77	77.15	0
08:00	47.2	1	70.80	65.4	0.59	59.07	0
09:00	47.2	1	70.80	65.4	0.36	35.61	0
10:00	47.2	1	70.80	65.4	0.18	17.54	0
11:00	47.2	1	70.80	65.4	0.18	17.54	0
12:00	47.2	1	70.80	65.4	0.18	17.54	0
13:00	47.2	1	70.80	65.4	0.18	17.54	0
14:00	47.2	1	70.80	65.4	0.41	41.00	0
15:00	47.2	0.50	35.39	65.4	0.00	0.00	0
16:00	47.2	0.50	35.39	65.4	0.00	0.00	0
17:00	47.2	0.82	58.36	65.4	0.00	0.00	0
18:00	47.2	1	70.80	65.4	0.05	5.36	0
19:00	47.2	1	70.80	65.4	0.29	28.82	0
20:00	47.2	1	70.80	65.4	0.88	88.43	0
21:00	47.2	1	70.80	65.4	0.47	46.90	0
22:00	47.2	1.00	70.78	65.4	0.00	0.00	0
23:00	47.2	0.75	53.08	65.4	0.00	0.00	0
			1279.54			452.51	

Table 26: Natural Gas CHP Function Load

Electricity Production									
Time	El. Capacity Engine 1 in kWh	Load Engine 1	El. Efficiency	Electricity Prod. 1 in kWh	El. Capacity Engine in kWh	Load Engine 2	El. Efficiency	Electricity Prod. 2 in kWh	Total Electricity Prod.
00:00	20	0.50	0.95	9.55	30	0.00	0.00	0.00	9.55
01:00	20	0.50	0.95	9.55	30	0.00	0.00	0.00	9.55
02:00	20	0.25	0.86	4.31	30	0.00	0.00	0.00	4.31
03:00	20	0.25	0.86	4.31	30	0.00	0.00	0.00	4.31
04:00	20	0.25	0.86	4.31	30	0.00	0.00	0.00	4.31
05:00	20	0.25	0.86	4.31	30	0.00	0.00	0.00	4.31
06:00	20	0.50	0.95	9.55	30	0.00	0.00	0.00	9.55
07:00	20	1.00	1.00	20.00	30	0.77	0.98	22.70	42.70
08:00	20	1.00	1.00	20.00	30	0.59	0.95	16.89	36.89
09:00	20	1.00	1.00	20.00	30	0.36	0.86	9.19	29.19
10:00	20	1.00	1.00	20.00	30	0.18	0.86	4.52	24.52
11:00	20	1.00	1.00	20.00	30	0.18	0.86	4.52	24.52
12:00	20	1.00	1.00	20.00	30	0.18	0.86	4.52	24.52
13:00	20	1.00	1.00	20.00	30	0.18	0.86	4.52	24.52
14:00	20	1.00	1.00	20.00	30	0.41	0.95	11.72	31.72
15:00	20	0.50	0.95	9.55	30	0.00	0.00	0.00	9.55
16:00	20	0.50	0.95	9.55	30	0.00	0.00	0.00	9.55
17:00	20	0.82	0.98	16.20	30	0.00	0.00	0.00	16.20
18:00	20	1.00	1.00	20.00	30	0.05	0.86	1.38	21.38
19:00	20	1.00	1.00	20.00	30	0.29	0.86	7.43	27.43
20:00	20	1.00	1.00	20.00	30	0.88	1.00	26.47	46.47
21:00	20	1.00	1.00	20.00	30	0.47	0.95	13.41	33.41
22:00	20	1.00	1.00	19.99	30	0.00	0.00	0.00	19.99
23:00	20	0.75	0.98	14.74	30	0.00	0.00	0.00	14.74
									483.17

Table 27: Electricity Production

Total Electricity Production													
kWh	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Tot.
Prod.	14490	13800	12240	8070	2040	3870	5280	5070	2010	4770	10140	12150	93930
Cons.	6764	6764	6009	5394	5393.6	3899	4104	3591	5598.8	5599	6559	7072	66748
Balance	7726	7036	6231	2676	-3354	-29	1176	1479	-3589	-828.8	3581	5078	27182

Table 28: Total Electricity Production

From all the above, the following conclusions can be reached:

- The mCCHP system covers the peak thermal energy demand and the monthly and annually thermal needs. The peak hourly demand is 105 kWh, occurring in January, while the total nominal capacity of the system is 112 kWh. Therefore, the thermal energy demand of the group of buildings is satisfied.

- The same, as previously, electrical energy production procedure is followed resulting in an annual surplus of 27,182 kWh. This electrical energy can be fed and 'sold' to the central electrical power grid
- May, June, September and October are the months that electricity production cannot cover the demand. As the system is connected to the central electrical power grid, the missing electricity is procured by the grid.
- The PGU of the mCCHP system operate only in case of thermal demand. Therefore, no excessive thermal energy is produced and no thermal storage tank is needed.

4.4 Case 4

Location: Thessaloniki

Climatic zone: C

Scenario: 1

Power Generation Unit: Natural gas CCHP

Cooling Device: Absorption chiller

Max hourly electrical energy demand: 19 kWh

Max hourly thermal energy demand: 155 kWh (typical day of January)

Connection to the centralized electrical power grid: YES

Thessaloniki belongs to the Greek climatic zone C. The winter in Thessaloniki is mild but harsher than Athens and Irakleio and so is the summer, rather cooler than Athens and Irakleio. For the thermal and electrical energy needs of the buildings, a natural gas power mCCHP system is reviewed. Like Athens, two engines will be assumed, with a cascading function. The first (type 1) has nominal thermal energy capacity of 65 kWh and the second (type 2) of 101 kWh, resulting in 166 kWh of installed nominal thermal energy capacity. This combination succeeds in covering the greatest hourly thermal energy demand that occurs in January (typical day of January) at 7 am which is 155 kWh. In Figure 17 there is a representation of the mCCHP system and on Table 29 the technical characteristics of the operation of the CHP engines.

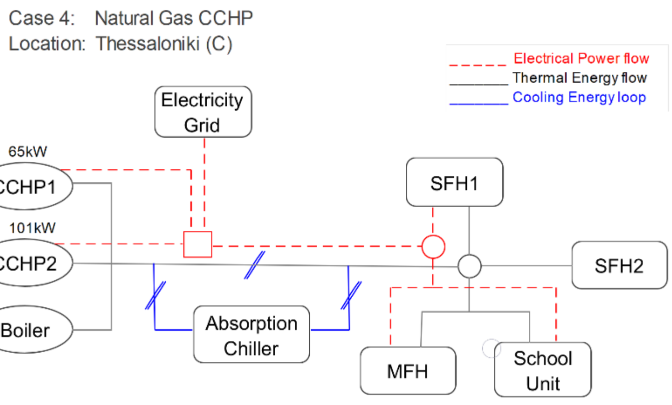

Figure 17: Micro CCHP system, Thessaloniki

CHP Natural Gas – Power Production Unit							
Natural Gas	Electrical output in kWh	Heat output in KWh	Electrical/ Heat ratio	Electrical efficiency	Heat efficiency	Total efficiency	Energy Input in kWh
Engine 1	20	47.2	0.42	30.70	64.10	94.80	70.80
Engine 2	30	65.4	0.46	32.40	62.80	95.20	100.21
Engine 3	50	101.5	0.49	34.20	60.60	94.80	159.81

Table 29: CHP Natural Gas – Power Generation Unit

Natural Gas CHP Function Load							
Time	Capacity 1 in kWh	Load Engine 1	Primary Energy Cons. 1 in kWh	Capacity 2 in kWh	Load Engine 2	Primary Energy Cons. 2 in kWh	Boiler Load
00:00	65.4	0.48	47.87	101.5	0.00	0.00	0.00
01:00	65.4	0.48	47.87	101.5	0.00	0.00	0.00
02:00	65.4	0.24	23.93	101.5	0.00	0.00	0.00
03:00	65.4	0.24	23.93	101.5	0.00	0.00	0.00
04:00	65.4	0.24	23.93	101.5	0.00	0.00	0.00
05:00	65.4	0.24	23.93	101.5	0.00	0.00	0.00
06:00	65.4	0.48	47.87	101.5	0.00	0.00	0.00
07:00	65.4	1.00	100.21	101.5	0.89	141.58	0.00
08:00	65.4	1.00	100.21	101.5	0.73	116.99	0.00
09:00	65.4	1.00	100.21	101.5	0.53	85.45	0.00
10:00	65.4	1.00	100.21	101.5	0.38	60.85	0.00
11:00	65.4	1.00	100.21	101.5	0.38	60.85	0.00
12:00	65.4	1.00	100.21	101.5	0.38	60.85	0.00
13:00	65.4	1.00	100.21	101.5	0.38	60.85	0.00
14:00	65.4	1.00	100.21	101.5	0.58	92.39	0.00
15:00	65.4	0.48	47.87	101.5	0.00	0.00	0.00
16:00	65.4	0.48	47.87	101.5	0.00	0.00	0.00
17:00	65.4	0.78	78.56	101.5	0.00	0.00	0.00
18:00	65.4	1.00	100.21	101.5	0.01	2.35	0.00
19:00	65.4	1.00	100.21	101.5	0.21	33.88	0.00
20:00	65.4	1.00	100.21	101.5	0.72	114.61	0.00
21:00	65.4	1.00	100.21	101.5	0.37	58.48	0.00
22:00	65.4	0.96	95.74	101.5	0.00	0.00	0.00
23:00	65.4	0.72	71.80	101.5	0.00	0.00	0.00
			1783.71			889.14	

Table 30: Natural Gas CHP Function Load

Table 30 shows the primary energy consumed, along with the load rates of the power production units. Finally, the total primary energy consumed in the system is calculated.

This operational pattern of the power production engines leads to the following electrical energy production. As in the previous cases, the mCCHP system in Thessaloniki follows a TDM operational strategy, meaning that the production of the system follows the thermal energy demand. Table 31 shows the electricity production of the mCCHP system.

Electricity production									
Time	El. capacity Engine 1 in kWh	Engine 1 load	Efficiency	Electricity Prod. Engine 1 in Kwh	El. capacity Engine 2 in kWh	Engine 2 load	Efficiency	Electricity Prod. Engine 2 in kWh	Total Electricity Prod.
00:00	30	0.48	0.95	13.68	50	0.00	0.00	0.00	13.68
01:00	30	0.48	0.95	13.68	50	0.00	0.00	0.00	13.68
02:00	30	0.24	0.86	6.17	50	0.00	0.00	0.00	6.17
03:00	30	0.24	0.86	6.17	50	0.00	0.00	0.00	6.17
04:00	30	0.24	0.86	6.17	50	0.00	0.00	0.00	6.17
05:00	30	0.24	0.86	6.17	50	0.00	0.00	0.00	6.17
06:00	30	0.48	0.95	13.68	50	0.00	0.00	0.00	13.68
07:00	30	1.00	1.00	30.00	50	0.89	0.98	43.54	73.54
08:00	30	1.00	1.00	30.00	50	0.73	0.95	34.95	64.95
09:00	30	1.00	1.00	30.00	50	0.53	0.86	23.03	53.03
10:00	30	1.00	1.00	30.00	50	0.38	0.86	16.40	46.40
11:00	30	1.00	1.00	30.00	50	0.38	0.86	16.40	46.40
12:00	30	1.00	1.00	30.00	50	0.38	0.86	16.40	46.40
13:00	30	1.00	1.00	30.00	50	0.38	0.86	16.40	46.40
14:00	30	1.00	1.00	30.00	50	0.58	0.95	27.60	57.60
15:00	30	0.48	0.95	13.68	50	0.00	0.00	0.00	13.68
16:00	30	0.48	0.95	13.68	50	0.00	0.00	0.00	13.68
17:00	30	0.78	0.98	23.12	50	0.00	0.00	0.00	23.12
18:00	30	1.00	1.00	30.00	50	0.01	0.86	0.63	30.63
19:00	30	1.00	1.00	30.00	50	0.21	0.86	9.13	39.13
20:00	30	1.00	1.00	30.00	50	0.72	0.98	35.25	65.25
21:00	30	1.00	1.00	30.00	50	0.37	0.95	17.47	47.47
22:00	30	0.96	1.00	28.66	50	0.00	0.00	0.00	28.66
23:00	30	0.72	0.98	21.13	50	0.00	0.00	0.00	21.13
									783.23

Table 31: Electricity Production

Based on the same methodology as in the previous cases, the monthly and annual electrical energy production along with the electrical energy balance throughout the year are calculated.

Total Electricity Production													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot.
Production	23490	22470	19920	12900	2910	3900	5220	4890	2910	7560	16350	19830	142350
Consumption	6764	6764	6009	5394	5393.6	3899	4104	3591	5598.8	5599	6559	7072	66748
Balance	16726	15706	13911	7506	-2484	1.2	1116	1299	-2689	1961	9791	12758	75602

Table 32: Total Electricity Production

As, the same phenomenon with the previous cases happens in Thessaloniki, in May and September, the mCCHP system fails to cover the electrical energy demand of the group of buildings. The 5,173 Kwh that are missing to meet the demand of these months are covered by the centralized electrical power grid. However, the annual production of electricity is higher than the consumption leading to a positive balance, from the consumer's point of view.

4.5 Case 5

Location: Irakleio, Athens, Thessaloniki, Kastoria

Climatic zone: A, B, C, D

Scenario: 3

Power Generation Unit: Flat plate and High Concentrate solar collectors

Collector area: 950 m^2

Devices: Organic Rankine engine, Absorption Chiller, Thermal storage

Central electrical power grid connection: Yes

In this case, solar thermal collectors are used in order to produce the thermal energy needed to cover the buildings' demands. Solar collectors cover a 950 m^2 rooftop area of the buildings. The thermal energy produced can be directly used or stored in a thermal energy storage tank. Apart from covering the thermal energy demand during night or periods without significant energy production from the solar radiation, implementing a thermal storage tank leads to a better matching of production with end-users demand. Moreover, it results in a higher efficiency and overall performance as it can allow reduced components and system sizes. Sizing of the thermal storage device can be either based on a 'partial load' strategy or a 'full storage' strategy. In the first case, storage tank is used as a buffer for the variations of thermal energy production and the intermittency of renewable energy source, such as solar radiation, while in the second the operation of a thermal energy tank can offset the peak in demand. Thermal storage materials can be of conventional type and materials or based on phase change materials. The optimal sizing and type of the storage tank in this case is above the scope of this dissertation.

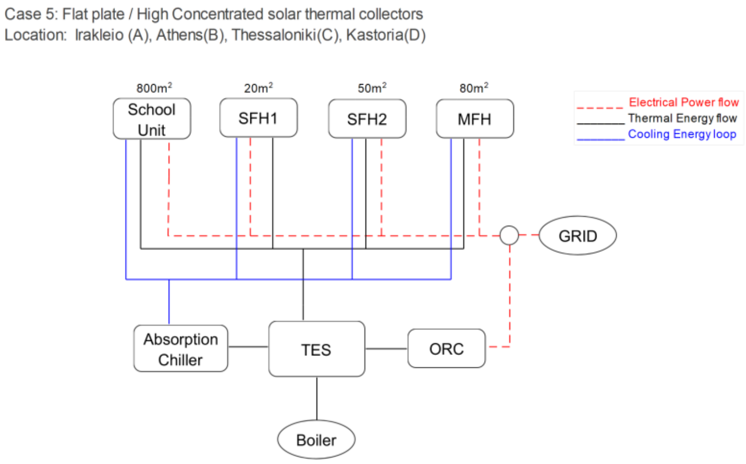

Figure 18: Micro CCHP system, Flat plate and Concentrated solar thermal Collectors

Apart from the solar thermal collectors and the storage device, the mCCHP system contains, an absorption chiller, an Organic Rankine engine and an electric boiler as a thermal energy auxiliary unit. The absorption chiller, with a COP of 0.7, is used to produce the cooling energy needed during the summer months to meet the cooling demand of the buildings. The Organic Rankine engine is used to produce electrical power from the surplus of the hot water production, which is stored in the thermal energy storage. In this way the thermal energy that is not use for heating and cooling purposes will not be wasted and will be used to produce electricity. This electricity can either feed the buildings demand or be dumped into the central electrical power grid. The Organic Rankine engine is preferred from Stirling or steam-Rankine engines as it can be more efficiently integrated in low-temperature power production solution. Organic Rankine engines also tend to be smaller than a Stirling engine power plant[85]. In this case the inlet temperature of the Rankine engine is assumed 70°C. Concerning the electric boiler, it will be used during the periods that the solar thermal PGU is not able to meet the thermal energy demand. This shortcoming will be satisfied by consuming electricity procured by the centralized electrical power grid.

In this case solar collectors’ area is limited by the defined by the building rooftops area. The calculated rooftop array covers in total 950 m^2, as it is assumed that the school can accommodate a 800 m^2 rooftop array. SFH1 has a useful rooftop area of 20 m^2, SFH2 a 50 m^2 area and the MFH has a useful area for solar collector installation of 80 m^2. In total 950 m^2 of area is covered by solar collectors. The collectors are south-oriented and their inclination, following KENAK’s instructions, matches the latitude of each location accordingly. In other words, in Irakleio the panels are installed with a 36° inclination, in

Athens 38º, in Thessaloniki 40º and finally in Kastoria 40º. This inclination results in the highest annual efficiency, compared to wider inclinations that are more advantageous in strictly summer or winter use.

The solar collectors that are used for the calculation, derive from the retail market and their efficiency and the produced thermal energy is calculated according to KENAK. The f-chart method is used and the technical characteristics are extracted from the technical papers of the products. In specific, for the flat plate solar collector a zero-loss optical efficiency of 0.73, a heat loss coefficient of 5.151 [W/ (m^2*K)] and a temperature dependence coefficient of 0.006 [W/ (m^2*K^2)] were assumed. The values for the high concentrated solar collector are 0.77, 3.75 [W/ (m^2*K)] and 0.015 [W/ (m^2*K^2)] respectively. In the following tables (33-42), the annual solar thermal production, the total efficiency of the PGUs and the respective consumption of each location for the flat plate and the high concentrate collectors are presented.

a) Irakleio (Climatic zone A)

Table 33 presents the thermal and electrical energy production of the mCCHP system power by evacuated flat plate solar collectors in Irakleio.

Flat plate solar collector (Irakleio)													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Irrad. Beam	96	107	140	163	180	177	185	186	176	151	124	101	1786
n	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	
Prod/m²	24.96	27.82	36.4	42.38	46.8	46.02	48.1	48.36	45.76	39.26	32.24	26.26	464.36
Area	950	950	950	950	950	950	950	950	950	950	950	950	
Prod.	23712	26429	34580	40261	44460	43719	45695	45942	43472	37297	30628	24947	441142
Cons.	33187	28190	19922	13801	5096	15530	21748	20200	5096	9073	23551	30536	225930
Bal.	-9475	-1761	14658	26460	39364	28189	23947	25742	38376	28224	7077	-5589	215212
Rank. El. Prod.	0	0	3383	6106	9084	6505	5526	5940	8856	6513	1633	0	53547
El. E. Cons	6487.2	6487.2	5744.6	5166.8	5166.8	3659.4	3852	3370.5	5359.4	5359.4	6294.6	6776.1	63724
Balance El.E.	-6487.2	-6487	-2362	939.35	3917.2	2845.8	1674.2	2570	3496.6	1153.8	-4661	-6776	-10177

Table 33: Flat plate solar collector (Irakleio)

And the same calculation for the concentrated solar collector.

Concentrated solar collector (Irakleio)													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Irrad. Beam	96	107	140	163	180	177	185	186	176	151	124	101	1786
n	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	
Prod./ m^2	27.84	31.03	40.6	47.27	52.2	51.33	53.65	53.94	51.04	43.79	35.96	29.29	517.94
Area	950	950	950	950	950	950	950	950	950	950	950	950	
Prod.	26448	29479	38570	44907	49590	48764	50968	51243	48488	41601	34162	27826	492043
Cons.	33187	28190	19922	13801	5096	15530	21748	20200	5096	9073	23551	30536	225930
Bal.	-6739	1288.5	18648	31106	44494	33234	29220	31043	43392	32528	10611	-2711	266113
Rank. El. Prod.	0	267	3858	6436	9206	6876	6045	6423	8978	6730	2195	0	57013
El. E. Cons	6487.2	6487.2	5744.6	5166.8	5166.8	3659.4	3852	3370.5	5359.4	5359.4	6294.6	6776.1	63724
Balance El.E.	-6487	-6221	-1886	1269	4039	3216	2193	3052	3618	1370	-4099	-6776	-6711

Table 34: Concentrated solar collector (Irakleio)

With the exception of January, February and December, the solar mCCHP system is able to cover the thermal energy need of the group of buildings. As it has already been noted, thermal energy cannot be stored for long terms as, for example, a month and therefore, the deficit of January and December cannot be covered by the thermal energy production of other months. So, even if the annual production is greater than the annual demand, there is a significant period, a month in this case, that the system falls short of covering the energy need. An electrical boiler is used for this purpose. Assuming a 99% efficiency of an electric boiler, 16,994 kWh for the flat plate collector system and 9,544 kWh for the concentrated solar system, of additional energy is used to cover the demands. This energy is provided by the centralized electrical power grid.

On the other hand, and during the sunny summer months, thermal energy production is significantly higher than the demand during the other months. In order to take advantage of this energy production surplus, an Organic Rankine engine is used, that produces as much electrical power as it can be produced by the thermal energy, stored in the thermal storage device of the system. As it is shown on the above table an amount of 53,547 kWh for the flat plate collector system and 57,013 kWh for the concentrated collector system are produced and cover the 84% and the 89.4% of the annual demand for electrical power of the buildings (excluding the electrical power consumed by the electric boiler).

Taking also into consideration the electricity consumption of the electric boiler, which secures the total coverage of the thermal load for the group of building, the respective percentages of the electrical energy coverage are 66.3% for the flat plate collector powered system and 77.8% for the concentrated collector powered system. In other words, the PGUs of the mCCHP systems in this cases secure the 66.3% and the 77.8% respectively of the total energy needs of the group of buildings in heating, cooling, DHW and electricity.

b) Athens (Climatic zone B)

Tables 35 and 36 present the thermal and electrical energy balance of the mCCHP systems for the climatic zone B, Athens.

Flat plate solar collector (Athens)													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Irrad. Beam	98	103	124	137	154	156	171	178	159	140	118	99	1637
n	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	
Prod./ m²	26.46	27.81	33.48	36.99	41.58	42.12	46.17	48.06	42.93	37.8	31.86	26.73	441.99
Area	950	950	950	950	950	950	950	950	950	950	950	950	
Prod.	25137	26420	31806	35141	39501	40014	43862	45657	40784	35910	30267	25394	419891
Cons.	34453	33247	29630	19983	5512	14230	19736	18360	5512	12747	24806	29630	247846
Bal.	-9316	-6828	2176	15158	33989	25784	24126	27297	35272	23163	5461	-4237	172045
Rank. El. Prod.	0	0	484	3368	7553	5730	5361	6066	7838	5147	1214	0	42761
El. E. Cons	6764	6764	6009	5394	5394	3899	4104	3591	5599	5599	6559	7072	66748
Balance El.E.	-6764	-6764	-5526	-2025	2160	1831	1257	2475	2239	-451	-5346	-7072	-23987

Table 35: Flat plate solar collector (Athens)

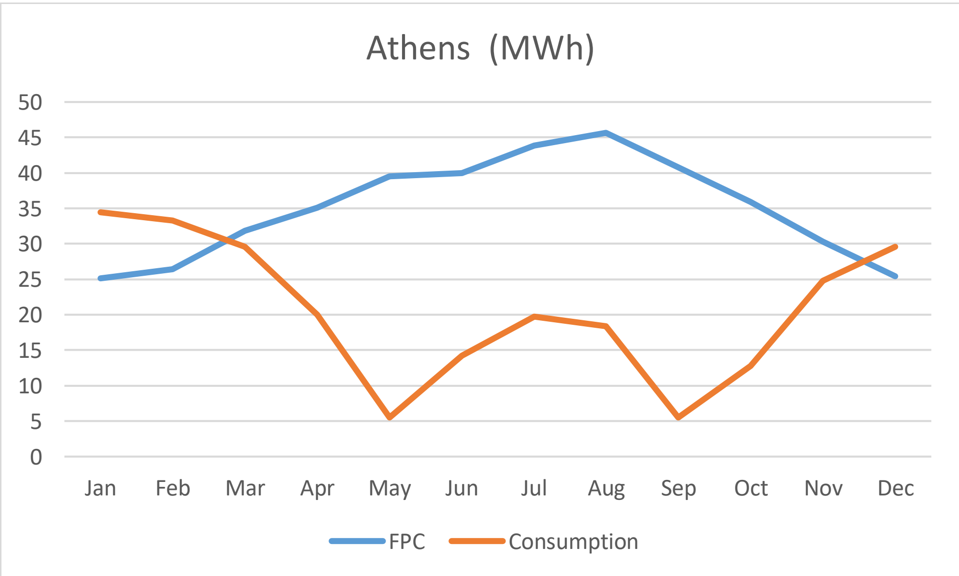

Figure 19: Thermal energy production and consumption

Concentrated solar collector (Athens)													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Irrad. Beam	98	103	124	137	154	156	171	178	159	140	118	99	1637
n	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	
Prod./ m²	29.4	29.9	36.0	39.7	44.7	45.2	49.6	51.6	46.1	40.6	34.2	28.7	475.71
Area	950	950	950	950	950	950	950	950	950	950	950	950	
Prod.	27930	28377	34162	37744	42427	42978	47111	49039	43805	38570	32509	27275	451925
Cons.	34453	33247	29630	19983	5512	14230	19736	18360	5512	12747	24806	29630	247846
Bal.	-6523	-4871	4532	17761	36915	28748	27375	30679	38293	25823	7703	-2356	204079
Rank. El. Prod.	0	0	906	3552	7383	5750	5475	6136	7659	5165	1541	0	43566
El. E. Cons	6764	6764	6009	5394	5394	3899	4104	3591	5599	5599	6559	7072	66748
Balance El.E.	-6764	-6764	-5103	-1842	1989	1851	1371	2545	2060	-434	-5019	-7072	-23183

Table 36: Concentrated solar collector (Athens)

c) Thessaloniki (Climatic zone C)

Tables 37 and 38 present the thermal and electrical energy balance of the mCCHP systems for the climatic zone C, Thessaloniki.

Flat plate solar collector (Thessaloniki)													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Irrad. Beam	86	92	110	130	148	150	168	163	144	119	94	85	1489
n	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	
Prod./ m²	21.5	23	27.5	32.5	37	37.5	42	40.75	36	29.75	23.5	21.25	372.25
Area	950	950	950	950	950	950	950	950	950	950	950	950	
Prod.	20425	21850	26125	30875	35150	35625	39900	38713	34200	28263	22325	20188	353637.5
Cons.	51863	50003	44421	29537	7211	12890	17551	16386	7211	18374	36979	44421	336847
Bal.	-31438	-28153	-18296	1338	27939	22735	22349	22327	26989	9888.5	-14654	-24234	16790.5
Rank. El. Prod.	0	0	0	268	5588	4547	4470	4465	5398	1978	0	0	26713
El. E. Cons	6764	6764	6009	5394	5394	3899	4104	3591	5599	5599	6559	7072	66748
Balance El.E.	-6764.4	-6764	-6009	-5126	194	648	366	874	-201	-3621	-6559	-7072	-40035

Table 37: Flat plate solar collector (Thessaloniki)

Concentrated solar collector (Thessaloniki)													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Irrad. Beam	86	92	110	130	148	150	168	163	144	119	94	85	1489
n	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28	
Prod./ m^2	24.08	25.76	30.8	36.4	41.44	42	47.04	45.64	40.32	33.32	26.32	23.8	416.92
Area	950	950	950	950	950	950	950	950	950	950	950	950	
Prod.	22876	24472	29260	34580	39368	39900	44688	43358	38304	31654	25004	22610	396074
Cons.	51863	50003	44421	29537	7211	12890	17551	16386	7211	18374	36979	44421	336847
Bal.	-28987	-25531	-15161	5043	32157	27010	27137	26972	31093	13280	-11975	-21811	59227
Rank. El. Prod.	0	0	0	901	5742	4823	4846	4816	5552	2371	0	0	29052
El. E. Cons	6764	6764	6009	5394	5394	3899	4104	3591	5599	5599	6559	7072	66748
Balance El.E.	-6764	-6764	-6009	-4493	349	924	742	1225	-46	-3227	-6559	-7072	-37696

Table 38: Concentrated solar collector (Thessaloniki)

d) Kastoria (Climatic zone D)

Tables 39 and 40 present the thermal and electrical energy balance of the mCCHP systems for the climatic zone D, Kastoria

Flat plate solar collector (Kastoria)													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Irrad. Beam	86	91	125	137	159	162	177	178	157	140	104	81	1597
n	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	
Prod./ m^2	20.64	21.84	30	32.88	38.16	38.88	42.48	42.72	37.68	33.6	24.96	19.44	383.28
Area	950	950	950	950	950	950	950	950	950	950	950	950	
Prod.	19608	20748	28500	31236	36252	36936	40356	40584	35796	31920	23712	18468	364116
Cons.	64593	62202	55030	35902	7211	11014	14754	13819	7211	21557	45466	55030	393789
Bal.	-44985	-41454	-26530	-4666	29041	25922	25602	26765	28585	10363	-21754	-36562	-29673
Rank. El. Prod.	0	0	0	0	4840	4320	4267	4461	4764	1727	0	0	24380
El. E. Cons	6487	6487	5745	5167	5167	3659	3852	3371	5359	5359	6295	6776	63724
Balance El.E.	-6487	-6487	-5745	-5167	-327	661	415	1090	-595	-3632	-6295	-6776	-39344.33

Table 39: Flat plate solar collector (Kastoria)

Concentrated Solar collector (Kastoria)													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Irrad. Beam	86	91	125	137	159	162	177	178	157	140	104	81	1597
n	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	
Prod./ m^2	23.22	24.57	33.75	36.99	42.93	43.74	47.79	48.06	42.39	37.8	28.08	21.87	431.19
Area	950	950	950	950	950	950	950	950	950	950	950	950	
Prod.	22059	23341.5	32062.5	35140.5	40783.5	41553	45400.5	45657	40270.5	35910	26676	20776.5	409630.5
Cons.	64593	62202	55030	35902	7211	11014	14754	13819	7211	21557	45466	55030	393789
Bal.	-42534	-38861	-22968	-762	33573	30539	30647	31838	33060	14353	-18790	-34254	15842
Rank. El. Prod.	0	0	0	-113	4974	4524	4540	4717	4898	2126	0	0	25666
El. E. Cons	6487	6487	5745	5167	5167	3659	3852	3371	5359	5359	6295	6776	63724
Balance El.E.	-6487	-6487	-5745	-5280	-193	865	688	1346	-462	-3233	-6295	-6776	-38058

Table 40: Concentrated solar collector (Kastoria)

e) Aggregated results

Tables 41 and 42 present the total performance of the solar thermal mCCHP systems. Table 41 shows the total performance of a mCCHP system with a flat plate solar thermal collector as PGU and Table 42 the performance of a mCCHP system powered by concentrated solar collectors.

Flat plate solar collector										
Location	Thermal En. Prod.	Thermal En. Cons	% Th. En. coverage	Months with deficit	Electricity Prod.	Electricity Cons.	% El/ En. coverage	Boiler	Tot. Deficit El.	Total % En coverage
Irakleio	441142	225930	100	3	53547	63724	0.84	16994	27171	66.3
Athens	419891	247846	100	3	42761	66748	0.64	20586	44573	48.9
Thessaloniki	353637	336847	100	5	26713	66748	0.40	117954	157989	14.4
Kastoria	364116	393789	0.92	6	24380	63724	0.38	177728	217072	10

Table 41: Flat plate solar collector

Concentrated solar collector										
Location	Thermal En. Prod.	Thermal En. Cons	% Th. En. coverage	Months with deficit	Electricity Prod.	El. En. Cons.	% El. En. coverage	Boiler	Tot. Deficit El.	Total % En coverage
Irakleio	492043	225930	100	2	57013	63724	0.89	9545	16256	77.8
Athens	451925	247846	100	3	43566	66748	0.65	13889	37071	54
Thessaloniki	396074	336847	100	5	29052	66748	0.44	104510	142206	16.9
Kastoria	409630	333789	100	6	25666	63724	0.40	159765	197823	11.4

Table 42: Concentrated solar collector

In the following section, some remarks over the aggregated results are made.

- It is worth to note that, with the exception of the flat plate solution in Kastoria, for all the other occasions the total annual thermal energy production is higher than the total annual thermal energy consumption. However, this does not mean that the systems cover the respective monthly demands. For the months with deficit in thermal energy production, the electric boiler covers the missing thermal energy. This electric boiler, with an efficiency of 99%, consumes electrical power and adds to the total electricity demand.
- All the systems have difficulty in covering the winter thermal demand. Especially in Kastoria and Thessaloniki, with six and five months of thermal energy deficit, while in Athens and Irakleio are only three. On the other hand, space cooling is totally covered by the solar systems in all the aforementioned four locations. That is a much anticipated result as, along with the lower compared to heating thermal energy needs of the cooling process, the thermal energy production by the solar systems during summer is much higher than during winter.
- From the total percentage of energy coverage column it is easily understood that only in Irakleio (67%-78%) and partially in Athens (49%-54%) can a solar system of this type be considered as the main PGU of a mCCHP system. In Thessaloniki (14%-17%) and in Kastoria (10%-11%), a solar thermal system can only be considered as an auxiliary PGU.
- However, excluding the function of the boiler, in other words, excluding the coverage of the deficit in thermal energy production during the months of thermal energy deficit, the electrical energy production of the system can be satisfactory.

4.6 Case 6

Location: Irakleio, Athens, Thessaloniki, Kastoria

Climatic zone: A, B, C, D

Scenario: 4

Power Generation Unit: Hybrid Photovoltaic solar panels

Panel area: 950 m^2

Devices: Absorption Chiller, Electric boiler

Connection to the centralized electrical power grid: YES

In case 6, a different type of photovoltaic panels, the hybrid photovoltaic panels are used as the PGU of the mCCHP system. This type of solar collectors can produce both electricity and thermal energy at the same time. In this simulation, the collectors are installed on the rooftops of the buildings and cover an area of 950 m^2. The mCCHP system is connected to the centralized electrical power grid, which means that the excessive or the missing electrical power is absorbed or provided, respectively, by the centralized grid. There is no excessive thermal energy production that justifies the incorporation of a larger than the operational system's need, thermal energy storage device. In other words, the system does not produce excessive thermal energy that needs to be stored for later use.

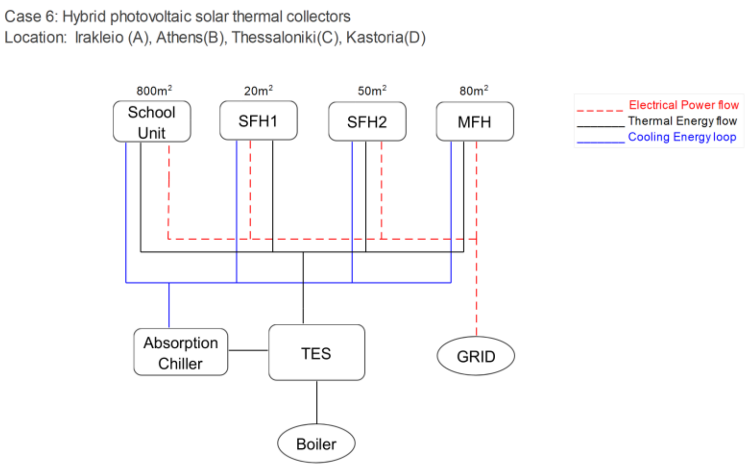

Figure 20: Micro CCHP system, Hybrid panels

In the following Tables (43-50) the thermal energy and electricity production is presented along with the respective demands, the balances and the electric boiler's production for all the four locations.

a) Irakleio

Irakleio Electricity													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total prod.	4121	3748	6042	9344	8886	9757	11185	12586	10810	5267	5883	2959	90588
Cons.	6487	6487	5745	5167	5167	3659	3852	3371	5359	5359	6295	6776	63724
Balance	-2366	-2739	297	4177	3719	6098	7333	9216	5451	-92	-412	-3817	26864

Table 43: Irakleio Electrical Power

Irakleio Thermal Energy													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total prod.	2473	2249	3625	5606	5332	5854	6711	7552	6486	3160	3530	1775	54353
Cons.	33187	28190	19922	13801	5096	15530	21748	20200	5096	9073	23551	30536	225930
Balance	-30714	-25941	-16297	-8195	236	-9676	-15037	-12648	1390	-5913	-20021	-28761	-171577
Saving %	7.5	8.0	18.2	40.6	100.0	37.7	30.9	37.4	127.3	34.8	15.0	5.8	24
Boiler	0	0	294	4135	3682	6037	7260	9123	5396	0	0	0	35928
En. Saving%													40

Table 44: Irakleio Thermal Energy

b) Athens

Athens Electricity													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total prod.	5015	4798	7432	8784	9262	13407	13179	10874	7611	5169	4258	3809	93598
Cons.	6764	6764	6009	5394	5394	3899	4104	3591	5599	5599	6559	7072	66748
Balance	-1749	-1966	1423	3390	3868	9508	9075	7283	2012	-430	-2301	-3263	26850

Table 45: Athens Electrical Power

Athens Thermal Energy													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total prod.	3009	2879	4459	5270	5557	8044	7907	6524	4567	3101	2555	2285	56159
Cons.	34453	33247	29630	19983	5512	14230	19736	18360	5512	12747	24806	29630	247846
Balance	-31444	-30368	-25171	-14713	45	-6186	-11829	-11836	-945	-9646	-22251	-27345	-191687
Saving %	8.7	8.7	15.0	26.4	100.0	56.5	40.1	35.5	82.8	24.3	10.3	7.7	20
Boiler	0	0	1409	3356	3830	9413	8984	7210	1992	0	0	0	36194
En. Saving%													37

Table 46: Athens Thermal Energy

c) Thessaloniki

Thessaloniki Electricity													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total prod.	4263	4290	6224	6321	8374	10386	12648	11211	8827	5787	5458	1959	85748
Cons.	6764	6764	6009	5394	5394	3899	4104	3591	5599	5599	6559	7072	66748
Balance	-2501	-2474	215	927	2980	6487	8544	7620	3228	188	-1101	-5113	19000

Table 47: Thessaloniki Electrical Power

Thessaloniki Thermal Energy													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total prod.	2558	2574	3734	3793	5024	6232	7589	6727	5296	3472	3275	1175	51449
Cons.	51863	50003	44421	29537	7211	12890	17551	16386	7211	18374	36979	44421	336847
Balance	-49305	-47429	-40687	-25744	-2187	-6658	-9962	-9659	-1915	-14902	-33704	-43246	-285398
Saving %	4.9	5.1	8.4	12.8	69.7	48.3	43.2	41.1	73.4	18.9	8.9	2.6	15
Boiler	0	0	213	918	2951	6422	8459	7544	3196	186	0	0	29888
En. Saving%													24

Table 48: Thessaloniki Thermal Energy

d) Kastoria

Kastoria Electricity													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total prod.	3933	3146	3408	5208	6652	7879	11069	9295	5769	3945	2725	2397	65426
Cons.	6487	6487	5745	5167	5167	3659	3852	3371	5359	5359	6295	6776	63724
Balance	-2554	-3341	-2336	41	1485	4220	7217	5925	410	-1414	-3570	-4380	1702

Table 49: Kastoria Electricity

Kastoria Thermal Energy													
kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Total prod.	2742	2194	2381	3632	4636	5486	7696	6463	4019	2752	1901	1678	45581
Cons.	64593	62202	55030	35902	7211	11014	14754	13819	7211	21557	45466	55030	393789
Balance	-61851	-60008	-52649	-32270	-2575	-5528	-7058	-7356	-3192	-18805	-43565	-53352	-348208
Saving %	4.2	3.5	4.3	10.1	64.2	49.8	52.1	46.7	55.7	12.7	4.1	3.0	12
Boiler	0	0	0	40.9	1469.9	4177.6	7144.8	5865.3	405.7	0	0	0	19104
En. Saving%													16

Table 50: Kastoria Thermal Energy

As it is easily understood from the above tables, the thermal energy produced by the hybrid photovoltaic panels is not sufficient to cover the building demands. The production falls well short and therefore, another thermal energy source is needed to cover the demand. This source can be an electrical boiler, or a natural or biogas CHP engine, rendering the system a hybrid mCCHP system. On this occasion, an electric boiler is used to take advantage of the excessive electrical power production of the system and produce thermal energy. In this way, the mCCHP system minimizes the thermal energy deficit, which nonetheless still exists. Therefore, as the system cannot be deemed as a PV powered system, the aim of this simulation is to calculate the saving in primary energy consumption by utilizing the hybrid photovoltaic panels. Keeping all the aforementioned points in mind, the energy savings from the operation of a MCCHP system that is powered by Hybrid photovoltaic panels is 40% in Irakleio, 37% in Athens, 24% in Thessaloniki and 16% in Kastoria.

Concerning the electricity, the production of the system is sufficient to cover the electricity demand in all four cases. As it will be shown on the tables, there is excessive electrical power production in the majority of the months and a definite positive balance from the consumers' point of view. This is the reason why, the installation of electric boiler is advantageous compared to other means of thermal energy production.

5 Conclusion

CHP units as cogeneration units are widely used in the power production industry. Over the past decades heavy steam turbines and reciprocating engines are used worldwide to produce energy and at the same time take advantage of the thermal energy produced in the production units' boilers. This technology is the ancestor of the mCHP systems and the mCCHP systems, in case of space cooling inclusion in the system. These systems are the main component of micro grids, in other words group of buildings that share energy consumption and production.

Through the calculation of six different case studies, a deep insight of different mCCHP configurations is attempted. The group of buildings under review contains different building types, with diverse construction dates and different operational and occupational patterns. In this way, a representative selection of the Greek building stock which combines different thermal energy and electricity demand patterns in the same mCCHP system is achieved. Two single family house buildings (SFH1 and SFH2) along with a school unit and a multifamily house building (MFH) is the group of building that the author uses throughout all the cases. In this way, the author tries to achieve the clustering of demands and loads, which is crucial in order to get the maximum of a mCCHP system.

Another key issue, is the calculation of the space heating, DHW and electricity demands of the group of building. It is vital that this information is, to a possible extend, accurate and reliable. Based on this data and the next step of data processing, the designer would not only make a selection of the devices-components of the system but also design the optimal operational and control strategy. In this dissertation, the thermal and electricity load calculations are on the official Greek statistical agency and the SAM simulation program.

These cases apart from the difference in the location, meaning apart from the different weather condition and irradiance level, differ with each other in the PGU. Natural gas engines which are the current trend over the past years and alternative fuel powered PGUs along with renewable energy solutions are included. Biogas and natural gas engines are selected with the view to matching the thermal energy loads, while for the sizing of solar collectors and panels' installed capacity there is a restrictive construction parameter. As the solar collectors and panels are assumed to be installed on the rooftops of the buildings, their capacity is limited by construction restrictions. However, throughout all the simulations the rooftop array operational area remains the same, giving the opportunity to compare different scenarios under the same capacity.

Last but not least, apart from the PGU, numerous types of devices are used to cover specific needs of the mCCHP system. First of all, for space cooling, absorption chillers are installed. This type of cooling engines are preferred over desiccant cooling devices and electrical chillers. Absorption chillers fit in this type of system well as their usual inlet temperature falls within the range of hot water production of both fuel engines and solar thermal collectors. Electric boilers is used as an auxiliary device for the production of thermal energy in case that the PGU falls short to the thermal demand of the buildings. In the first four cases, as the biogas and natural gas engines are scheduled to follow the thermal demand, their function is limited to the unlikely event of extremely high loads or to maintenance shutdown of the engines. On the other hand, in cases of solar power mCCHP systems, the electric boiler can be an integral part of the everyday thermal energy production. Moreover, Organic Rankine engines are used to produce electricity from the solar energy in cases five and six. Thermal energy tanks are used in all cases for operational purpose, especially when it comes to the alternative energy source powered systems. Fossil fuel or biogas engines can follow continuously the thermal load while solar powered systems are heavily dependent on solar irradiation.

At the same time, electricity is constantly exchanged between the mCCHP system and the central electrical energy grid. The fact that the micro grid can exchange electricity with the central system is very advantageous compared to thermal energy as the central electrical power grid can be seen as a huge electricity storage, continuously available for the mCCHP system to absorb by or feed in electricity.

Concluding, some remarks are made:

-Cooling demand of Greek buildings is significantly lower than the heating demand, which is also the case for the group of buildings under review. Therefore, a mCCHP sized to meet the heating energy demand of a building or a group of buildings is oversized concerning its summer function. In this case, the selection of the school unit to the group of building aggravates this issue, as the school unit is assumed to be closed during summer time. Concluding, significant role to the system's design success is a seasonally well-balanced heating and cooling load. The same applies to the thermal and electrical energy balance. As the mCCHP system usually produces a surplus of electricity in order to meet its thermal energy demand, effective ways of taking advantage of the overproduction of electricity should be devised. One of those could be the charging and discharging of electrical powered vehicles. The intergradation of a system of charging and discharging electrical vehicles can result in multifaceted benefits for the mCCHP system. However, reviewing this subject is beyond the scope of this dissertation.

-The following diagrams are indicative of the importance for a system designer to select the appropriate PGU to fit in a mCCHP system. For example, as it can be noted from the following diagrams, the flat plate solar thermal collectors fail to meet the load demand for an extensive period, a significant part of the year percentagewise. This is highly expected since, in Kastoria the winter is harsh and solar irradiation during that time is scarce. In practice, and as the systems' thermal energy production is much lower than consumption from April till October, it is obvious that flat plate solar thermal collectors can only function as an auxiliary system combined with another heating energy source. This is not the case in Irakleio, where flat plate collectors can produce a major part of the thermal energy needed for an extended period of the year.

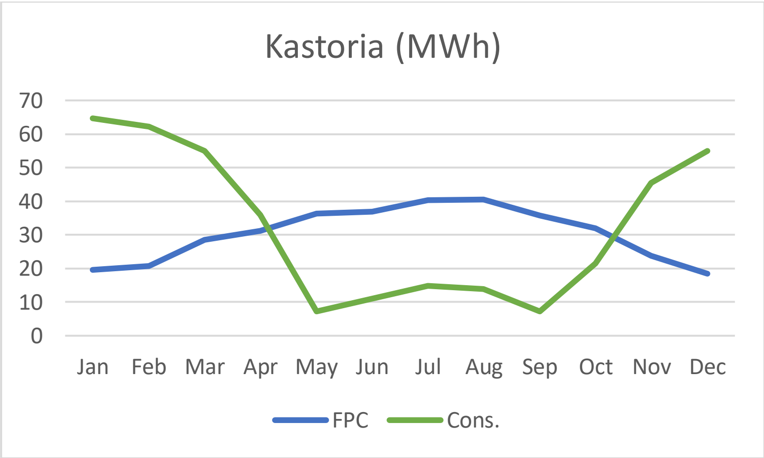

Figure 21: Flat Plate Collector Production, Kastoria

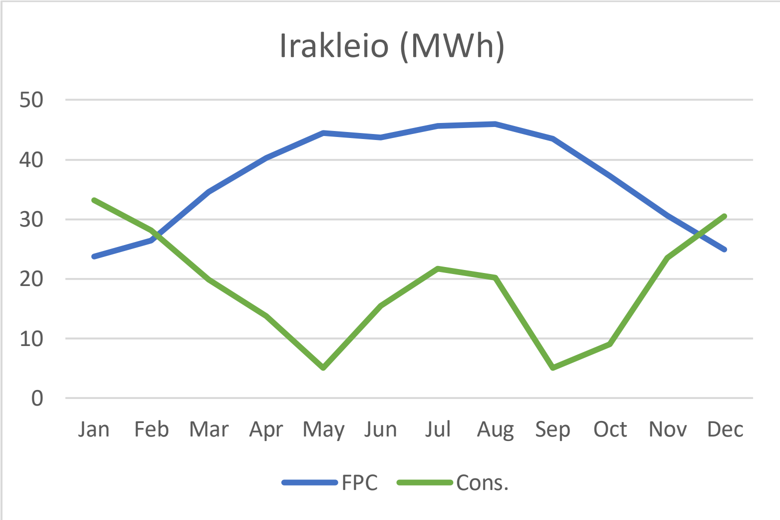

Figure 22: Flat Plate Collector Production, Irakleio

Athens and Thessaloniki lay between these two extreme conditions.

Concerning the concentrated solar thermal powered mCCHPs, the results are almost the same (six months of thermal energy deficit in Kastoria). Apart from opting for a hybrid PGU, a combination of solar thermal and an alternative fuel, for instance biogas is advisable. At the same time, it is advisable that the solar thermal arrays would have a 'winter' set up. In other words, the designer should focus on the winter thermal energy production, setting a steeper inclination that produces more thermal energy during winter. In this dissertation, this is not the case as the flat plate and the concentrated collectors are inclined in order to achieve a high energy production throughout the year. A mechanical driven, axial or bi-axial, solar array can be a solution to the productivity deficit, but results in higher installation costs and complexity of the system which can be in many cases deterrent factors. Concluding, and as far as this dissertation concerns, flat plate and concentrated solar thermal collectors are inadequate to cover the thermal demands for extended time throughout the year in Kastoria and Thessaloniki.

- Figure 23 shows the load curves of the biogas engines in Kastoria.

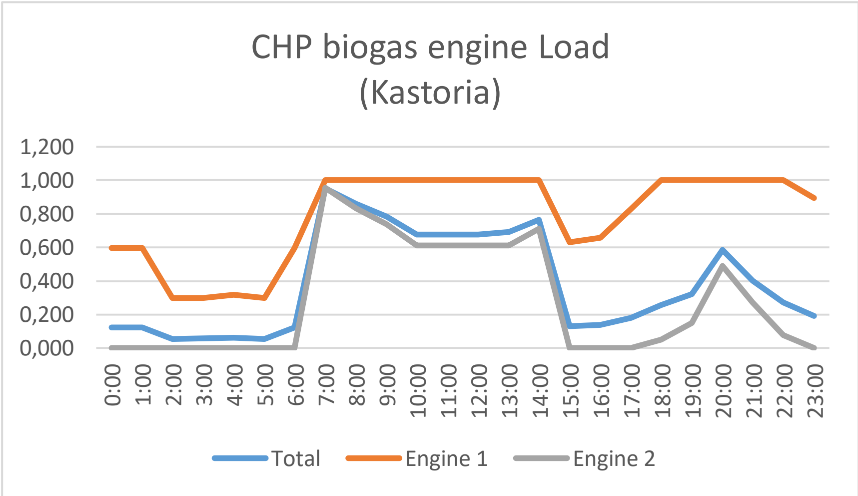

Figure 23: CHP load

This diagram is very useful, as it gives to the reader a full insight of the operational rates of these CHP engines. As it has already been said, the electrical production efficiency of this type of engines is connected to their operational load. Therefore, this diagram is a plausible indicator of how much the mCCHP system takes advantage of the electricity production potential. This is the reason, why the configuration of two engines of limited capacity was preferred to a single engine configuration. Last but not least, this diagram shows the exact time periods in which further thermal and electrical energy demands can be imposed to the system. In other words, in case of a system's extension and an induction of further loads, this diagram shows the part of the day, when this can be more efficient.

-Figure 24 shows the contribution of the ORC and the central electrical power grid to the total electrical energy load of the group of buildings in Athens. This diagram refers to case five, which is the mCCHP system with the concentrated solar thermal collector as PGU.

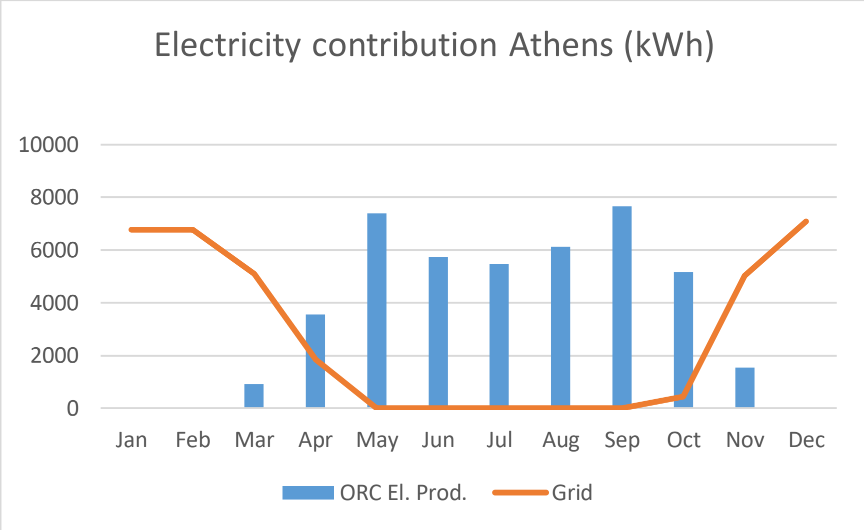

Figure 24: Electricity contribution, Athens

This diagram visualizes the reason why renewable energy sources cannot support a mCCHP stand-alone system in Greek climatic conditions yet. As one can notice, during the months of December, January and February, there is no electrical energy production, and therefore 100% of the systems need are covered by the centralized electrical power grid. In fact the thermal energy production of the solar thermal cells is not enough to cover even the thermal energy needs of the group of buildings, let alone feed the ORC in order to produce electricity.

In order to cover the demands, apart from the decline in thermal and electrical energy loads, this could be done, by oversizing the mCCHP systems and their PGU, ending up in extensive areas of solar harvest, which is not viable in urban environment. Moreover, higher efficiency solar panels and higher capacity thermal energy storage devices should be installed, with heavy impact on the cost management and the designing of the system. For now, solar thermal energy sources in Greece can be used in the context of a hybrid mCCHP system, resulting in energy saving as it is calculated in cases five and six and is shown in Figure 25. The review of a stand-alone and cost effective renewable energy power mCCHP system in Greece can be a subject for a future research.

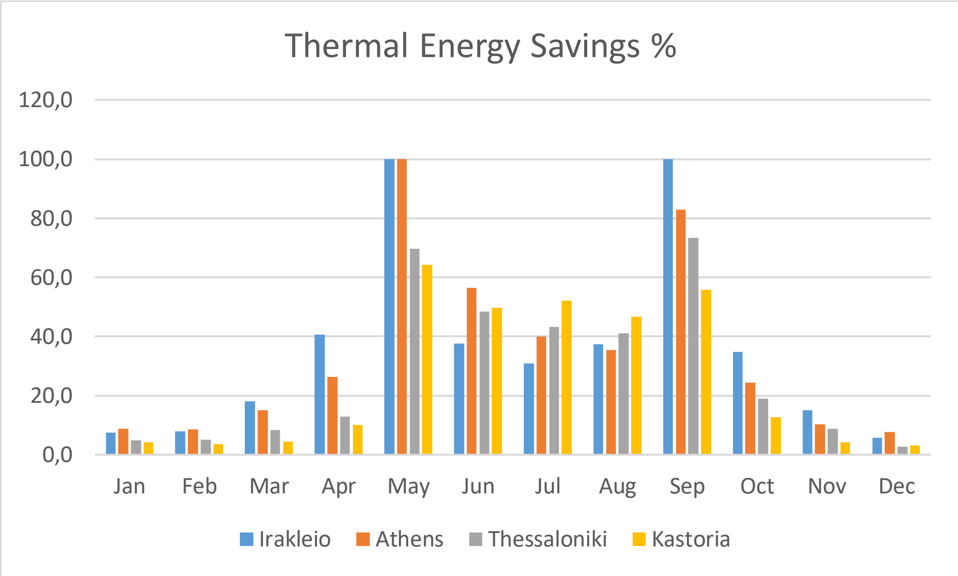

Figure 25: Hybrid photovoltaic solar thermal collectors' savings

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Appendix

Appendix B

In this section, the results of the simulation of the mCCHP system are presented. The simulation was executed individually for each group's building. System Advisory Model (SAM 2018.11.11 edition) was used. Along with the electricity production results, the global irradiance of the four location is presented.

1) Irakleio

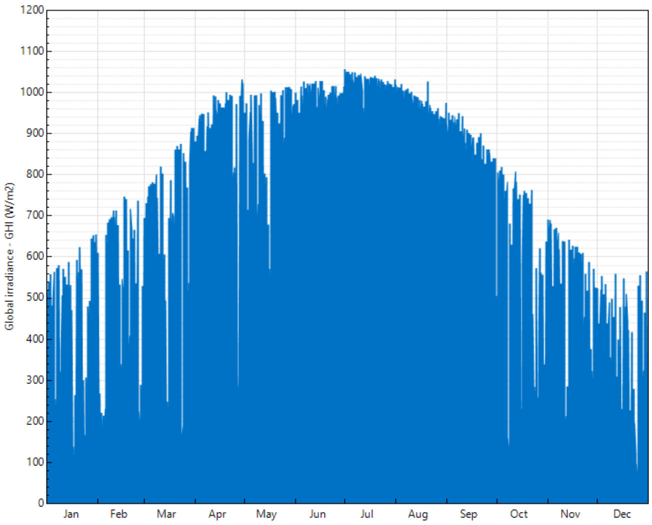

Figure 26: Global Irradiance (Irakleio)

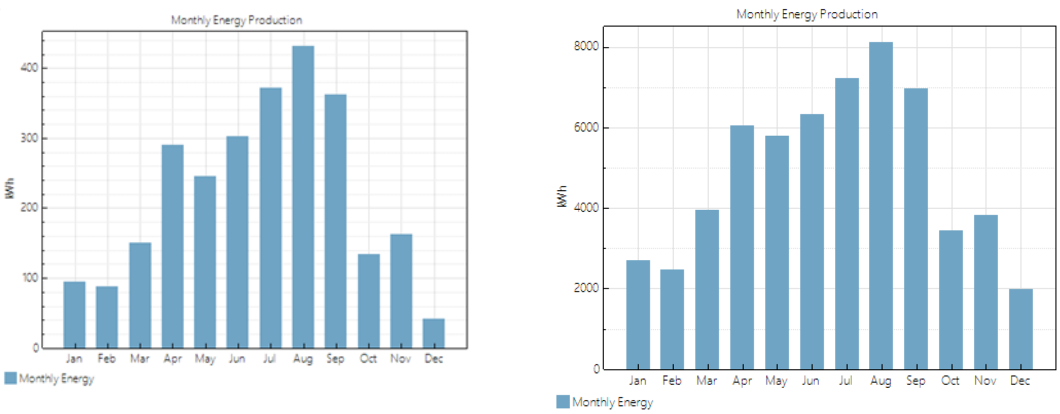

Figure 27: SF1 and School unit (Irakleio)

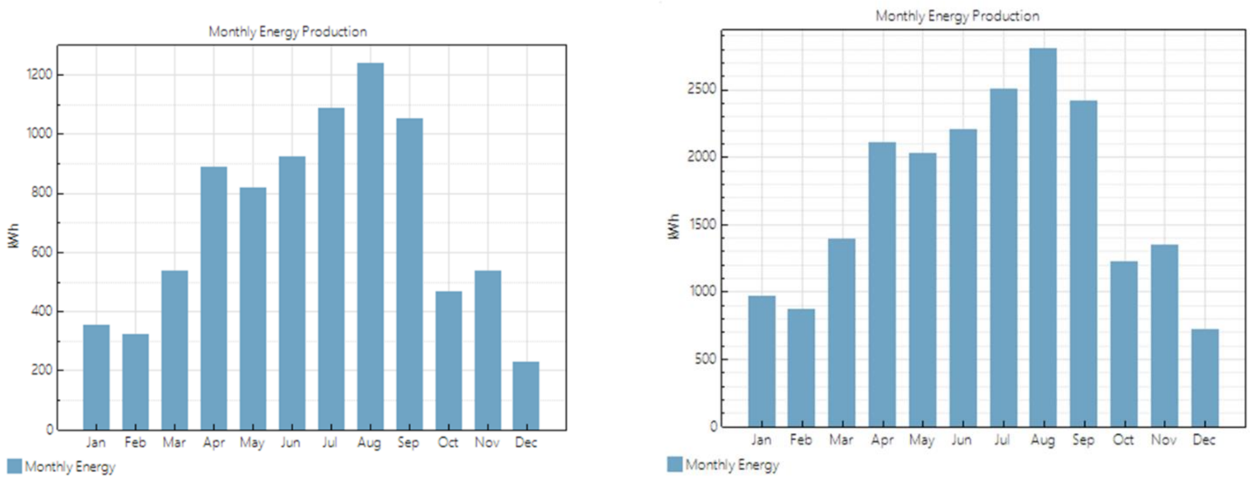

Figure 28: SFH2 and MFH (Irakleio)

2) Athens

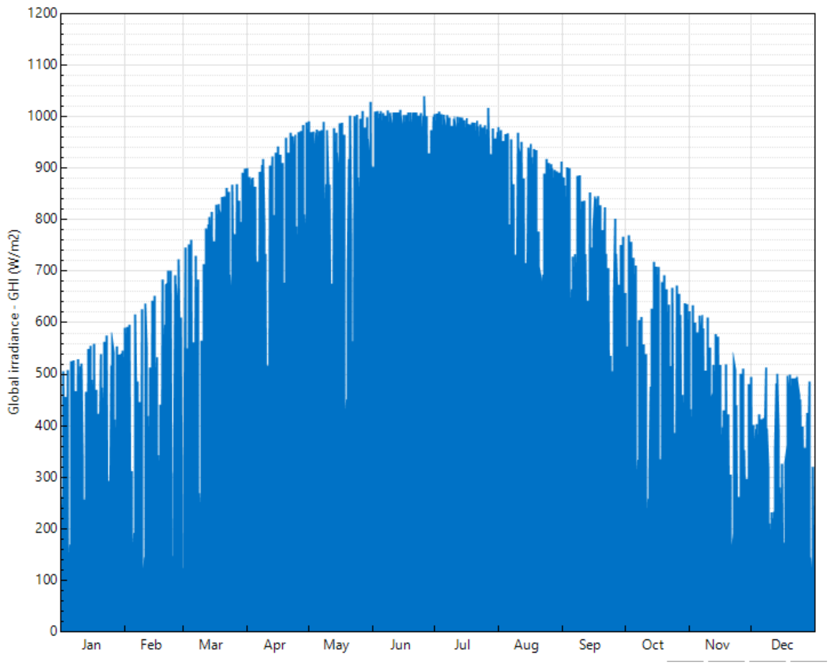

Figure 29: Global Irradiance (Athens)

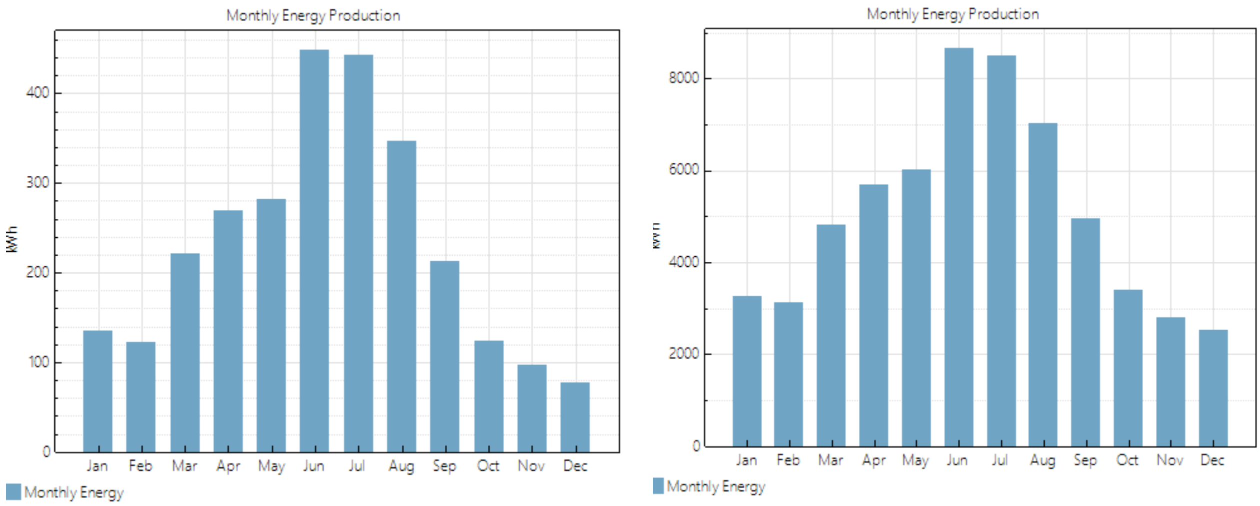

Figure 30: SF1 and School unit (Athens)

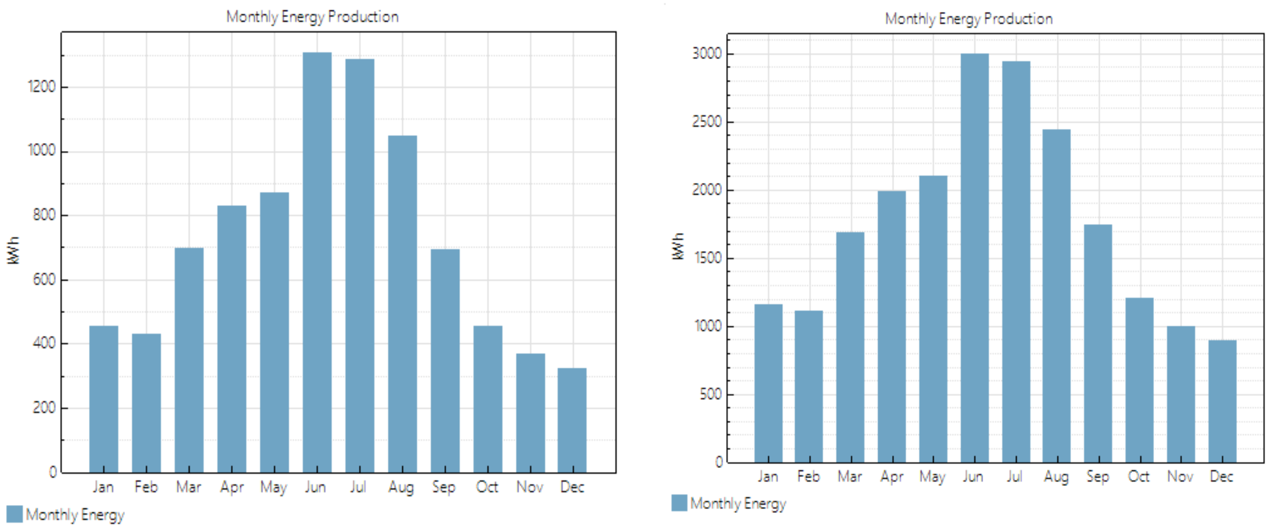

Figure 32: SFH2 and MFH (Athens)

3) Thessaloniki

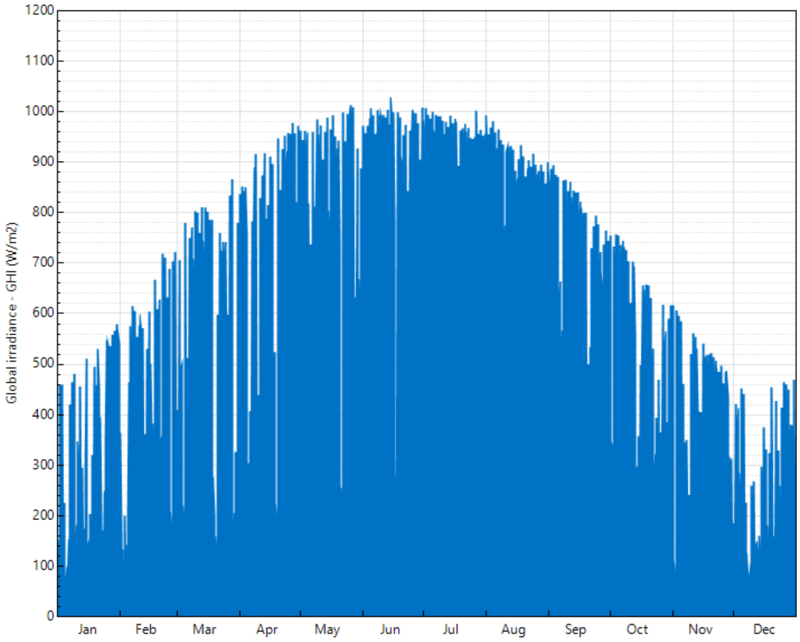

Figure 33: Global Irradiance (Thessaloniki)

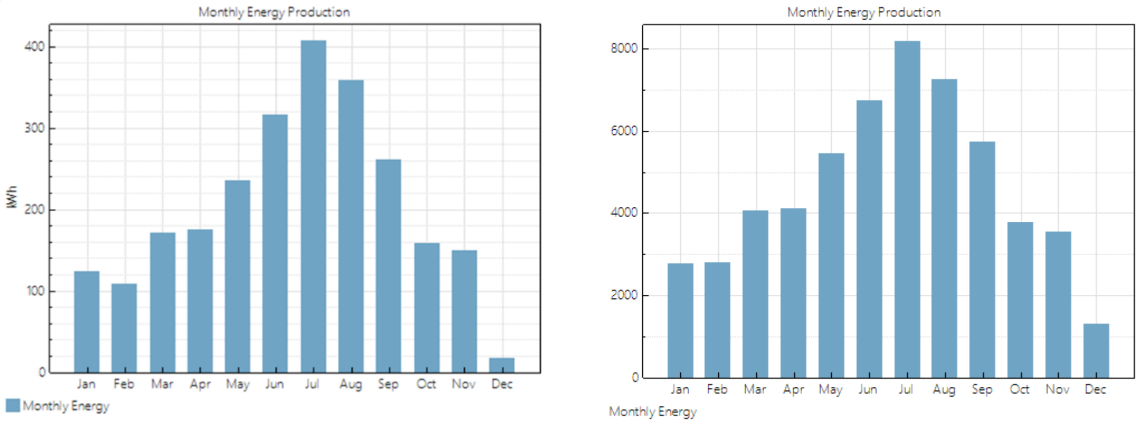

Figure 34: SF1 and School unit (Thessaloniki)

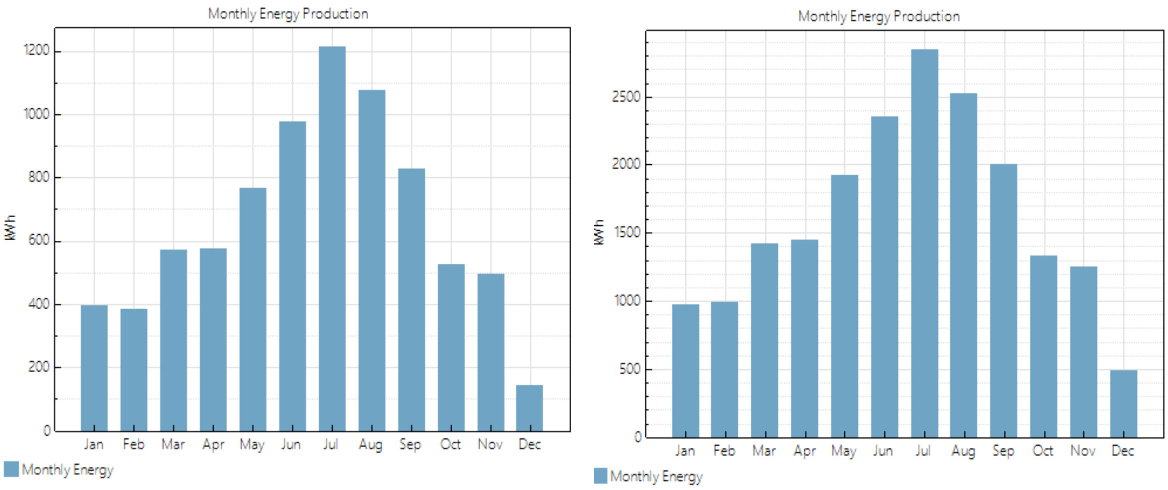

Figure 35: SFH2 and MFH (Thessaloniki)

4) Kastoria

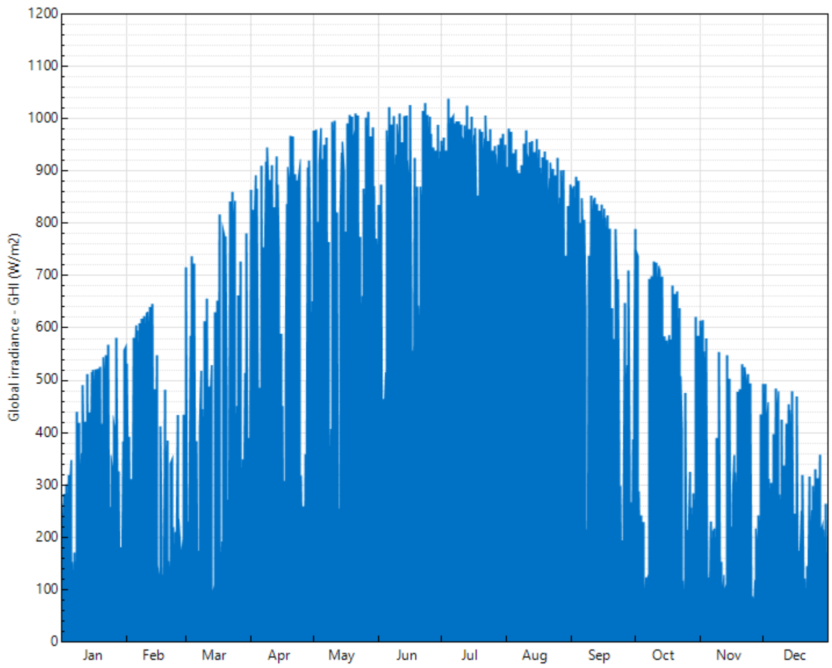

Figure 36 : Global Irradiance (Kastoria)

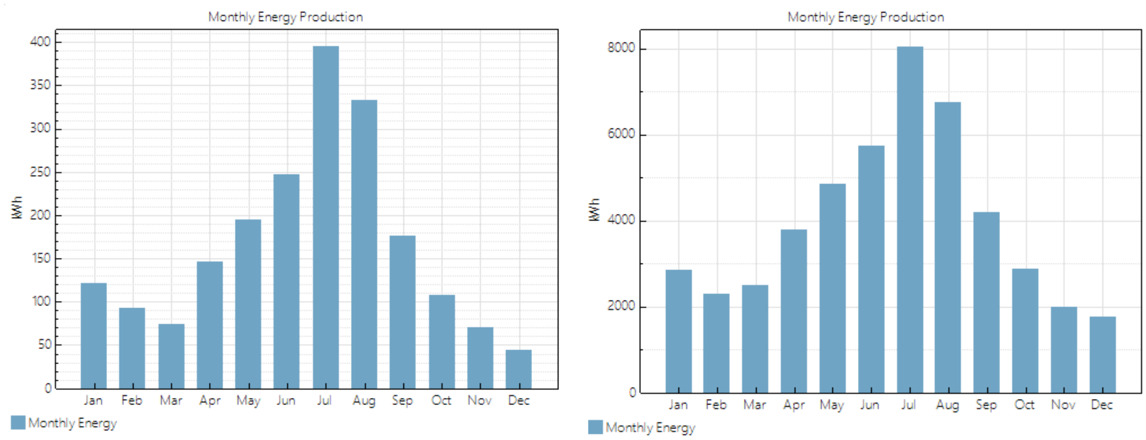

Figure 37: SF1 and School unit (Kastoria)

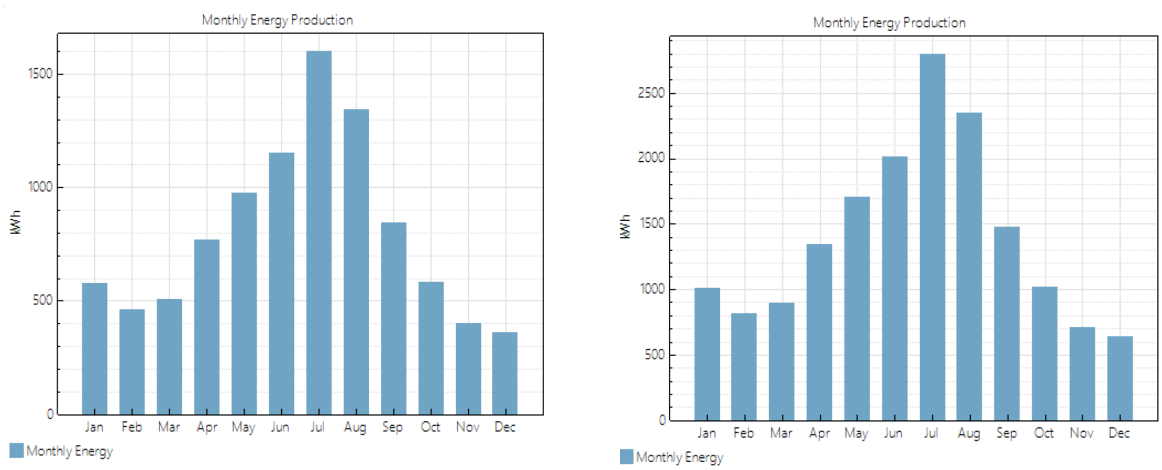

Figure 38: SFH2 and MFH (Kastoria)