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Optimization of a small-scale polygeneration system for a household in Turkey

Master's thesis, which has been submitted for verification of professional development for the degree of Master of Science.

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Abstract

With environmental concerns, alternative solutions for generating electricity while decreasing the consumption of fossil fuels have gained a great importance. Polygeneration is one of these solutions which is also capable to increase the technical performance of electricity generation. Polygeneration systems are available in large scale, medium scale and small scale. This study focuses on small scale polygeneration systems specifically for residential applications. Type and size of the components and the system's operational strategy plays a significant role in polygeneration system design as these factors affect the system cost and also environmental impacts. This study aims to propose a guide for component selection, sizing and addressing a suitable operational strategy for a predefined system configuration.

Decision making criteria is defined for component selection by a comprehensive literature review. Internal combustion engines, Stirling engines, micro gas turbines and fuel cells are investigated within these criteria. This provides the user an insight on component selection. When combined with factors such as market conditions, location and especially household demand profile, a selection can easily be made by the customer. For component sizing and operational strategy, a model has been implemented in Matlab. A baseline case model with a predefined system configuration and operational strategy was defined. The baseline case system includes a prime mover, a back-up auxiliary boiler, a vapor compression refrigeration chiller, a thermal energy storage and solar thermal collectors for the domestic hot water demand. The operational strategy is defined as thermal load following. For the case study, this model was altered for different cases with alterations on the operational strategy and the system configuration in order to identify the optimal solution for the user where the total annual cost is minimized while satisfying all kinds of end-use demands of a single-family household in Ankara, Turkey. The results also give insights on the effect of having solar thermal collectors and a thermal energy storage coupled with a CHP unit on the overall system.

Keywords Polygeneration, cogeneration, system configuration, component selection, component sizing, optimization, genetic algorithm

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Nomenclature

AHP	Analytical hierarchy process
C_{F}	Fuel cost
C_{GRID}	Cost of buying electricity from the grid
CC	Capital cost
CCHP	Combined cooling, heat and power
CHP	Combined heat and power
COP	Coefficient of performance
CO_2	Carbon dioxide
D_{E}	Electricity demand
D_{H}	Heating demand
D_{C}	Cooling demand
DHW	Domestic hot water
E_{GRID}	Electricity bought from grid
E_{VCR}	Electricity consumption of electrical chiller
f	Load factor
F_{BOILER}	Fuel consumption by the boiler
F_{PGU}	Fuel consumption by the PGU
FESR	Fuel energy saving ratio
GA	Genetic algorithm
GHG	Greenhouse gas
i	Interest rate
ICE	Internal combustion engine
IRR	Internal rate of return
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized cost of electricity
LOLH	Loss of load hours
LOLP	Loss of load probability
LP	Linear programming
LPG	Liquefied petroleum gas
LPSP	Loss of power supply probability
M_{BOILER}	Maintenance cost of boiler
M_{PGU}	Maintenance cost of PGU
M_{SOLAR}	Maintenance cost of solar thermal collectors
M_{VCR}	Maintenance cost of electric chiller
MC	Maintenance cost
MILP	Mixed integer linear programming
MWh	Megawatt-hour
ηpgu	Efficiency of primary generation unit
NO_x	Nitrogen oxides
NPV	Net present value
O & M	Operation and maintenance
OC	Operational cost

PE_{CHP}	Primary energy input to combined heat and power
PE_{SP}	Primary energy input to separate production
PEC	Primary energy cost
PEFC	Polymer electrolyte fuel cell
PEMFC	Proton exchange membrane fuel cell
PES	Primary energy savings
PGU	Primary generation unit
PSO	Particle swarm optimization
Q_{BOILER}	Heat generated by boiler
Q_{SOLAR}	Heat generated by solar thermal collectors
Q_{VCR}	Cooling generated by electric chiller
Qs	Amount of heat inside storage
Qs_in	Heat flowing in storage
Qs_out	Heat flowing out of storage
R	Capital recovery factor
REV_{SOLD}	Revenue gained by selling electricity to grid
RICE	Reciprocating internal combustion engine
SOFC	Solid oxide fuel cells
SPL	System performance level
t	Time
TAC	Total annual cost
TES	Thermal energy storage
TOPSIS	Technique for order of preference by similarity to ideal solution
VCR	Vapor compression refrigeration

1 Introduction

As the population, thus the energy demand is increasing, there is a need of finding alternative ways for energy supply considering the sensitive environmental situation that the world is in. Therefore, distributed energy supplies has been becoming a trend [1]. Distributed energy systems located close to local end-use customers [2]. The polygeneration concept combines several processes in a single system to be able to obtain other products besides power, such as space heating, cooling, domestic hot water and renewable energy sources like hydrogen. Cogeneration and trigeneration systems can be evaluated as polygeneration systems as in cogeneration, heat is produced besides power and in trigeneration systems cooling and heat are byproducts [3]. These systems are capable of reducing greenhouse gas (GHG) emissions as well as achieving higher efficiencies and higher reliability [1]. Combined cooling, heat and power (CCHP) systems are promoted due to issues regarding separate production. The efficiency of separate generation is low as the byproduct heat goes to waste. Therefore, approximately, only 30% of the fuel's available energy is converted into electricity [4]. Moreover, there are losses regarding the transmission and distribution of electricity through the grid. CCHP systems, on the other hand, are distributed systems so losses due to transmission and distribution are negligible and as the waste heat is utilized, they are capable of converting 75-80% of the fuel's energy into useful energy [4]. Polygeneration systems are available in different sizes and applications, e.g. large-scale, medium-scale and small-scale. Large scale systems are power plant applications, thus for meeting the energy demand in a region. Medium scale applications include polygeneration solutions for buildings such as offices and hospitals. Small scale systems are used in applications for residential buildings. These are systems with a capacity of less than 1 MW [5]. Residential energy consumption has a big share in the total energy consumption. Figure 1 shows this share as 31.5% for the year 2013. The figure also shows that the share of energy consumption by the industry has decreased whereas the consumption by the service sector and the residential sector has increased.

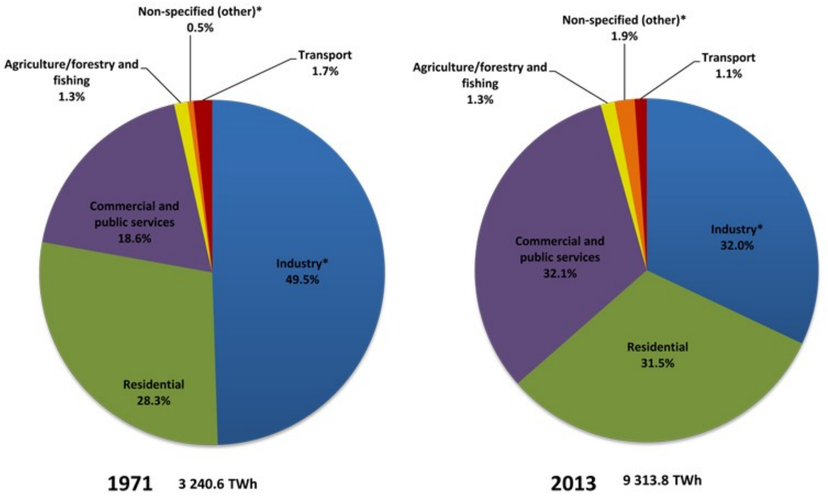


Figure 1: Shares of energy consumption by economic sectors [6]

This indicates that in order to make an impact on the energy mix, changing the energy profile of the service sector and the residential sector is quite significant for the transition to a cleaner and sustainable energy profile.

2 Objective and Scope

System configuration, operation strategy and sizing of the components within the system are significant factors for small scale polygeneration system design [7]. This thesis mainly focuses on providing an insight for identifying the best components for a small scale polygeneration system and determining the optimal sizes of the components for the given system. Different system configurations and operational strategies are also analyzed techno-economically.

This study investigates a small-scale trigeneration system, e.g. combined cooling, heat and power (CCHP) system, which is to be implemented to a single-family household. The system is integrated with thermal solar collectors which is to meet part of the heat demand. This case is altered for evaluation of different scenarios. The baseline system is composed of the following components:

- Primary generation unit (PGU) that consists of the prime mover and a generator
- Heat recovery system
- Vapor compression refrigeration (VCR), e.g. electrical chiller
- Thermal energy storage (TES)
- Auxiliary boiler

Figure 2 shows the system configuration.

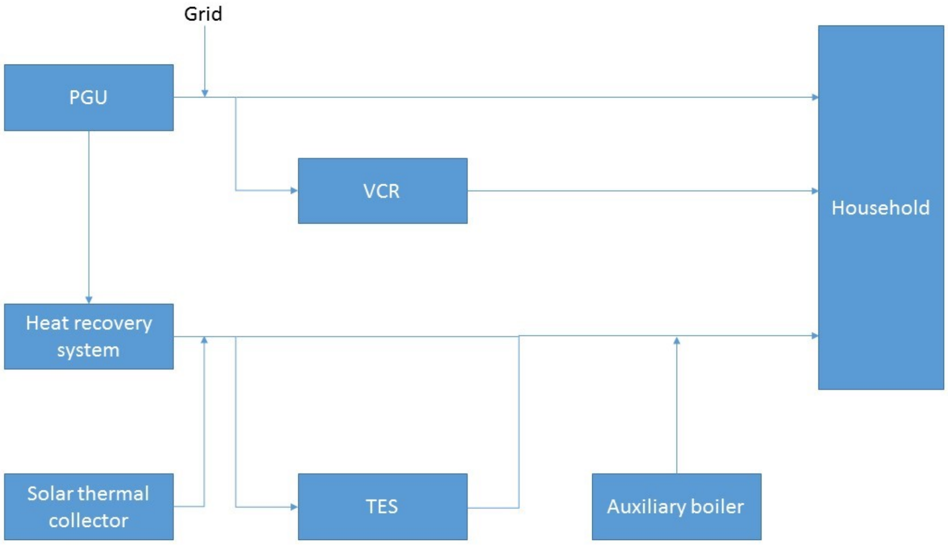


Figure 2: System configuration

The operation strategy of the baseline system is pre-determined. PGU is the primary energy provider for meeting the electricity, heating and cooling demands of the household. The system allows electricity being bought from the grid if there is a deficiency in electricity production or being sold to the grid when there is a surplus of electricity production by the PGU. The auxiliary boiler is operated when the PGU, solar thermal collectors and the amount of heat in the TES is not sufficient to meet the heat demand, i.e. when there is a deficiency in heating supply. A vapor compression chiller is operated for meeting the cooling demand. A storage is also placed in the system as the heat produced by the solar thermal collectors are fluctuating due to changes in solar irradiation and for possible excess heat supply from the PGU. In case the sum of the heat recovered from the PGU and the solar thermal collectors is more than the heat demand of the household, the surplus heat is storage in the TES. In case the thermal energy production is not sufficient to meet the demand, the stored heat is used if it is available.

The results of this study aim to present a comparison between different operational strategies and system configuration, and optimal sizes for such a system that is defined above, to be used with the minimum annual cost while satisfying the demand by a single-family household. Thus, the main objective is to provide a guidance to customer that are willing to invest in small-scale polygeneration systems.

3 Methodology

The methodology for this study consists of the following main steps:

- Literature review
- Decision making criteria for system configuration
- Mathematical model for energy balance and optimization process sizing the components
- Case study: Implementation of the system to a Turkish household
- Results and discussion

The literature review is a significant step in the methodology for getting an overview on current small scale polygeneration systems, identifying different prime mover types and their applications, gathering information on characteristics of prime movers and investigating different optimization techniques that are used for small scale polygeneration systems.

According to the knowledge gathered during the literature review, the decision making criteria for selecting the suitable prime mover for a CCHP system was determined. The criteria to be used were grouped in three main categories: technical, economic and environmental. The characteristics of prime movers were gathered in a table for comparison according to this decision making criteria. The Pugh Matrix was used to compare the prime movers among themselves and chart was generated for all the prime movers to get an overall idea of in which category they perform the best.

Existing optimization studies on determining the optimal CCHP system design were reviewed. The optimization model for this study was constructed based on existing studies, however aiming for improvements regarding the gaps identified in these models. The objective of the model was chosen as minimizing the annual total cost of the system since the application is small scale and minimizing the cost of a system is the priority for the customer side. For solving the optimization model, different techniques were investigated such as linear programming, mixed integer programming, particle swarm algorithm and genetic algorithm. As the operational strategy in this study was pre-determined, it was integrated in the optimization model which increased the complexity of the problem. Thus, linear programming and mixed integer linear programming were ruled out due to the challenge of defining the conditional constraints of the problem. Even though particle swarm algorithm is simpler, as MATLAB offers genetic algorithm in its “Optimization Toolbox”, the model was constituted on MATLAB and solved by genetic algorithm.

4 Decision making for system configuration

4.1 Prime mover selection

4.1.1 Decision making criteria

The main focus for the decision making process for the system configuration is selecting the prime mover as it is the key component in a CCHP system [3]. All kinds of energy demands, e.g. electricity, heating and cooling, are met by operating the prime mover, thus affecting the performance of the overall system [8]. After selecting the prime mover, different configurations of CCHP can be constructed [9]. However, in this study, the only component type to be selected is the prime mover as the other components are pre-determined.

The decision making criteria consists of three main categories: technical, economic and environmental. This structure is implemented from [10]. Table 1 shows the criteria that are considered for selecting the prime mover in this study.

Table 1: Decision making criteria for prime mover selection

Technical	**Economic**	**Environmental**
Electrical efficiency	Operation and maintenance costs	CO_2 emissions
Overall efficiency	Investment cost	NO_x emissions
Heat to power ratio	Fuel cost	
Start-up time	Electricity cost	
Noise	Service life	
Part-load performance	Carbon taxes	
Fuel flexibility		
Space occupied		

4.1.1.1 Technical

Technical criteria are defined by a comprehensive review regarding the characteristics of prime mover types. The parameters used for comparing the prime movers in [1]–[4], [11] were used as a baseline for choosing the technical criteria for this study.

The overall efficiency of a prime mover is defined by the sum of its electrical and thermal efficiency. Thus, only the electrical and overall efficiency of the prime mover were considered in the criteria. Waste heat produced as a byproduct of electricity generation by the prime mover was defined with the heat to power ratio [12]. For most of the prime movers, the electrical efficiency is correlated with the operating load [13]. For instance, the electrical efficiency of internal combustion engines is known to drop with part-load operation [14]. Hence, part-load performance is a decisive parameter for prime mover selection.

Even though there is not a formal definition for micro-scale polygeneration systems, most studies delineate these systems having a prime mover with a capacity of lower than 50 kW [15]. This restricts the prime mover selection; therefore, the capacity of available prime movers is also considered as a criterion. Moreover, the size of the prime mover influences the electrical efficiency. For internal combustion engines, electrical efficiency increases with increasing size [14].

Fuel flexibility is another decisive factor for prime mover selection. This factor is closely related to the location that the system is planned to be installed. The prime mover should be selected regarding available fuels in that region [1]. Therefore, it is favorable for a prime mover to be able to use different fuels, i.e. by having fuel flexibility.

Start-up time is another factor that influences the selection of the prime mover [1], [16]. If the system is stand-alone, the start-up time of the prime mover affects the power supply to the household as long start-up cycles may cause performance losses [17]. However, if there is access to the electricity grid, i.e. the system is not stand-alone, the start-up time is of less importance for the system as the CCHP system is not the main energy supply for the household [11].

Noise is also a factor that influences the decision making for prime mover selection. It is rather related to the convenience of using such a system inside the household which naturally affect the customer's decision [18]. This criterion is also related to where the system will be installed inside the household. A CCHP unit can be installed in several locations inside the residence such as the storage room, garage, kitchen etc. as it can be quite compact depending on the prime mover type such as gas engines [5]. This also brings out the criterion of space occupied by the CCHP unit. The company M-Trigen manufactures commercial micro trigeneration systems for household with a size of 1.52*0.76*1.77 meters [19] which can be fit in the locations that are previously mentioned. Having the unit in the kitchen, for instance, would indicate more significance given to the noise level for comfort.

4.1.1.2 Economic

Economy is one of the most decisive factors affecting the feasibility of a micro trigeneration system. The CCHP system needs to present an advantage economically for the customer compared to conventional systems [20]. The sub-criteria under economy are investment cost, maintenance cost, the cost of purchasing electricity from the grid, the income from selling excess electricity to the grid if possible, fuel cost and service life as stated in Table 1. By calculating the total cost of the system, i.e. the capital cost and the operating cost, and the revenue that can be obtained if excess electricity is allowed to be sold to the grid, some additional parameters can be defined such as internal rate of return and payback period. These parameters strongly assist the investor during decision making [21].

In order to assign numbers to the parameters stated above regarding a system, a comprehensive literature review is done to gain an insight on the policies regarding installing micro trigeneration or cogeneration systems in the location of the project. It is significant to find out whether there are economic incentives such as feed in-tariffs for CCHP systems [22]. Moreover, one has to ascertain whether it is allowed for a customer to sell the excess electricity from the CCHP unit back to grid and at what price it can be sold as this decreases the annual total cost and the payback period. Carbon taxes are also defined by the policies and is relevant to both the economic and environmental criteria for selecting a prime mover as it contributes to the annual total cost of operating a CCHP unit [22].

Electricity and fuel prices are highly crucial parameters for investing in a CCHP system as they are pertinent to the operating cost of the system [22], [23]. The fuel cost forms a significant portion of the operating cost of the system. If the fuel cost is relatively higher than the electricity cost, this would indicate that installing a CCHP system would rather be an economic burden for the customer when it is possible to buy electricity from the grid for a cheaper price [23]. Therefore, evaluating available fuels in the area where the CCHP unit will be installed and determining their prices is significant for the prime mover selection.

The service life of the system is decisive for the annual cost, internal rate of return and the payback period of the system as time has a crucial role on an investment [24].

4.1.1.3 Environmental

One of the main reasons of preferring polygeneration systems is to decrease the emissions caused by energy production [1], [3], [16], [25]. As polygeneration systems utilize the waste heat that occurs during electricity production for getting different forms of end-use energy such as heating and cooling, they have less full consumption compared to separate generation [4]. This also indicates that a reduction in emissions is achieved as less fuel is burned. Moreover, the amount of electricity bought from the grid is reduced with the production from the CCHP unit, which also contributes to emission reduction [1]. Therefore, the environmental criteria for selecting a prime mover for the system are GHG emissions, e.g. CO_2, NO_x and SO_x [17]. This criteria are defined by the amount of emissions emitted in kilograms for every MWh of electricity that is produced.

Another motivation for evaluating prime mover candidates environmentally for micro-cogeneration or trigeneration systems is to reduce the risk of such systems leading to local air pollution. The fact that some prime movers emit more GHG gasses when operating in part load should be valued during environmental analysis [21].

4.1.1.4 Decision making technique

The general steps for multi criteria decision making processes are stated as follows:

- Preliminary evaluation of candidates depending on the criteria and eliminating the unacceptable candidates
- Examining the candidates that has passed the preliminary evaluation
- Ranking the acceptable candidates

Multi criteria decision making is a research topic itself and several advanced methods have been developed for this purpose such as fuzzy “Technique for Order of Preference by Similarity to Ideal Solution” (TOPSIS) and “Analytical Hierarchy Process” (AHP) which are aimed for larger scaled problems [26], [27]. Even though these methods are suitable for prime mover selection for polygeneration systems, as this study’s main focus is finding the optimal system configuration and component sizes for a pre-defined operational strategy, a simpler method, namely the weighted sum method, was implemented in this study for making a comparison of different prime movers and selecting the most suitable one for a given project as defined in Chapter 2.

The flow chart of the prime mover selection process that is implemented in this study is presented below in Figure 3.

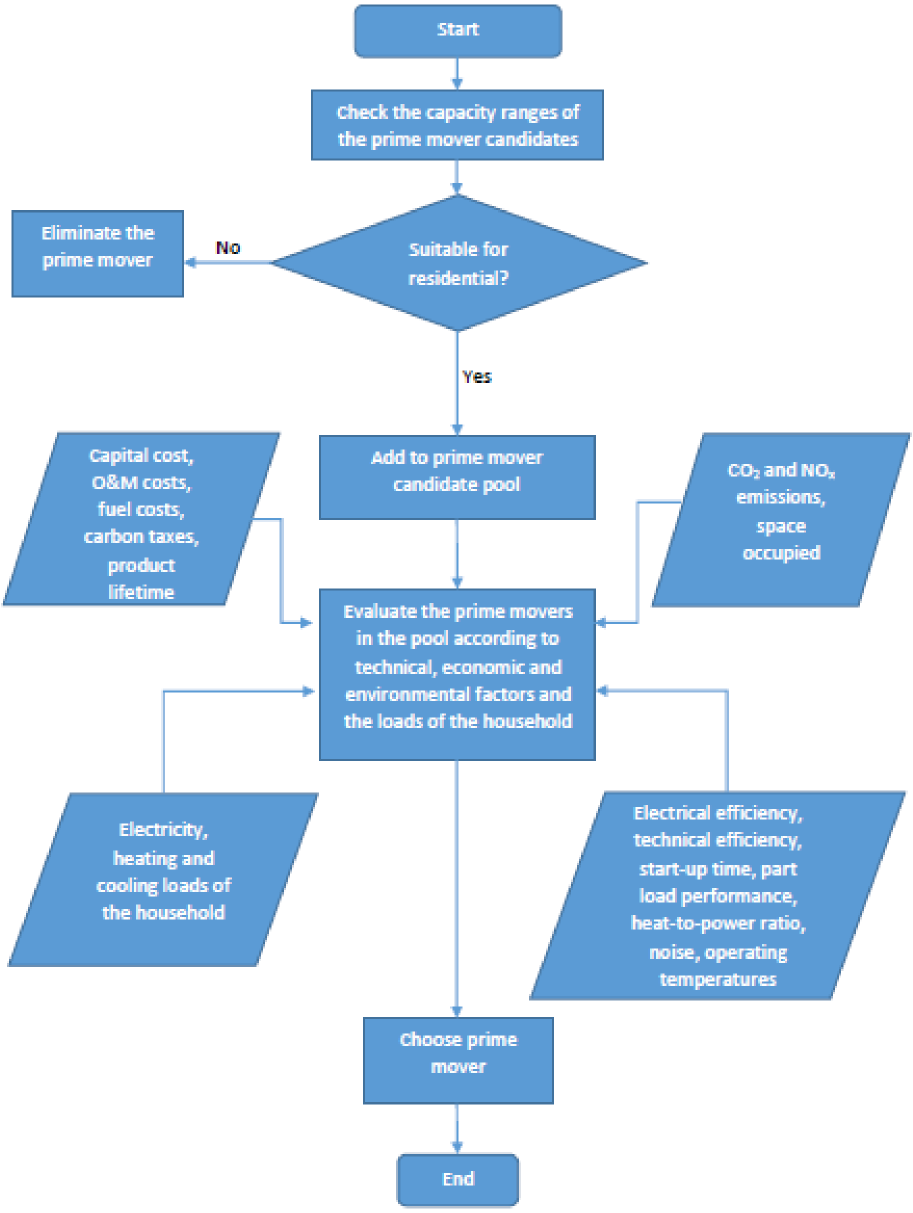


Figure 3: Flow chart of the prime mover selection process

The selection process starts with the elimination of prime mover types that are not suitable for residential applications. If the prime mover type is available in a size range that is suitable for bigger scale applications, it is not included in the candidate pool. For every prime mover type in the candidate pool, technical, economic and environmental data is gathered. The criteria that are defined in the previous chapter were used for forming the data that is collected in a structuralized way for ease of future analysis for the decision making process. Table 2 presents the general characteristics of each prime movers for every criterion. The prime mover types that were considered in the beginning of the selection process were, reciprocating internal combustion engines, gas turbines, steam turbines, microturbines, fuel cells and Stirling engines. Gas turbines and steam turbines were eliminated in the first step as they are available in sizes that are more than 50 kW which makes them unsuitable for residential applications. Therefore, the candidate pool was narrowed down to internal combustion engines (ICE), Stirling engines, fuel cells and microturbines.

Table 2: General prime mover characteristics

	ICE	**Stirling engine**	**Fuel cell**	**Micro turbine**
Technical				
Electrical efficiency	22-40 [11]	35 [11]	30-50 [11]	18-27 [11]
Overall efficiency	77-78 [5]	60-80 [5]	55-80 [5]	63-70 [28]
Heat to power ratio	0.5-1 [5]	0.15-0.4 [5]	1-2 [5]	0.4-0.7 [11]
Part-load performance	Moderate [11]	Good [11]	Good [11]	Moderate [28]
Fuel flexibility	Good [16]	Good [16]	Good [16]	Very good [16]
Capacity range (kW)	1-75000 [11]	1-55 [11]	5-2000 [11]	30-250 [11]
Noise	High [11]	Moderate [11]	Low [11]	Moderate [11]
Start-up time	10 s [11]	15 min [11]	3 h [11]	60 s [11]
Economical				
O & M costs ($/kWh)	0.014 [28]	0.013 [14]	0.035 [28]	0.018 [28]
Investment cost (CHP) ($/kW)	1650 [11]	1300 [11]	5750 [11]	2700 [11]
Service life	20 [11]	20 [5]	10 [11]	10 [11]
Market penetration	97 [28]	87 [11]	95 [28]	98 [28]
Environmental				
CO2 emissions (kg/MWh)	650 [5]	672 [5]	460 [5]	725 [11]
NOx emissions (kg/MWh)	10 [5]	0.23 [5]	0.075 [5]	0.18 [11]

It is significant to emphasize that this table is not a tool by itself for the decision making, it is rather for providing an overview of the prime mover characteristics and ranking the prime movers among themselves depending on each criteria. For ranking, the Pugh Matrix is used. Pugh Matrix is used for comparing a number of design candidates according to determined criteria [29]. It is a simple yet effective approach for choosing the best design candidate. A reference candidate is selected among the candidates. The reference candidate gets neutral points, “S”, for the criteria that the concepts are being evaluated by. The rest of the candidates are compared to the reference by means of the determined criteria and get a “S” if they are the same with the baseline candidate, get a “+” if they are better or get a “-” if they are worse. “++” indicates that the candidate is significantly better than the reference, whereas “--” indicates that the candidate is considerably worse [30]. When evaluating the candidates, namely internal combustion engines, Stirling engines, fuel cells and micro turbines, both the general characteristics and products for each candidate that are already in the market are considered. These products and their scores are shown in Table 3.

Table 3: Pugh matrix of design candidates

	ICE (baseline)	**Stirling engine**	**Fuel cell**	**Micro turbine**
	Vaillant Ecopower [31]	**Senertec Dachs Stirling** [32]	**Hexis Galileo 1000N** [33]	**MTT EnerTwin** [34]
Technical				
Electrical efficiency	S	-	+	-
Overall efficiency	S	S	+	+
Heat to power ratio	S	++	-	+
Part-load performance	S	+	+	S
Fuel flexibility	S	S	S	-
Noise	S	-	+	S
Bottom area	S	--	+	-
Start-up time	S	-	--	-
Score	0	-2	2	-2
Economical				
O & M costs	S	--	--	-
Investment cost	S	-	--	-
Service life	S	S	-	-
Market penetration	S	-	-	S
Score	0	-4	-6	-3
Environmental				
CO2 emissions	S	S	+	-
NOx emissions	S	+	+	++
Environmental score	0	1	2	1
Sum of + s	0	4	7	4
Sum of - s	0	9	9	8
Total score	0	-5	-2	-4

	ICE	**Stirling engine**	**Fuel cell**	**Micro turbine**
Technical	23	22	24	18
Electrical efficiency	2	3	4	1
Overall efficiency	4	3	2	1
Heat to power ratio	3	1	4	2
Part-load performance	2	3	3	2
Fuel flexibility	3	3	3	4
Capacity range*	4	4	3	2

Noise	1	3	4	3
Start-up time	4	2	1	3
Economical	12	12	6	10
O & M costs	3	4	1	2
Investment cost	3	4	1	2
Service life	3	3	2	2
Market penetration	3	1	2	4
Environmental	4	4	8	4
CO2 emissions	3	2	4	1
NOx emissions	1	2	4	3

According to these scores, the overview of performances of each prime mover candidate by means of each sub-criteria is determined and presented in Figure 4 below.

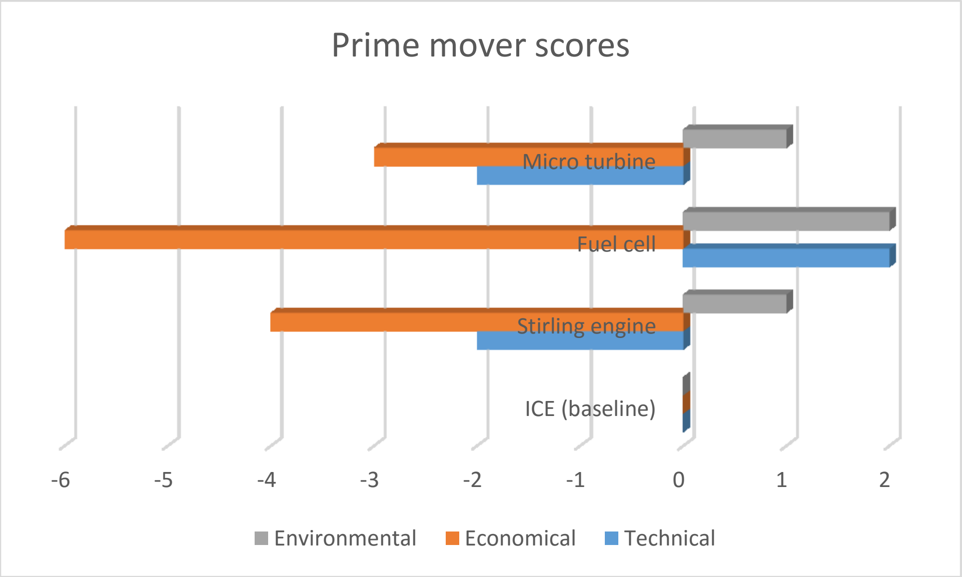


Figure 4: Performances of prime movers by means of technical, economic and environmental criteria

As it can be seen in the chart, technically the best performance is achieved by fuel cells owing to their good overall efficiencies. Economically, internal combustion engines would be the best choice due to their low investment, operation and maintenance costs and market penetration. Environmentally, fuel cells would be the clear choice according to the chart due to their low emission values. This gives a general opinion to the customer on the potential preference reasons of each prime mover and it should not be the only tool for selecting the prime mover of a polygeneration system.

As shown in the flow chart, apart from the criteria that is presented in Table 1, the location of the household where the polygeneration system will be installed is an additional determinant for prime mover selection. Several factors are closely related with the location such as the demand profile of the household and the policies that are in application regarding polygeneration systems. The load profile of a household determines the application of a trigeneration system. The decisive criteria for prime mover selection for this case would be the heat to power ratio. The heating and cooling demands of the household are used for determining the heat to power ratio of the prime mover [11]. If the heating and/or cooling demand of a household is relatively high, selecting a prime mover with a higher heat to power ratio would be favorable in order to reduce the total annual cost of the system by eliminating the need of operating an auxiliary boiler or an electrical chiller as much as possible. These load profiles also effect the overall efficiency of the system [4]. Policies play a role in selection of both the prime mover and the operational strategy. There might be incentives for investing in polygeneration systems. Moreover, the policies define whether excess electricity that is produced by the system can be sold to the grid or not. This would affect the annual total cost of the system which is one of the economic criteria.

4.2 Components apart from the prime mover

After making the decision on the prime mover, one should decide on the other components of the system such as the cooling device to be used. Thermally activated cooling devices has been a trend for polygeneration systems as they are capable to utilize heat in order to produce cooling energy [5]. Nevertheless, many examples of polygeneration systems also involve conventional vapor compression chillers, e.g. electric chillers mainly due to their good coefficient of performance (COP) and lower cost [35]. The criteria to be considered when choosing the cooling device for a polygeneration system can be investigated in two main categories: technical and economic. These criteria are stated in Table 4 below.

Table 4: Criteria for cooling device selection

Technical	**Economic**
Heat to power ratio of the prime mover	Capital cost
Coefficient of performance	Operation and maintenance cost
Operating temperatures	
Equipment size	

Besides the listed criteria, the features and the location of the household should not be disregarded. The cooling load of the household is of great importance for selecting the cooling device and it depends on the outdoor temperature, the size of the household, which direction the walls and windows are facing [36]. The flow chart for choosing the cooling device is presented in Figure 5.

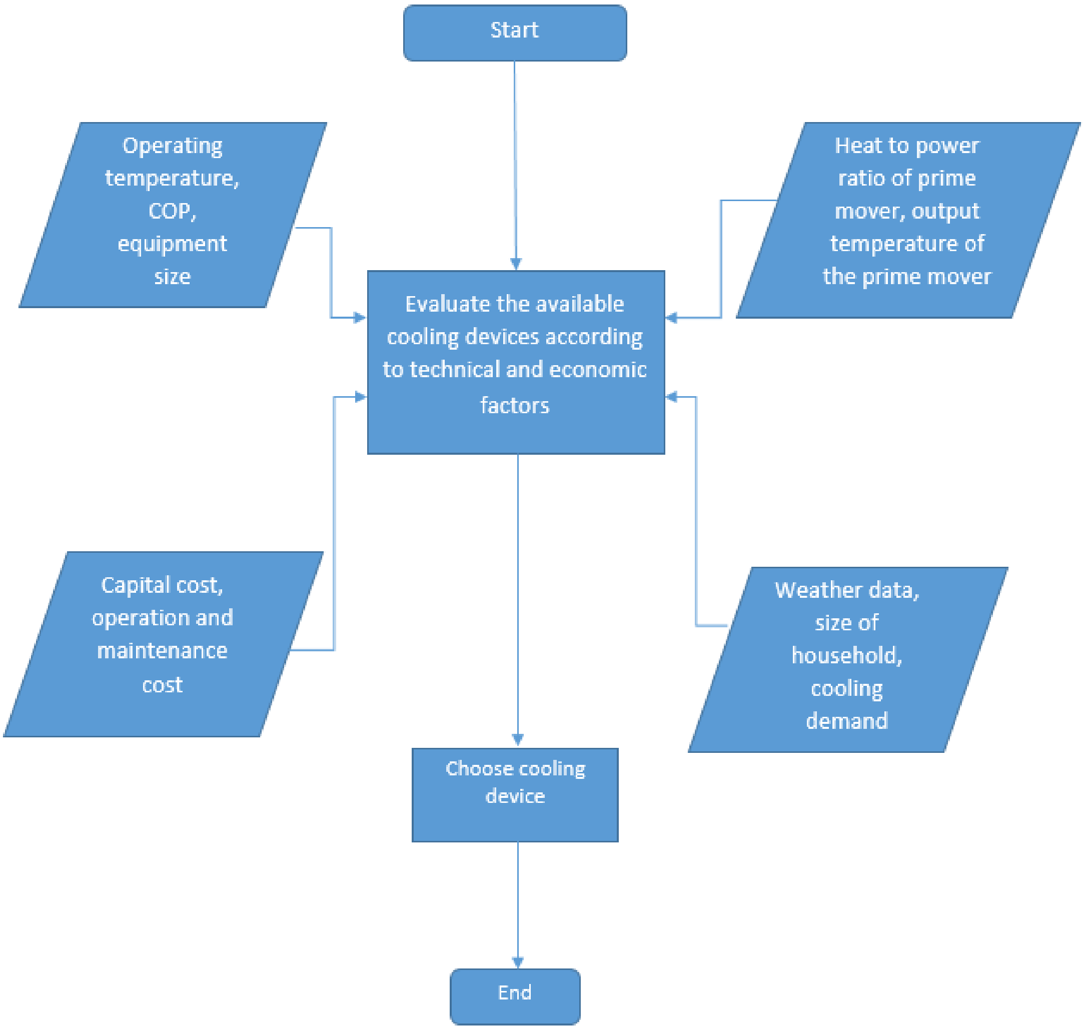


Figure 5: Flow chart for selecting the cooling device

As shown in the flow chart, the selection of the cooling device also depends on the selected prime mover. The temperature of the waste heat the prime mover produces should be a decisive when choosing the cooling device as different devices have different input temperatures [37]. Thus, the cooling devices and the prime mover should be compatible with each other. Heat to power ratio of the prime mover is another parameter that concerns the cooling device to be used in the system [21]. For instance, if the heat to power ratio of the selected prime mover is low, the amount of waste heat to drive a thermally activated cooling device as well as supplying heat to the household is lower. This would require more additional supply to meet the cooling and heating demand and cooling supplied by the thermally activated cooling device may be very low compared to the additional cooling device, e.g. electric chiller as thermally activated chillers have lower coefficient of performance [38]. In this case, having a thermally activated device may be economically infeasible.

4.3 Overview of polygeneration systems

4.3.1 Prime movers

4.3.1.1 Micro-turbines

Micro turbines are small scale gas turbines. Their operation principle is based on combustion. The mixture of compressed air and fuel is ignited in a combustion engine which drives a turbine [14]. Currently, micro turbines are commercially available in sizes for more than 25-30 kW, however there is ongoing research for microturbines with sizes smaller than 25 kW [16].

Micro turbines' most recognized advantages are compact size, low weight, low noise, fast response and less maintenance requirement. These advantages are mostly related with having less number of moving parts [1]. Another advantage of microturbines is their low NO_x emissions. This is achieved by low inlet temperature and high fuel to air ratios [1]. Fuel flexibility is also a benefit of microturbines. There are microturbines that are commercially available which use natural gas, propane, biogas, LPG, diesel and kerosene as fuels. However, it is significant to state that the fuel affects the performance of the micro turbine by means of the electrical and the total efficiency [14].

The major disadvantages of microturbines are their high capital costs compared to internal combustion engines and low electrical efficiency. However, for residential applications, low electrical efficiency is not a crucial detriment due to lower load profile compared to medium and large scale applications [1]. Thus, despite the high capital costs, microturbines are good candidates for residential applications.

4.3.1.2 Stirling engines

Stirling engines are external combustion engines which relates to some advantages of them. They have more efficient combustion processes than internal combustion engines and good fuel flexibility [14]. The combustion process that is outside the chamber enables the usage of solid fuels such as wood [37]. They can be also integrated with renewable energy sources such as solar power [3]. Moreover, as the combustion process is continuous and controlled, the emissions emitted by generation is lower, contributing to less pollution [1]. Stirling engines are claimed to be one of the most promising prime movers for small scale applications due to their high overall efficiency, fuel flexibility and reliability [39]. Moreover, they have low noise and good part load performance which makes them better candidates for small scale CCHP applications. Besides, their integration in combined cooling, heating and power is practical since there already exists Stirling engine based combined heat and power (CHP) units in the market [40]. Micro CHP Stirling systems are available in sizes lower than 10 kW [17]. Figure 6 shows two of these commercially available micro CHP Stirling systems.

Figure 6: Stirling engine based micro CHP systems available in the market [37]

Both of these units also include a boiler for meeting the peak demands [37]. As it can be seen in the figure, both units are quite compact and easy to be integrated inside a household which makes them attractive for residential applications.

Even though Stirling engines are able to provide good overall efficiencies, for small scale applications, their electrical efficiencies are low compared to internal combustion engines, e.g. 10-15%. Moreover, the fact that they are still in the research and development phase and there are a low number of products available in the market, Stirling engines have the disadvantage of having high capital costs [5].

4.3.1.3 Reciprocating internal combustion engines

Reciprocating internal combustion engines (RICE) are heat engines that provide rotary motion by converting pressure by one or more pistons. There are two main kinds of reciprocating internal combustion engines: spark-ignition and combustion-ignition. The combustion is set off by a spark that is provided by an igniter in spark-ignition engines whereas the combustion is auto-ignited by high pressure in combustion-ignition engines [1]. Combustion-ignition engines are also known as diesel engines. They use diesel fuel, heavy oil or, if operated in dual mode, natural gas and diesel fuel. These type of RICE are generally used for large-scale applications, however it is possible to use them for small scale applications too. Spark-ignition engines are proposed as better candidates for small scale applications due to better heat recovery, e.g. hot water production of up to 160°C. They mostly use natural gas for small scale applications, however propane, landfill gas and gasoline can also be fed to these engines [14]. The sizes of reciprocating internal combustion engines vary between a few kW and 75 MW [11].

RICE engines are the most mature technology in CCHP applications [17]. Even though, they are mostly used for large and medium scale CCHP applications such as in office building or hospitals nowadays [41], there are existing examples of residential use. Moreover, there are CHP generation units based on internal combustion engines in the market due to their relatively high electrical efficiencies and fuel flexibility [17]. These units are attractive for small scale applications as they occupy small installation space and they have acceptable noise levels compared to bigger scale internal combustion engines. Furthermore, they have a short start-up time and satisfactory part load performance that makes them a flexible choice residential applications [2]. Apart from the technical aspect, RICE engine based CHP units are also favorable by means of economic factors as they have low maintenance and installation costs [21]. Even though, the costs are low, regular maintenance is required for RIC engines due to the high number of moving parts [1].

4.3.1.4 Fuel cells

Fuel cells use an electrochemical process to produce electricity, i.e. a reaction of hydrogen with oxygen having the by-product of water [41]. The components of a typical fuel cell are the fuel cell stack with cathode, anode and electrolyte and a fuel reformer, and a power converter for transforming DC electricity to AC. Depending on the application, different types of fuel cells can be used, e.g. solid oxide fuel cells (SOFC), polymer electrolyte fuel cells (PEFC) and proton exchange membrane fuel cells (PEMFC). The most striking feature of PEFC is its small size and low cost compared to other fuel cell types. However, PEFCs have lower electrical efficiencies. SOFCs are identified with their high operating temperatures that can reach up to 1000 °C. For micro CHP applications, they can be fed with natural gas which eliminates to problem of challenging access to pure hydrogen and provide an electrical efficiency up to 55%. PEMFCs, on the other hand, operate at low temperatures, at about 80 °C [17], and enable flexibility in operation, i.e. quickly adapt to shifts in power load [5]. Moreover, they have excellent part load management [14].

One of the distinguishing features of fuel cells in general is that they have less moving parts compared to internal combustion engines and turbines which reduces the need of frequent maintenance and increases the reliability. Another reason for preferring fuel cells would be the fact that they are environmental friendly as they only produce water as the by-product during the process of generating electricity [1]. It is significant to note that even though the electricity generating process itself is emission-free, the fuel reforming process cause some emissions, e.g. reforming natural gas for obtaining the hydrogen needed to be fed to the fuel cell. However, it is possible to use wind or photovoltaic-powered electrolysis which would make fuel cell systems renewable and carbon free [42]. Low noise is also another advantage of fuel cells along with compact size which makes them convenient for residential applications [2]. Nonetheless, fuel cells also have some disadvantages. The most salient drawback is their complex design and high investment costs. Moreover, very few CHP units with fuel cells are available in the market as work on fuel cells is still in the research and development phase [5].

4.3.2 Cooling systems

For cooling purposes, several kinds of cooling devices are available to be integrated in a polygeneration system. These devices can be evaluated in two categories: thermally activated cooling and traditional vapor compression cooling. Absorption chillers, adsorption chillers and desiccant dehumidifiers are under the category of thermally activated devices as they are driven with the waste heat from the prime mover. Vapor compression chillers, i.e. electrical chillers, are classified under traditional cooling devices and may be used in addition to thermally activated devices in polygeneration applications [5]. Thermally activated devices are considered to be increasing the efficiency of CCHP applications as they utilize the waste heat that is rejected from the prime mover and decreasing the usage of vapor compression chillers as they require electricity which contributes to GHG emissions [1].

4.3.2.1 Absorption chillers

Absorption chillers compress the refrigerant vapor by using heat instead of rotating motion. Thus, they can utilize hot water, steam or hot pressure exhaust gas. There are existing examples of absorption chillers coupled with SOFC, micro turbines, gas turbines and combustion engines [1].

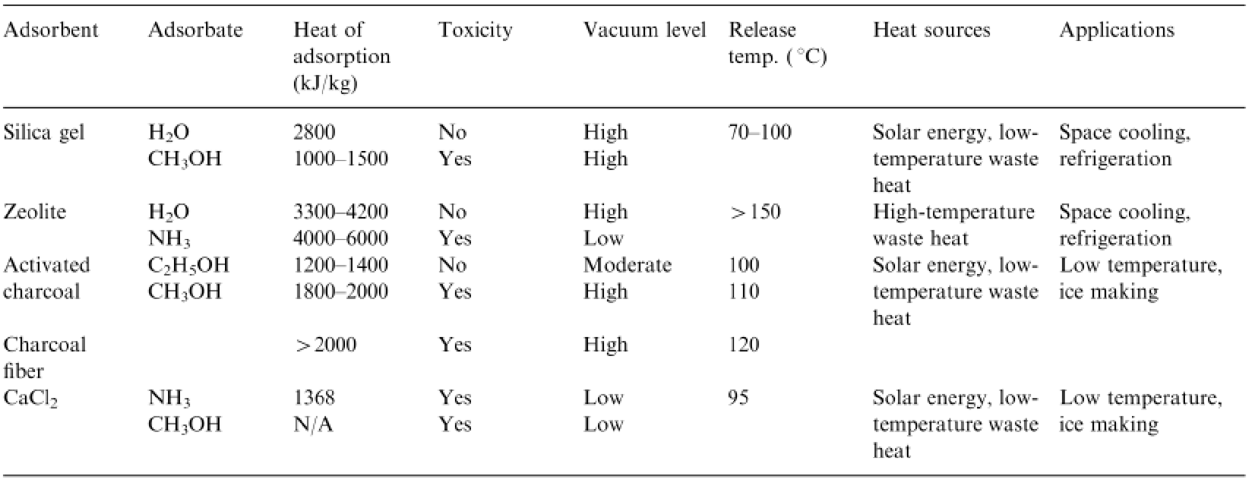
Absorption chillers have four main components: an absorber, a generator, a condenser and an evaporator. An absorbent and a refrigerator form a working fluid which is passing over the components of the device. The most preferred working pairs are lithium bromide-water and water-ammonia [5]. The choice of the working fluid pair depends on the evaporation temperatures required by an application. Lithium bromide-water is mainly used for air cooling applications where the evaporation temperatures vary between 5-10 °C whereas the water-ammonia pair is preferred in application with evaporation temperatures lower than 0 °C which are typically small size air conditioning and large size industrial applications [43]. Moreover, the working fluid selection has influence on the overall system performance since it affects the energy utilization factor [3].

The advantages of absorption chillers compared to traditional vapor compression chillers include no emissions since they do no need electricity for their operation and less noise and vibration as they have few moving parts. However, they have lower coefficient of performance and higher costs compared to electrical chillers [16].

4.3.2.2 Adsorption chillers

A typical adsorption cycle has one or more adsorber beds, a condenser and an evaporator [5]. The adsorber beds enable the adsorption and desorption of a refrigerant. The cycle starts with the adsorber bed being connected to the condenser. The refrigerant is condensed in the condenser with the low temperature heat source. As a result of this process, heat is released. Following this process, the adsorber bed is disconnected from the condenser and connected to the evaporator. Cooling is obtained by evaporation and adsorption [1]. Likewise, absorption chillers, adsorption chillers are characterized by the working pairs. A working pair consists of an adsorbent and an adsorbate. Commonly used pairs are silica gel with water and methanol, zeolite with water and ammonia, activated charcoal with methanol and ethanol, and charcoal fiber with ammonia and methanol. These working pairs define the heat of adsorption which identifies the heat sources that can be used to drive the chiller and thus the applications they are suitable for [2]. The characteristics of different working pairs are presented in Table 5.

Table 5: Adsorption chiller working pairs [2]



Adsorbent	Adsorbate	Heat of adsorption (kJ/kg)	Toxicity	Vacuum level	Release temp. (°C)	Heat sources	Applications
Silica gel	H_2O	2800	No	High	70–100	Solar energy, low-temperature waste heat	Space cooling, refrigeration
	CH_3OH	1000–1500	Yes	High			
Zeolite	H_2O	3300–4200	No	High	> 150	High-temperature waste heat	Space cooling, refrigeration
	NH_3	4000–6000	Yes	Low			
Activated charcoal	C_2H_5OH	1200–1400	No	Moderate	100	Solar energy, low-temperature waste heat	Low temperature, ice making
	CH_3OH	1800–2000	Yes	High	110		
Charcoal fiber		> 2000	Yes	High	120		
$CaCl_2$	NH_3	1368	Yes	Low	95	Solar energy, low-temperature waste heat	Low temperature, ice making
	CH_3OH	N/A	Yes	Low			

The most significant benefit of adsorption chillers is their ability to utilize low grade heat which also distinguishes them from absorption chillers. On the other hand, they have some similarities with absorption chillers such as the fact that adsorption chillers also require less maintenance as the only moving part within the system is valves. Thus, adsorption chillers are considered to be simple [2]. Other advantages include noiseless operation, small occupied space, operation without corrosion and crystallization and no requirement for a solution pump. These advantages favor the usage of these devices for small scale CCHP applications. However, there are also some disadvantages associated with adsorption chillers. They are known to be a novel technology and they still need development. This effects the market penetration. They are mostly available on the American and Chinese markets and they have high capital costs, i.e. around 600 € per kW. Apart from the economic drawbacks, there are also some technical drawbacks. The coefficient of performance of these devices vary between 0.3 and 0.5 which is lower compared to other heat-driven cooling technologies. [37].

4.3.2.3 Desiccant dehumidifiers

Desiccant dehumidification is a technology that has been recently adapted to polygeneration applications [3]. One of the most important motivations behind this would be that desiccant dehumidifiers consume less than a quarter of the energy that conventional vapor compression refrigeration devices use [44]. Moreover, waste heat is efficiently utilized during the regeneration process of the desiccant material [1]. They are mainly for providing a better air quality and increasing comfort in a household by retaining the moisture in the air. The desiccant material is the key to this process. According to the desiccant component, desiccant dehumidification is evaluated in two main groups: solid desiccant dehumidification and liquid desiccant dehumidification [2]. In solid desiccant dehumidification, there is either a slowly rotating wheel or an adsorbent bed that is periodically regenerated. As the air flow goes through the wheel, the latent load is adsorbed by the desiccant material. Commonly used solid desiccant materials are lithium chloride, silica gels, zeolites or molecular sieves and aluminum oxides. Different types of solid desiccant materials enable different capacities of moisture content that can be captured. In liquid dehumidification, instead of a rotating wheel, a concentrated liquid desiccant solution is used to remove the moisture content of the air flow that is to be processed [43]. The selection of whether to use solid or liquid desiccant dehumidification depends on the desired application. Solid desiccant dehumidification is generally used for commercial HVAC applications whereas liquid desiccant dehumidification is preferred in industrial and residential applications [1]. It is also significant to consider the advantages and disadvantages of both types of desiccant dehumidification separately. One of the obstacles of using solid desiccant dehumidification for residential applications is the large size of the equipment. Moreover, even though they provide good air quality, they are not as effective in cooling as conventional vapor compression refrigeration. As it comes to economy, their higher investment costs are dissuasive. Like solid desiccant dehumidification, liquid desiccant dehumidification also requires a high investment costs. Additionally, there is the risk of corrosion caused by inorganic salts. [43]. However, compared to solid desiccant dehumidification, they require lower temperatures for regeneration and provide higher utilization flexibility and mobility [3].

4.3.2.4 Vapor compression chillers

Apart from thermally driven cooling devices, conventional vapor compression refrigeration devices such as electric chillers are still utilized in polygeneration systems. Even though the purpose for using thermally activated cooling devices is to decrease the electricity consumption of the system by eliminating the need of electric chillers, there are polygeneration systems that include both thermally activated cooling devices and electric chillers in addition [1]. Electric chillers are still preferred due to their maturity and reliability. Despite these advantages, meeting the cooling demand only with an electric vapor compression chiller that is powered by the prime mover might not be convenient in small scale polygeneration applications as small size prime movers have lower electrical efficiencies. Therefore, the usage of electric vapor compression chillers are only recommended when they are added in the system in addition to a thermally activated cooling device to improve the reliability and the economics of the CCHP system [2].

4.3.3 Storages

4.3.3.1 Thermal storages

Thermal storages are used when there is a surplus in the heating supply in polygeneration systems. The preference to include a thermal storage within the system depends on the determined operational strategy. For instance, if the system is electricity load following, i.e. the priority is to meet the electricity demand, using a thermal storage is favorable as the system produces more thermal energy than the demand or wastes it [38]. Storing the surplus heat and using it when required can increase the thermal efficiency of the system [45]. Moreover, the required chiller size, thus the cost of the system, can be reduced by including a thermal storage within the system [11]. Thermal storages can divided into three main groups: sensible heat, latent heat and thermochemical [46]. Table 6 shows some examples of thermal storage systems under these main categories.

Table 6: Thermal storage examples

Sensible heat	Latent heat	Thermochemical
Underground thermal energy storage	Ice storage	Chemical reactions
Pit storage	Phase change material storage	
Molten salts		
Solid media storage		
Hot and cold water storage		

4.3.3.2 Electricity storages

In a polygeneration system, while the surplus heat can be stored in thermal storages, it is possible to store the surplus electricity inside electrical storages device such as batteries or capacitors [14]. Electrical storages are devices that enhance the efficiency of polygeneration systems along with proper sizing of the equipment and suitable operation strategy [41]. Electrical storages can be grouped in several categories: mechanical, electrochemical, chemical and electrical [46]. Some examples for these categories are presented in Table 7.

Table 7: Electricity storage examples

Mechanical	Electrical	Electrochemical	Chemical
Pumped hydropower	Super capacitors	Lithium based batteries	Electricity to hydrogen
Flywheels	Superconducting magnetic energy storage	Sodium-sulphur batteries	
Compressed air storage		Lead-acid batteries	

Mechanical storages convert electricity to mechanical or potential energy to store it and they are the most mature way of storing electricity nowadays. 99% of the installed energy storage capacity is pumped hydropower which utilizes potential energy [46]. Electrical storages, on the other hand, are based on static electric or magnetic fields. Research is still going on, thus the cost of these storage is high. Electrochemical storage is another kind of storage that is based on the flow of electrons which is caused by chemical reactions of two or more electrochemical cells [46]. They are generally used in smaller applications due to their limited capacities Lead-acid batteries are electrochemical storages that are known to commonly used in back up power applications which include off-grid systems [47].

5 Optimization

5.1 Model

An energy system needs to be both cost-effective and reliable by effectively using local sources in order to be sustainable [48]. Therefore, the model used in this study analyzes the proposed system by means of technical and economic aspects. The purpose of the model is to optimize the sizes of the equipment with an economic objective with respect to technical constraints.

Techno-economic criteria used in optimizing the size of a CHP system is explained in detail below.

5.1.1 Technical criteria

Technical criteria is significant for the system design as it is associated with the reliability of the system. There are several indicators listed used for this purpose when sizing energy systems. Loss of power supply probability (LPSP) is one of the most preferred. It is defined as the ratio of the sum of deficits for every hour to the load demand [49]. LPSP is formulated as follows:

$$LPSP = \sum_{t=1}^{T} Deficit(t) / \sum_{t=1}^{T} Demand(t) * \Delta t \tag{1}$$

LPSP is chosen as the technical criteria for the model in this study. Some other technical criteria exist to ensure reliability such as loss of load probability (LOLP), system performance level (SPL) and loss of load hours (LOLH). LOLP measures the probability of the system demand exceeding the supply. SPL defines the probability that the load cannot be satisfied [50].

Measuring the energy performance of a cogeneration system can be also put under technical criteria. Some parameters used for energy analysis of such systems are primary energy consumption (PEC), primary energy savings (PES) and fuel energy saving ratio (FESR) [35]. The approach recommended in IEA Annex 54 is calculating the fuel energy saving ratio by means of primary energy saving [37]. It is formulated as follows:

$$FESR = \frac{PE_{SP} - PE_{CHP}}{PE_{SP}} \tag{2}$$

PE_{SP} is the primary energy input for separate production, i.e. conventional system and PE_{CHP} is the primary energy input to the cogeneration system. A conventional system consisting of a boiler for heating, electrical chiller for cooling and electricity supply from the power grid is suggested for the energy analysis by IEA [15].

5.1.2 Economic criteria

Several economic criteria are being used in polygeneration optimization problems. Net present value and total annual cost are frequently used economic criteria. The net present value (NPV) approach covers the whole lifetime of the period. The cost and emissions of the system throughout its lifetime need to be considered due to the changes of monetary value in time. When calculating the net present value, the discounted values of capital, operation and maintenance costs should be considered [51]. The annual total cost includes annualized capital, replacement, operation and maintenance costs [49]. Operation costs in a CCHP system includes the fuel costs [38]. By using annualized cost, levelized cost of electricity (LCOE) can also be calculated, which is another economic criteria for energy systems. It is defined as the ratio of the annualized cost of the system to the annual electricity produced by the system [50].

When optimizing component sizes for energy systems, many studies feature an economic objective besides thermodynamic and energy consumption based objectives [20]. For models regarding large-scale systems and long-term planning, maximizing the profit is generally the object [52]. In these cases, the highest NPV that can be achieved within the constraints of the model gives the optimum capacities for the equipment. To find the most profitable design, NPV is maximized whereas for the total annual cost approach, the objective is to minimize the annual cost [13]. While the economic criteria is preferred more commonly, determining the objective of an optimization model is a significant step as finding a compromise between the economic criteria and the design based criteria, which involves technical and environmental factors, is challenging [20].

Internal rate of return (IRR) and payback period are other economic criteria that are used when constructing optimization models for sizing CCHP systems. These parameters are decisive for an investment as they are affected by the initial investment cost of the system [53].

In this model, the main economic criteria is chosen as the annual total cost as the model is for a residential system, which is considered to be small-size. Therefore, minimizing the annual total cost of the system would be of more relevance for a customer who is considering to invest in a CCHP system. Thus the objective of the model is minimizing total annual cost of the system.

5.2 Mathematical formulation

The period of the model is determined to be one year and it uses hourly time steps. A representative day is chosen for every month, thus the number of time steps is a total of 288, i.e. a 24-hour day per month for 12 months. This approach is adopted from [54] and is for easing the input data gathering process and simplifying the optimization model.

There are 5 decision variables in the model which are listed below.

- x(1): Size of PGU
- x(2): Size of auxiliary boiler
- x(3): Size of electrical chiller
- x(4): Size of storage
- x(5): Number of solar thermal modules

The stated variables are optimized according to an objective which in this model defined as to minimize the total annualized cost as stated in Section 5.1.2. Determining the objective of a model is quite critical. One should decide from what perspectives they want to analyze their system, e.g. design oriented, profit oriented or social benefit oriented [20]. In this study, the main aim is to analyze the system economically. Nevertheless, the system is compared to a reference system and analyzed also environmentally and by means of energy. Thus, the objective of the optimization is economic since the purpose of sizing the components within the system is to lower the investment as much as possible [50]. When mathematically formulating the total annualized cost, three subcomponents were used, namely capital cost, operation cost, i.e. fuel cost, and maintenance cost. The annualized cost calculation is implemented from [55] where an efficient algorithm was proposed to solve an optimization model for sizing a CCHP system with the objective of minimizing the total annualized cost. The objective function is formulated in the equations below.

$$TAC = CC + OC + MC \tag{3}$$

TAC represents the total annualized cost which is the sum of CC, the capital cost, OC operational cost and MC, maintenance cost.

$$CC = R * [x(1) * C_{pgu} + x(2) * C_{boiler} + x(3) * C_{vcr} + x(4) * C_{storage} + x(5) * C_{solar}] \tag{4}$$

R is called the capital recovery factor and defined as follows where “i” represents interest rate and “l” represents equipment life [24].

$$R = \frac{i * (1 + i)^l}{(1 + i)^l - 1} \tag{5}$$

Total operational cost consists of fuel costs of the PGU and the boiler and the cost of buying electricity from the grid in case there is deficit in energy supply by the CHP. The revenue gained from selling excess electricity to the grid is subtracted from this sum.

$$OC = C_F * (F_{PGU} + F_{boiler}) + E_{grid} * C_{grid} - Rev_{sold} \tag{6}$$

Total maintenance cost is calculated by multiplying the production by the equipment with the specific maintenance costs determined by the equipment during the literature survey. The maintenance cost of the storage is neglected.

$$MC = M_{PGU} * E_{PGU} + M_{boiler} * Q_{boiler} + M_{solar} * Q_{solar} + M_{vcr} * Q_{vcr} \tag{7}$$

The objective function, i.e. the annualized cost, is minimized in this optimization problem within some constraints. The technical criteria, thus LPSP in this study, is the constraint of the optimization problem. LPSP should be zero, which indicates that all kinds of end-use demands, i.e. electricity, heating and cooling, should be satisfied.

As explained in Chapter 2, the operational strategy of the system is defined within the model. There are several commonly used operational strategies for cogeneration and trigeneration systems. These are heat demand following operation, electricity demand following application, continuous operation, peak shaving and base load operation [38]. Heat demand following and electricity demand following operations are conventional for CCHP systems [4]. As indicated by their names, in heat demand following strategy, the priority for the system is meeting the heat demand, whereas in electricity demand following operation, the priority is meeting the electricity demand. If the system is grid connected, when the system operates with the purpose of covering the heat demand first, the excess in electricity supply is compensated with electricity bought from the grid and the excess is sold to the grid [38]. For off-grid systems, excess electricity can be stored in a electrical storage such as a battery [50]. During electricity demand following operation, excess in heat supply can either be wasted or stored in a thermal storage and deficit can be compensated by an auxiliary boiler [38]. In continuous operation, meeting the energy demand is not the aim and the system operates for a predefined time. This strategy is chosen for engines that are not allowed to operate on partial load. In base load operation, the system only covers a certain amount of the load which is constant. In peak shaving operation, the system operates during the peak times to reduce the energy being bought form the grid. From these five strategies, the most commonly used conventional ones are electricity demand following and heat demand following operations [1].

In this model, the operational strategy is determined to be thermal demand following due to demand profiles of a single-family household. Thus, the capacity of the PGU is adjusted according to the electricity load of the household. The model prioritizes the operation of the PGU, i.e. electricity is only bought from the grid if there is a deficit in electricity supply. If there is an excess, it can be sold to the grid. The electricity balance is given below.

$$E_{PGU} + E_{grid} = E_{sold} + E_{VCR} + D_E \tag{8}$$

The PGU is able to operate at part load in the model. This affects the efficiency of the system. A decrease in the load factor also causes a decrease in the efficiency. Some studies assume this relationship is linear, however this relationship is presented better with the following equation [23].

$$\eta_{pgu} = a + b * f + c * f^2 \tag{9}$$

This approach is implemented from Li et. al [13]. a, b and c represent coefficients which were determined to be 0.1, 0.4 and -0.2 respectively by Li et. al and f is the load factor which is the division of the output from the PGU by the demand.

E_{VCR} is the electricity required by the VCR which serves the purpose of cooling in the system. The system defined in this model only uses an electrical chiller. Nevertheless, an absorption chiller may be added depending on the heating and cooling demand profiles of the household and the heat to power ratio of the PGU. The electricity required by the electrical chiller is calculated from the equation below.

$$E_{VCR} = \frac{Q_{VCR}}{COP_{VCR}} \tag{10}$$

In this equation Q_{VCR} represents the cooling energy supplied by the VCR and COP_{VCR} is the coefficient of performance of the device. The heating side of the model has the most components. The energy balance for heating is as follows.

$$Q_{PGU} + Qs_{out} + Q_{boiler} + Q_{solar} = D_H + Qs_{IN} \tag{11}$$

Q_{PGU} is the heat obtained from the prime mover. Q_{solar} is the heat obtained from the solar thermal modules which are used for meeting the domestic hot water demand. After operating the PGU and the solar thermal modules, if there is an excess in the supply, it can be stored inside the storage depending on the available space inside the storage and the maximum flow rate that the storage allows. Qs_{in} is the amount of heat that is put in the storage. A minimum and maximum level is defined for the heat that is allowed to be stored. The minimum level is defined as 10% of the total storage capacity, whereas the maximum level is determined to be 90% of the storage capacity. The maximum allowed flow rate, which is valid for the flow going inside the storage and out of the storage, is set as 50% of the storage capacity. Qs_{out} is the amount of heat that is used from the storage. The system has a boiler to compensate for the possible deficiencies in the heating supply provided by the PGU. If the heat from solar thermal modules, the PGU and the storage is not sufficient for the demand, the boiler is operated to compensate for the deficiency.

The calculation for the yield from solar thermal modules is implemented "Method for calculation of system energy requirements and system efficiencies" of the European Committee for Standardization [56].

The assumptions in this model are summed as follows::

- All variables are integers.
- The PGU, VCR and boiler can operate between load factors from 0 to 1 depending on the operational strategy that is being investigated.
- The operational and maintenance costs for the storage are neglected.
- The minimum amount of heat inside the storage is 10% of the total capacity and the maximum amount of heat allowed to be in the storage is 90% of the total capacity. 50% of the total capacity of the storage is assumed to be the maximum charging and discharging rate.
- Solar thermal modules are only used for domestic hot water heating purposes. They are assumed to have an operational cost of 5% of their capital cost.
- The prime mover in the model is an internal combustion engine running on natural gas as an outcome of the literature survey and the component selection process. The efficiency of the PGU drops with part load operation. The relationship between load factor and efficiency is quadratic unlike most of the previous studies [13].
- The system is assumed to be 100% reliable.
- A typical day for each month is used for the model, thus the model runs for a period of 288 (12*24) hours.
- Grid connection is possible in the system. Therefore, the deficit can be compensated by buying electricity from the grid and excess can be sold to the grid.

5.3 Solution algorithm

There are various solution algorithms used for sizing components. Some of these algorithms are genetic algorithm, particle swarm optimization, maximum rectangle method, linear programming, non-linear programming and mixed-integer programming [20], [55]. Even though, maximum rectangle method is very simple, it only allows modelling systems where the components can only run at full load and it maximizes the annually supplied heat at full load. Therefore, using this method does not allow one to focus on economic benefits [57]. Linear programming, as indicted by the name, is suitable for linear problems. It is known to be fast, thus used quite widely for size optimization problems. Some studies value speed to get results quickly for investigating a new concept, thus make assumptions to linearize the model, e.g. assume that the efficiency of the CHP unit is constant regardless of its part load operation [58]. However, this study aims to present results that can be valued in daily life operation, therefore the efficiency of the CHP drops by part load operation which makes the problem nonlinear. Thus, mixed integer linear programming (MILP) is also not an option for solving this particular model. Moreover, the results of MILP only offer a theoretical solution [38] which is contradictory with the purpose of this study. For nonlinear problems, some researches prefer to formulate the problem linearly by using methods such as linear piecewise function where a nonlinear function is divided into several linear regions [55]. As there are more efficient linear optimization solvers, formulating the problem linearly allows researchers to reach a conclusion faster [59]. However, finding the global optimum of a problem is also quite crucial. Both LP and MILP might fail to achieve this as during the solution process, there is a possibility that the algorithm gets stuck at a local minimum [38]. Global searching methods such as particle swarm optimization and genetic algorithm are methods that are capable to find the global minimum of a problem as due to their character, they can avoid running into local minimums unlike MILP and LP [13]. Particle swarm optimization is inspired by the movement and intelligence of swarms. Each potential solution is called a particle with a position and a velocity vector. The particles are thrown to the search space with random initial velocities. At each operation the particles move through the optimum solution through its present velocity, personal best solution obtained by themselves so far and global best solution obtained by all particles [51]. By using particle swarm optimization, studies such as [45] aim to get results that reflect real operation. Particle swarm optimization also has a computational advantage. It is fast and requires a small memory space [60]. However, PSO is less reliable compared to genetic algorithm and it is not recommended for energy systems with more than 3 components [51]. Genetic algorithm is a stochastic global search algorithm that is based on the biological natural evolution process [49]. It is an iterative process with 5 components: initial random population generator, fitness evaluation unit, genetic operators for selection, crossover and mutation. The initial random population consists of random sizes that satisfy all the end-use demands in a system. Each random solution is evaluated by means of the fitness function. The selection operator chooses the percentage of the initial random population according to their fitness value. Utilizing these selected solutions, the crossover generator generates new possible solutions with higher fitness values. The mutation operator prevents getting stuck at a local minimum. Reasons to choose GA include, efficiency when reaching the global minimum as it can easily jump out of local minimums. A downside that is mentioned is its complexity [51]. This complexity may be a drawback when constructing the code of GA, however MATLAB's

Optimization Toolbox has GA as a solution algorithm which is an advantage for researchers. Figure 7 shows a flow chart for the application of GA for CCHP systems.

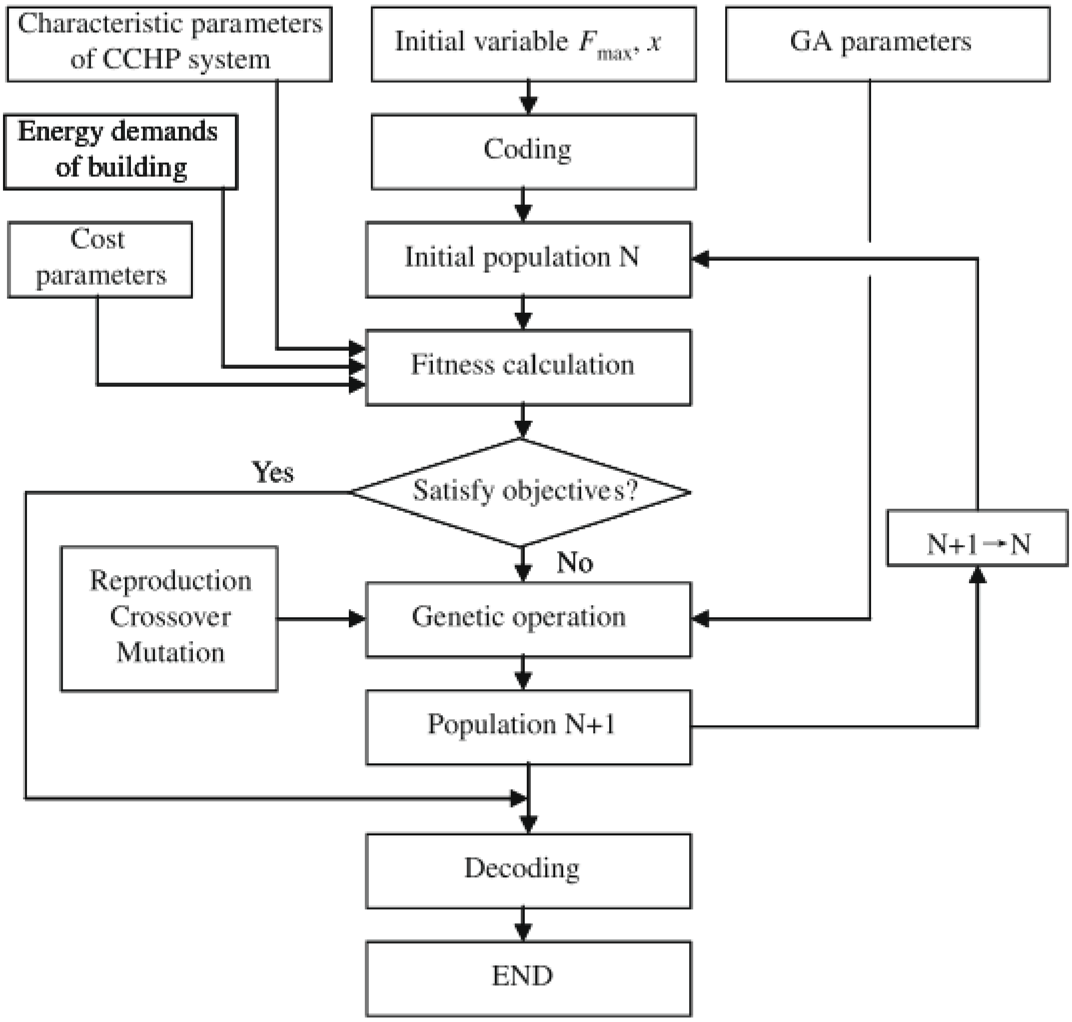


Figure 7: Flow chart of GA for its application on CCHP systems [8]

As seen in the flow chart, the inputs for GA are energy demands, and technical and economic characteristics of components within the CCHP system [8]. In MATLAB, the initial population is calculated randomly. Then, the algorithm creates a new population from the previous one according to the fitness values the populations achieve. The algorithm scores the population by means of its fitness value and scales the raw fitness scores for ease of use. Based on the fitness values, members to be called as parents are selected. When the object is to minimize the fitness function, individuals with lower fitness values are passed on to the next generation. Children are generated from the parents either by mutation, i.e. making random changes to a single parent or crossover, i.e. combining the vector entries of a pair of parents. These children then replace the current population to create the next generation.

The algorithm stops when it meets the following conditions.

- When the number of generations reach the defined number of generations
- When the optimization reaches the time limit that is defined
- When the fitness value reaches the defined fitness limit
- When the average relative change in the fitness function value over Stall generations is less than function tolerance [61].

6 Case study: Residential household in Turkey

6.1 Description of the household

The household to be analyzed in this study is chosen to be a single-family household, which accommodates a 5-member family. The size of the household is 250 m^2.

The household is located in Ankara, Turkey. The reason behind this choice is the fact that developing countries have been generating more emissions than industrialized countries [3]. Ankara has a continental climate which indicates that the difference between night and day temperatures is quite high. Moreover, the seasonal differences are also noticeable as seen in Figure 8.

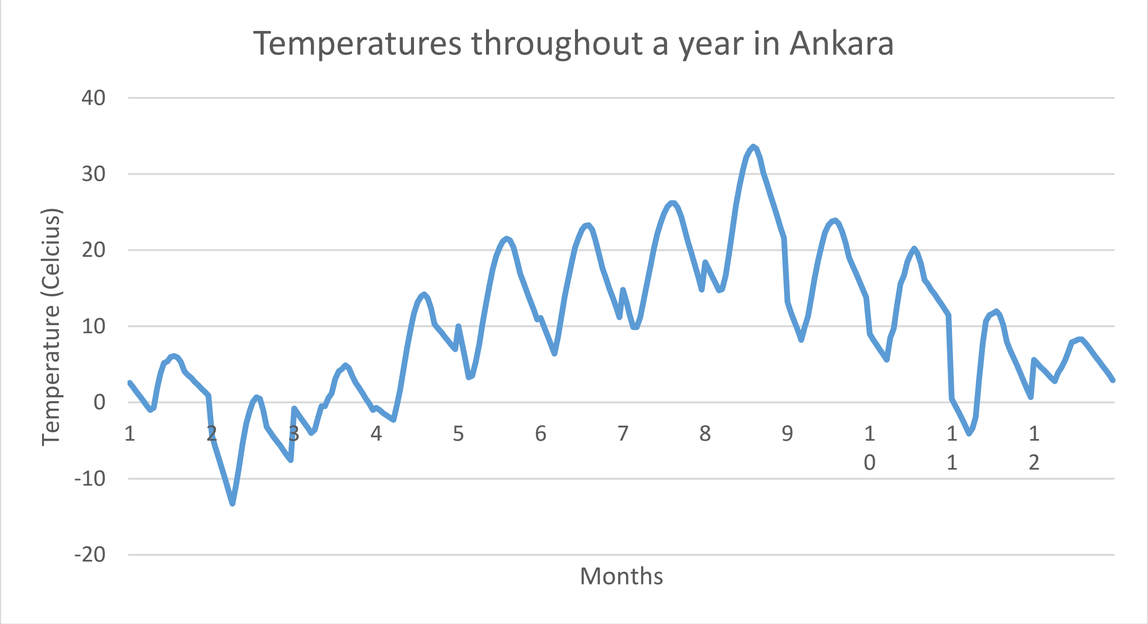


Figure 8: Yearly temperature distribution in Ankara

The temperature rises up to more than 30°C in summer, whereas it drops down to less than -10°C in winter. Therefore, the heating needs are quite high in winter and there is an apparent need of cooling during summer. These characteristics are distinctive for this location and this case study.

6.2 Inputs

6.2.1 Weather data

The weather data used for the model consists of the ambient temperature and solar irradiation. Hourly temperature data was obtained by using Meteonorm which is a software that offers temperature, solar irradiation and other climatic parameters for many locations worldwide [62]. Hourly solar irradiation data was found on “SoDa Service” online [63].

6.2.2 Demand profiles

Electricity, heating and cooling demand profiles were required as inputs to the model to be able to size the components within the system.

6.2.2.1 *Electricity demand*

The hourly electricity demand calculations are based on the monthly electricity bills of the household. Daily average electricity consumption for every month was determined according to the electricity meter data read and reported by the electricity distribution company in the area. For generating the hourly electricity load, hourly coefficients were calculated from Turkey's hourly electricity consumption data which is online on the "Load Dispatch Information System" webpage, constructed by Turkish State Electricity Transmission Company [64]. The electricity consumption of the household by months is shown in Figure 9.

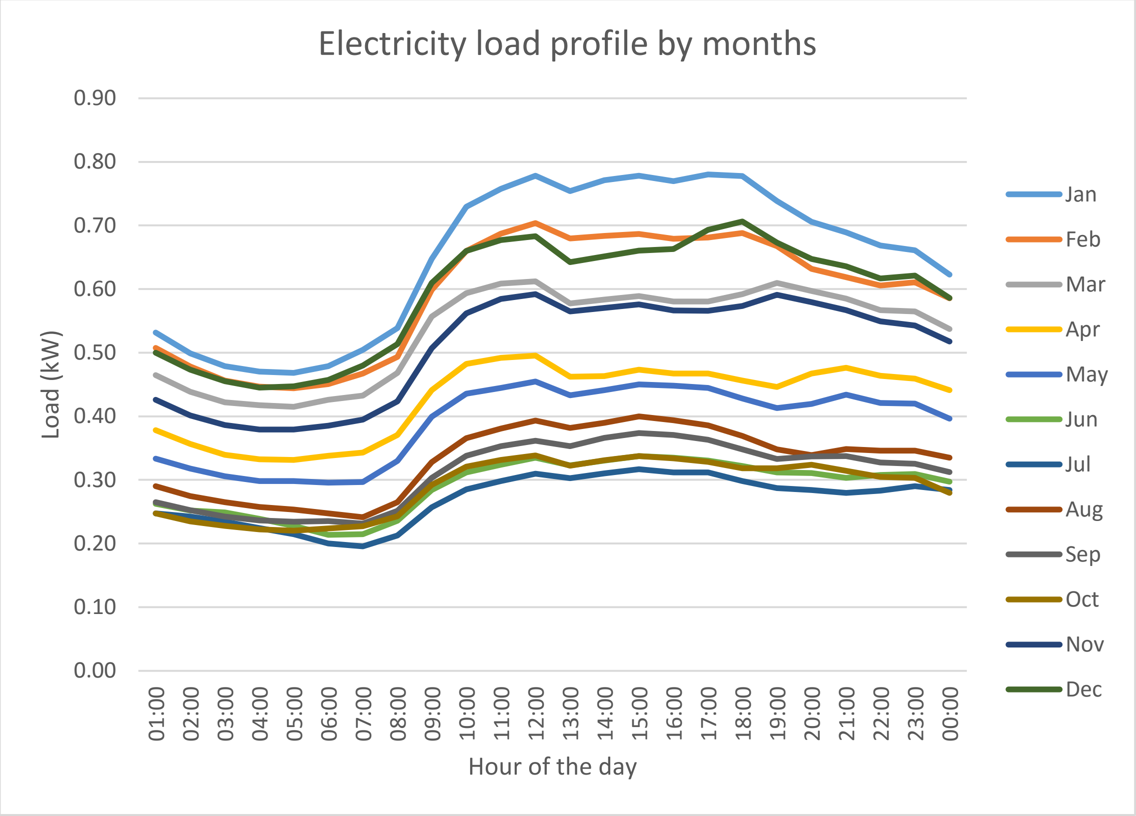


Figure 9: Monthly electricity consumption of the household in hourly time steps

As seen in the figure, the consumption in winter is more than the consumption in summer. The seasonal differences in consumption are seen more clearly on the annual electricity load profile in hourly time steps which is presented in Figure 10.

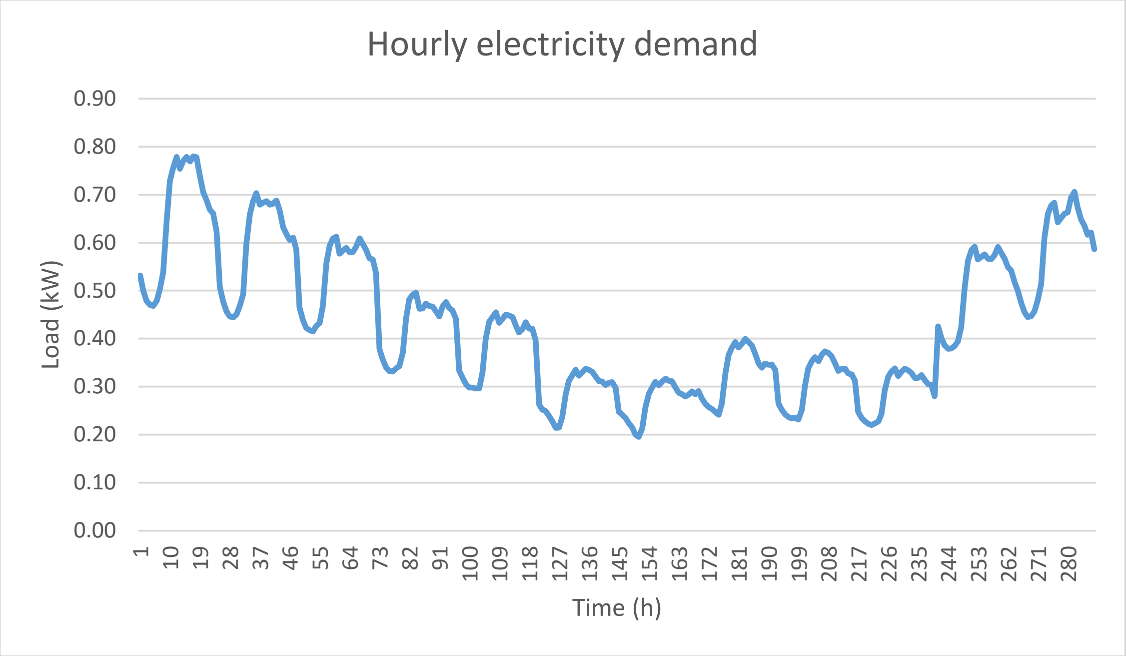


Figure 10: Annual electricity consumption of the household in hourly time steps

6.2.2.2 Heating demand

The hourly heating demand calculations are based on monthly natural gas consumption bills as natural gas is used for heating the pertinent household. The total monthly consumption is calculated from the volume of natural gas that has been consumed by Baskent Natural Gas Distribution which is the natural gas distribution company in Ankara owned by the state. This data was used to calculate the daily average consumption for every month. The hourly coefficients were based on the work of Bianchi et. al., where they have determined values for the daily distribution of the domestic hot water demand (DHW) and space heating demand for a single dwelling [65].

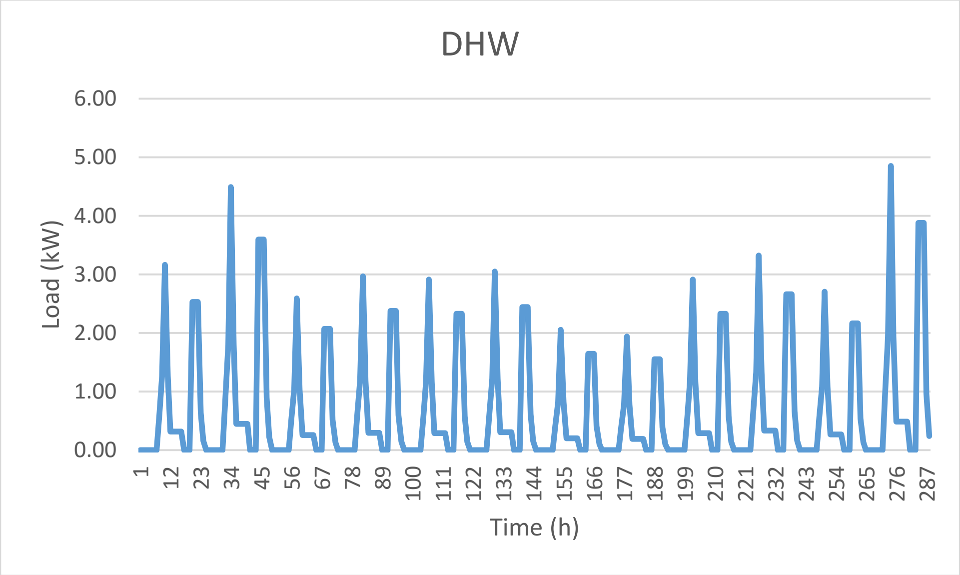


Figure 11: Domestic hot water demand throughout the year in hourly time steps

DHW is assumed to occupy 10% of the daily natural gas consumption. This assumption is based on seasonal consumption patterns, i.e. the comparison of summer and winter demand profiles as space heating is not required during summer. Figure 11 represents the DHW demand, while space heating demand throughout the year is shown in Figure 12.

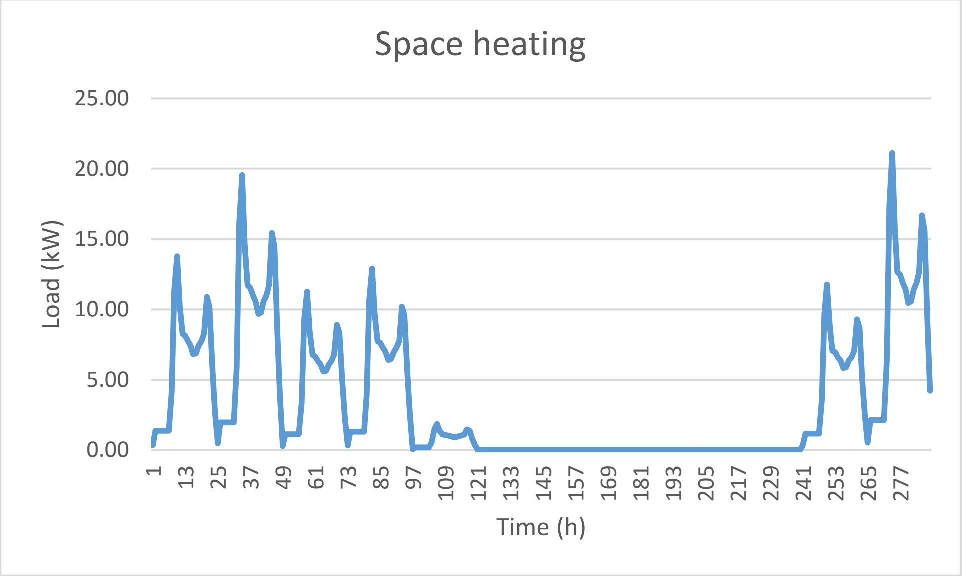


Figure 12: Space heating demand throughout the year in hourly time steps

6.2.2.3 Cooling demand

When calculating the cooling load, the work of Eskin et al. is implemented [36]. The paper presents the typical daily cooling load for a household, and a comparison of simulated values by the software EnergyPlus and measured values. For this case study, the measured values are used to generate coefficients for constructing the hourly load for a day. The coefficients are calculated based on the peak value during a day. The monthly differences in the consumption patterns, on the other hand, are constructed by monthly average cooling degree days which was obtained from the software Meteonorm [62]. Figure 13 shows the cooling demand profile of the pertinent household.

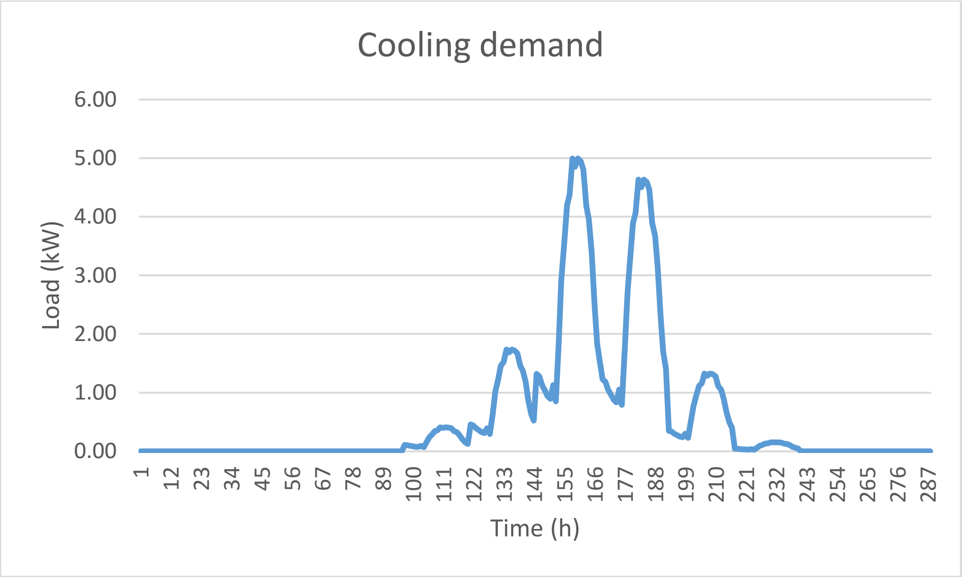


Figure 13: Cooling demand profile throughout the year in hourly time steps

6.2.3 Market conditions

There is nearly 1 GW of installed cogeneration plants in Turkey. Most of these plants are large-scale and powered by natural gas due to its lower prices and ease of transport [66]. Thus, the cogeneration products that are available in the Turkish market are mostly for large scale and medium scale applications. Some products that are available in the market are the CHP unit of Ener-G that is distributed by PNQ, and the CHP and CCHP units with gas engine which are manufactured by Teksan Generators. Ener-G is a company based in Manchester and they offer CHP units in capacities between 4 kW and 5 MW. PNQ is their distributor in Turkey [67]. The units offered by Teksan Generators have a capacity of 500 kW [68]. This pushes the customers that want to invest in micro cogeneration systems to buy the CHP unit from another country. As the CHP market in Germany and the UK are quite active [41], ordering these products could be a good choice for investors in Turkey. Example products include Dachs Stirling by Senertec [32], Ecopower (an ICE based unit) by Vaillant [31], EnerTwin (a micro turbine based unit) by MTT [34]and Galileo 1000N (a fuel cell based unit) by Hexis [33].

Regarding solar thermal collectors, the market in Turkey is active. The total installed area of solar thermal collectors in Turkey is reported as 13.3 million m^2 which makes Turkey the fourth country in the world by means of installed solar thermal collector capacity. Most of the capacity is installed in Aegean and Mediterranean regions [69]. This offers a good opportunity to utilize solar thermal collectors in CHP or CCHP systems.

6.2.4 Energy policies

The feasibility of CCHP systems highly depend on energy policies as they define electricity tariffs and operation of the system [38].

Regulations regarding cogeneration systems are defined by Energy Markets Regulatory Authority. There are some incentives available for renewable energy systems as well as cogeneration systems. Micro cogeneration systems are defined as cogeneration systems with a capacity under 50 kW by the authorities and such systems can be installed without the need of obtaining a license [70] which saves some time for the investors. Therefore, installing micro cogeneration systems becomes easier and less costly for the customer compared to larger systems that need a license.

Apart from the incentives, there are also some necessities for cogeneration systems that the law identifies. The regulations state that cogeneration systems should be tracked hourly by meters. Another item in the regulations limit the number of micro-cogeneration systems a person can install to one. Moreover, the person needs to get a permission for connecting system to the nearest distribution center. Every distribution center has a limit for the capacity of renewable energy and cogeneration systems that can be connected to the pertinent transformer. The investor needs to ensure that there is available space for their cogeneration system in the nearest transformer [70].

According to regulations regarding cogeneration systems published in the Official Gazette, there are some lower limits for the efficiencies of cogeneration systems to be installed. Depending on the prime mover type, different allowed lower limits for efficiencies are defined. Cogeneration systems powered by internal combustion engines, fuel cells, micro turbines and Stirling engines should be more than 75% efficient as defined in “Statement on calculation of efficiencies of cogeneration and micro-cogeneration systems” [71]. The heat to power ratio of the prime mover is also valued by the Ministry of Energy and Natural Resources and required to be submitted in the application for installing cogeneration systems. For instance, cogeneration systems with internal combustion engines are required to have a heat-to-power ratio of 1 or less [71].

As defined in Chapter 4, when there is an excess in electricity production by the polygeneration systems, this surplus can be sold to the electricity if possible. This is defined in by the law regarding electricity production from renewable energy sources which is enacted by the Energy Markets Regulatory Authority. The law states that it is possible to sell the excess electricity produced by a cogeneration system at 0.073 USD per kWh, the lowest feed in tariff described in the pertinent regulations, to the regional suppliers. However, another purchase price is offered by the government if the cogeneration system is operated on biomass. The law states that the purchase price offered by the government for biomass energy systems is 0.133 USD per kWh. The government offers an extra 0.004 USD per kWh for cogeneration systems operated on biomass as an incentive [72]. Thus, if an investor is to install a cogeneration system that uses biomass, they are able to gain 0.137 USD per every kWh of electricity sold to the grid.

The regulations regarding emissions should also be examined prior to planning a polygeneration system as there might be carbon taxes which would influence the annual total cost of the system. Turkey does not apply an emission tax however there are regulations on monitoring GHG emissions. Moreover, there are emission limits for the industry [73].

6.3 System configuration and parameters

The system to be implemented to the household consists of a CHP unit that has a prime mover of internal combustion engine, an auxiliary boiler, a VCR unit, i.e. electrical chiller, and solar thermal collectors. Electricity is primarily met by the CHP unit, the deficit in supply is bought from the grid and the excess is sold to the grid at the purchase price that the government states in the regulations. Cooling demand is only met by the electric chiller since absorption chillers are expensive and have lower COP values [37]. Solar thermal collectors are used to meet the DHW demand. If they are not sufficient to meet the DHW demand, the deficit is satisfied primarily by the CHP unit. If there is an excess from the solar thermal collectors, it is stored in the storage. The storage is also able to store the excess heat from the CHP unit and the boiler depending on the operational strategy, i.e. where it is integrated in the system. If there is a deficit in the heat supply from the CHP unit, the amount of heat inside the storage is checked. If there is available heat in the storage, it is used to compensate for the deficit. However, if there is no available heat in the storage or, the supply from the PGU and the storage is not sufficient to cover the demand, the auxiliary boiler is operated. The system configuration is shown in Figure 14.

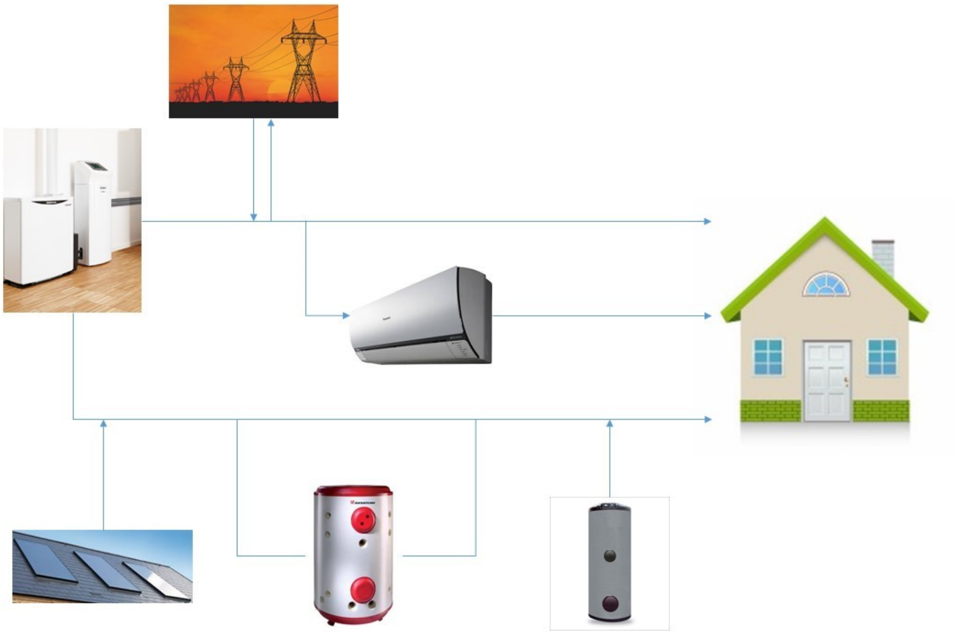


Figure 14: System configuration of the system to be used

Technical parameters are the efficiencies of the components that are in the system and the heat to power ratio of the PGU. The efficiencies of the components within the system are presented in Table 8. Heat to power ratio of the PGU is determined to be 0.7.

Table 8: Efficiencies of the components

	PGU	Boiler	VCR	Storage	Solar thermal collectors
Efficiency	0.30 (at full load)	0.80	3.8	0.90	0.90 (optical efficiency)

Cost parameters are listed below:

- The electricity cost is determined as 0.15 €/kWh and the cost for natural gas is determined as 0.03 €/kWh.
- Electricity sold to the grid is purchased by the government at 0.067 €/kWh.
- The interest rate is 0.07 [74].
- Cost parameters for the components are presented in Table 9.

Table 9: Cost parameters of the components

	PGU	**Boiler**	**VCR**	**Storage**	**Solar thermal collectors**
Capital cost	1000 €/kW	100 €/kW	100 €/kW	10 €/kWh	100 €/module
Maintenance cost	0.021 €/kWh	0.10 €/kWh	0.10 €/kWh	-	5% of the capital cost

These parameters are implemented from existing studies [45], [58], [75] and available products in the market [31], [76], [77].

6.4 Results

A model for a baseline case has been constructed. The operation strategy is thermal load following. The excess heat supply from the PGU and the solar thermal collectors can be stored in the TES. Stored heat can be used if the heat supply from the PGU and the solar thermal collectors is not sufficient. The boiler is operated when the heat supply from these three components is not adequate. The electricity is primarily supplied by the PGU. As defined in Chapter 6.2.4, cogeneration systems are allowed to be grid connected and electricity can be sold to the grid. Thus, if there is a deficit, electricity is bought from the grid and if there is an excess, electricity is sold to the grid. The only cooling supply is provided by the VCR. The PGU in this case study is determined to be an internal combustion engine due to market conditions, i.e. cost, availability and ease of maintenance and suggested by the results from the component selection process. The PGU and the VCR are allowed to be operated at part load, whereas the boiler is operated only at full load. The fuel to be used is natural gas due to its high share of usage in Turkey for energy consumption. The operational strategy is chosen as thermal load following in the baseline case as excess electricity is allowed to be sold to the grid and that heating demand is significantly higher than the electricity demand. An absorption chiller is not present within the system, due to its high cost, low coefficient of performance and the load profile of the household, i.e. relatively high heating demand. Different cases were created by altering the main operational strategy, i.e. heat led or electricity led, capability of the PGU and boiler to operate at part load or not, existence of a TES and where it is integrated in the system, and the existence of solar thermal collectors in the system. The cases are summarized in Table 10.

Table 10: Description of the cases

Case #	**Explanation**
1	Thermal led. PGU & VCR → load factor between 0 and 1. Boiler → full load. Storage → excess from PGU and STC
2	Electricity led. PGU & VCR → load factor between 0 and 1. Boiler → full load. Storage → excess from PGU & STC
3	Electricity led. PGU, VCR, boiler → load factor between 0 and 1. Storage → excess from PGU & STC
4	Electricity led. PGU & VCR→ load factor between 0 and 1. Boiler → full load. Storage → PGU, STC and boiler
5a	Separate production with storage. Boiler → full load. Storage → excess from PGU, STC and boiler
5b	Separate production. No storage
6	Electricity led. PGU → load factors between 0.4 and 1. Boiler → full load. VCR → load factor between 0 and 1. Storage → excess from PGU, boiler and STC
7	Same as Case #6 but no STC.

Table 11 shows the results for the baseline case after the optimization.

Table 11: Optimized values of the variables in the reference case (Case #1)

Variable	**Optimized size**
Capacity of PGU	25 kW
Capacity of boiler	0 kW
Capacity of VCR	6 kW
Capacity of storage	0 kWh
Number of solar thermal collectors	2

The total annual cost is 3787.40 €. As the size of the PGU is adjusted to the thermal demand, the supply from the PGU is enough for the heating demand which eliminates the need to have a storage as seen in Figure 15.

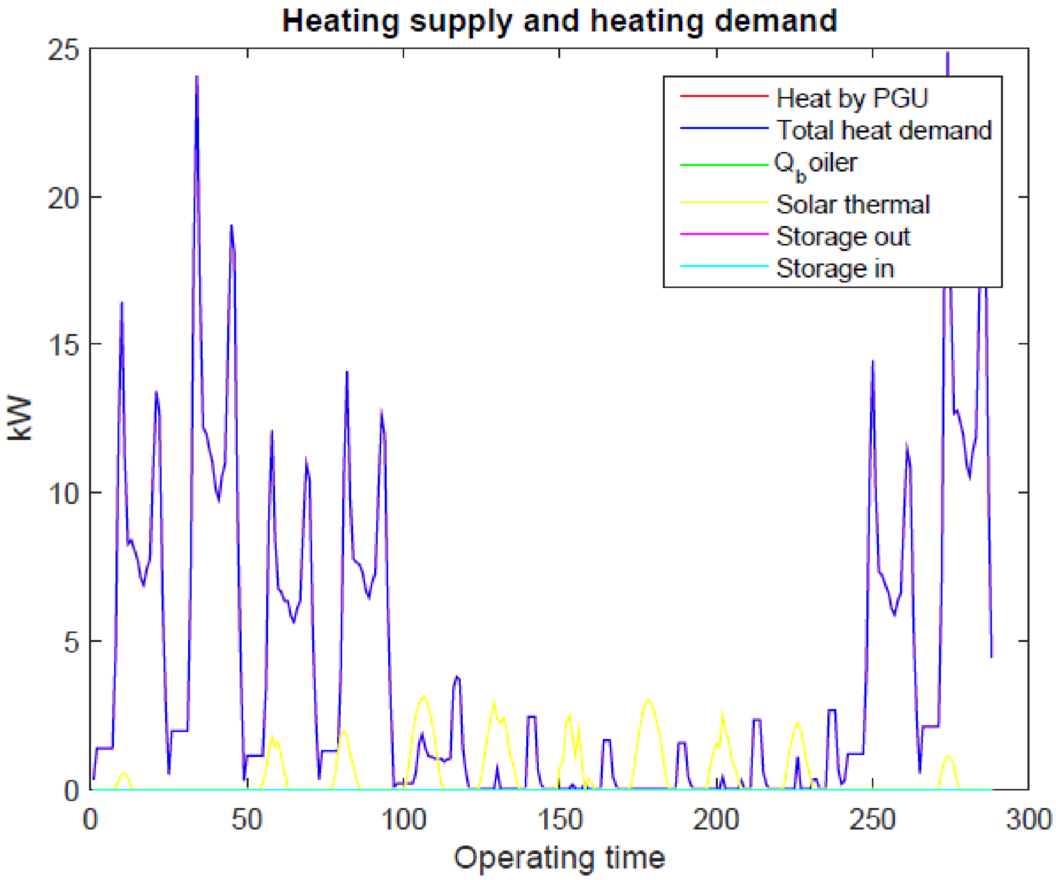


Figure 15: Heating supply and heating demand in Case #1

The heat supply by the PGU is adjusted to the demand, thus the curves are on top of each other. Electricity supply is also adjusted to the thermal demand. As shown in Figure 16 the electricity supply by the PGU has the same profile as the heat supply. There is no deficit for the auxiliary boiler to compensate for. Thus the capacity of the boiler in this case is zero.

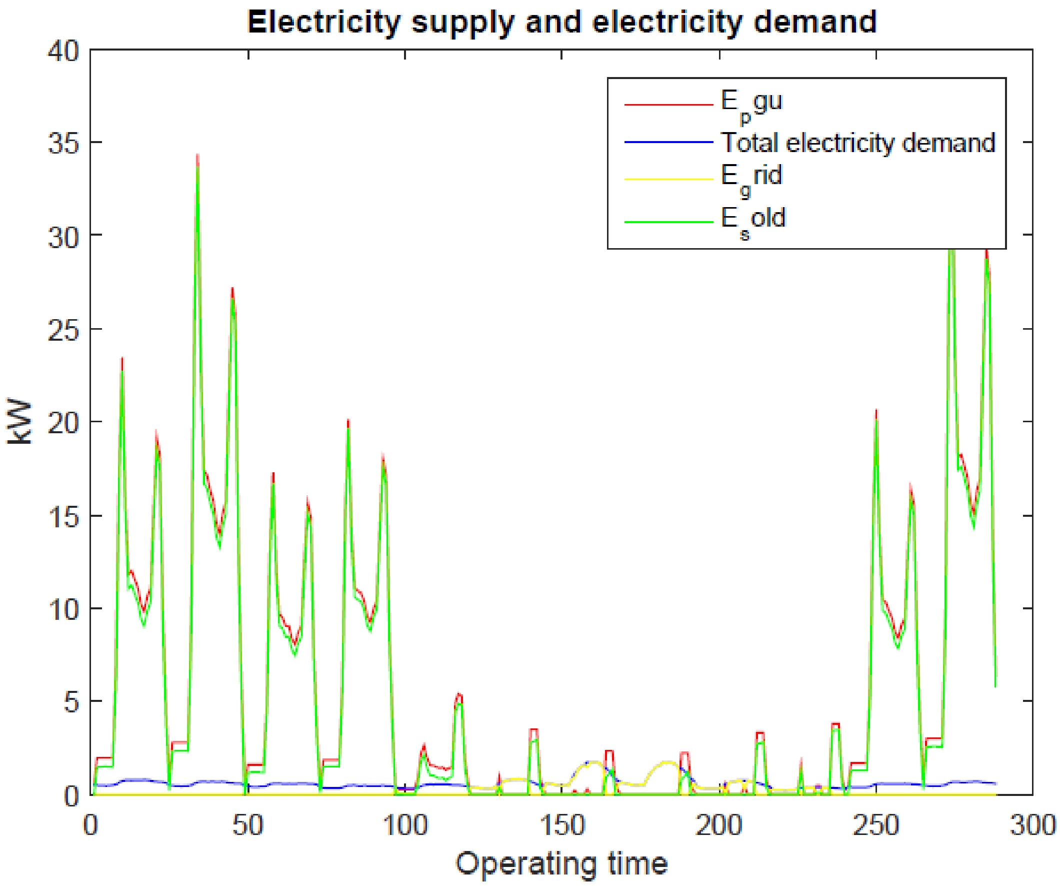


Figure 16: Electricity supply in Case #1

As the electricity demand is quite small compared to the heat demand, most of the electricity is excess and is sold to the grid, especially in winter. However, during the summer months, the heat demand is low, i.e. there is no space heating demand, only the hot water demand. Moreover, the cooling demand is high in summer months as seen in Figure 17. This adds up to the electricity demand. Therefore, the electricity supply by the PGU is not sufficient during summer months and the deficit is bought from the grid.

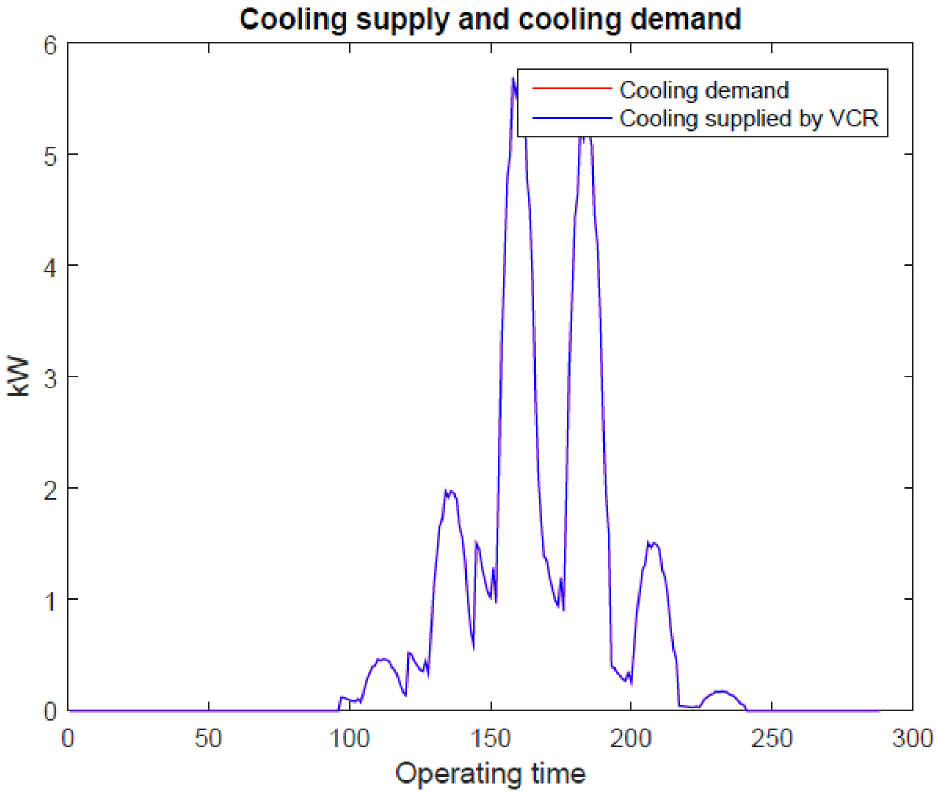


Figure 17: Cooling supply in Case #1

For the second case, the operational strategy is changed to electrical demand following operation. Apart from this alteration, this case is the same with the baseline case. By creating this case, the aim is to find out which operational strategy is better. Table 12 shows the optimum sizes of the components for this case.

Table 12: Optimized values of the variables in Case #2

Variable	**Optimized size**
Capacity of PGU	2 kW
Capacity of boiler	23 kW
Capacity of VCR	6 kW
Capacity of storage	5 kWh
Number of solar thermal collectors	2

The annual total cost is 1299.10 €. As the peak in the electricity demand is around 1.7 kW, the size of the PGU is 2 kW suggested by the results of the optimization process. The electricity supply is shown in Figure 18.

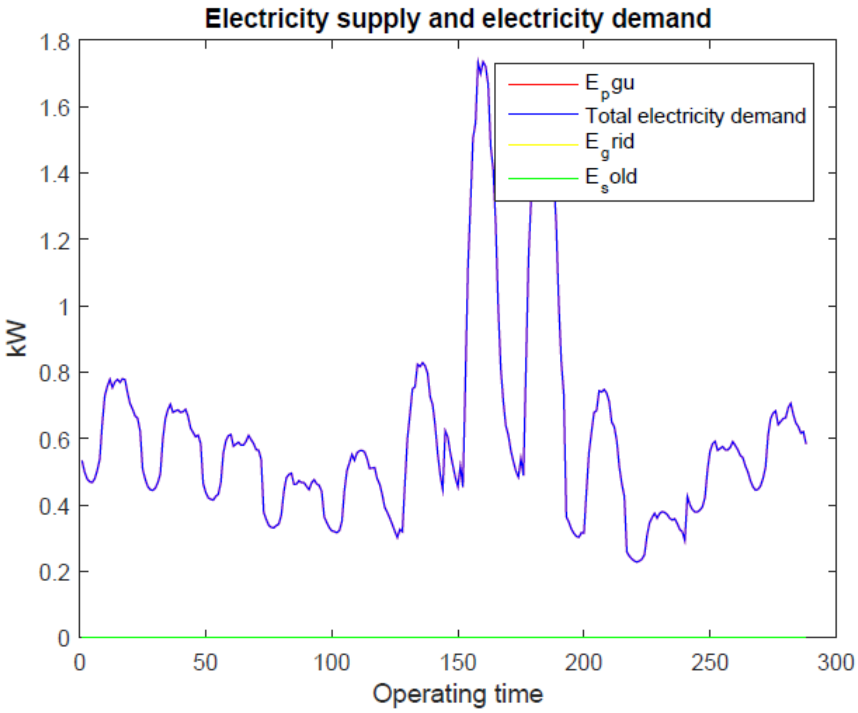


Figure 18: Electricity supply in Case #2

The supply is matches with the demand as the operational strategy is electricity load following and the PGU is allowed operated at any load factor between 0 and 1. Therefore, there is no excess and deficit and thus, no need to buy electricity from or sell electricity to the grid. The electricity demand shown in Figure 18 includes the electricity consumption by the VCR which is the same as Case #1. As the size of the PGU is determined by electricity load following operation, the heating supply by the PGU is adjusted to the electricity demand. As the heating demand is relatively high, there is need of operating the back-up boiler. As shown in Figure 19 the heat supply by the PGU is quite low compared to the thermal demand.

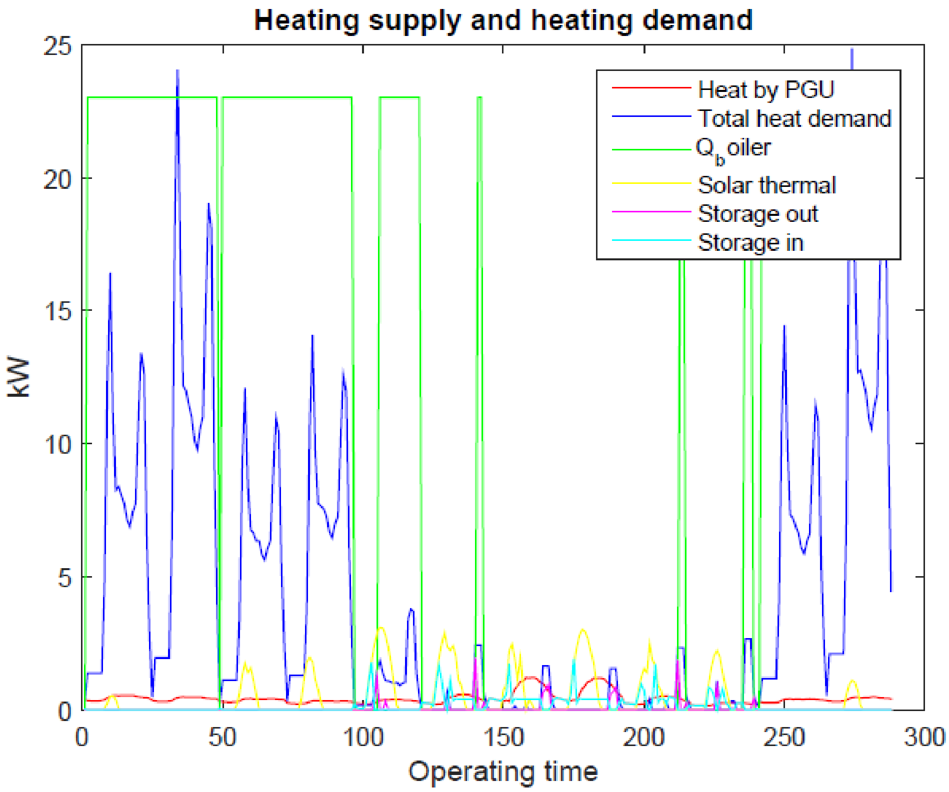


Figure 19: Heating supply in Case #2

The storage is placed before the boiler, thus the heat being stored in the storage is the excess heat from the solar thermal collectors which occurs during summer as solar irradiation is higher.

Case #3 is operated with electrical demand following strategy. The difference from Case #2 is that the boiler can run on part load in this case. When compared with the previous case, the results are expected to give an insight on how to operate the boiler. The results are presented in Table 13.

Table 13: Optimized values of the variables in Case #3

Variable	**Optimized size**
Capacity of PGU	2 kW
Capacity of boiler	25 kW
Capacity of VCR	6 kW
Capacity of storage	0 kWh
Number of solar thermal collectors	1

The total annual cost is 935.40 €. Heat supply for Case #3 is shown in Figure 20.

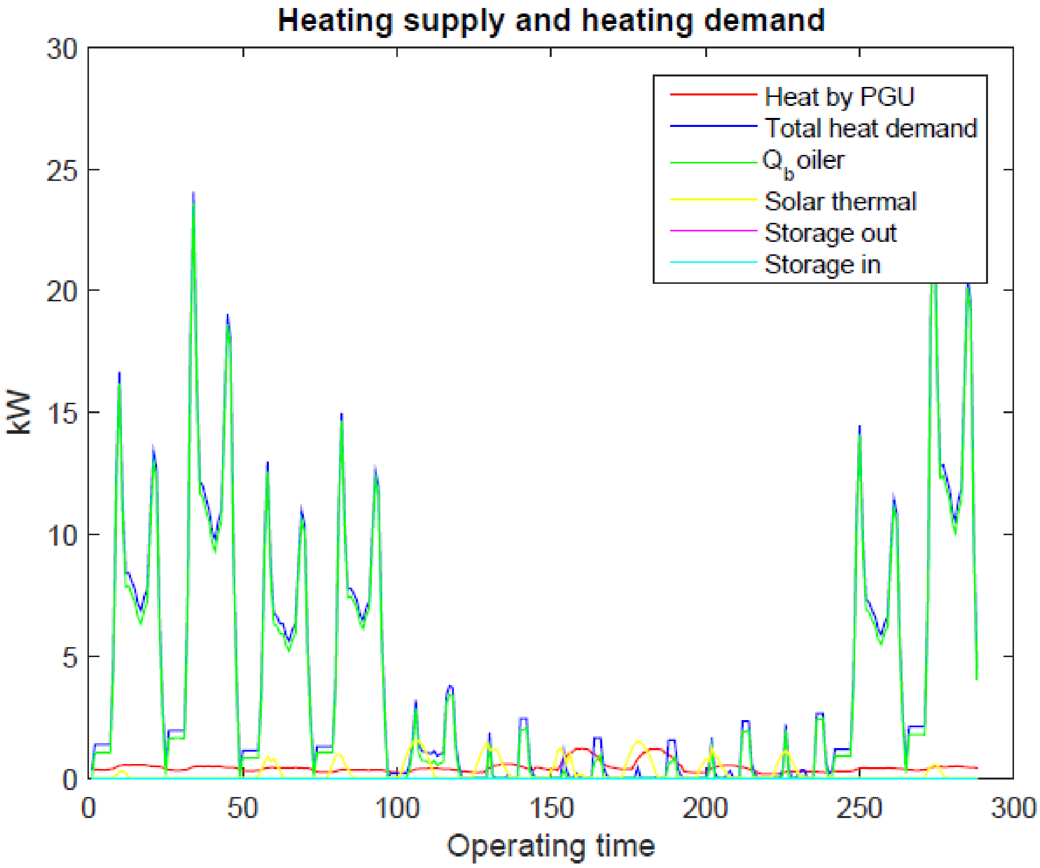


Figure 20: Heat supply in Case #3

As the boiler is operated at part load, its supply is able to match the demand. Therefore, there is no excess from the boiler. The storage is integrated before the boiler, thus it is only capable of storing the excess from the PGU and the solar thermal collectors which is zero in this case. As the electricity demand increases by the electricity consumption of the VCR and the operational strategy is electricity load following, there is excess in PGU heat supply in summer months. The electricity supply and the cooling supply are the same as the previous case.

In Case #4, the operational strategy is again electrical load following. The PGU and the VCR are operated at part load, whereas the boiler runs on full load at all times. The storage is integrated after the boiler. Thus, the excess heat from the PGU, solar thermal collectors and the boiler can be stored in the TES. The amount of heat available in the storage can be used after the PGU and solar thermal collectors are operated, and before the boiler. The aim in this strategy, thus this case is to see the effect of having a storage on the boiler size. Table 14 shows the results of this case.

Table 14: Optimized values of the variables in Case #4

Variable	**Optimized size**
Capacity of PGU	2 kW
Capacity of boiler	24 kW
Capacity of VCR	6 kW
Capacity of storage	37 kWh
Number of solar thermal collectors	0

The total annual cost is 1005.30 €. The capacity of the storage is large since the excess from the boiler is quite high when operated at full load at all times. A striking detail in these results is the size of the boiler. Compared to the previous case where there was not much heat stored in the storage, the capacity of the boiler has decreased. This points out to the importance of system configuration, e.g. where and how the storage is integrated in the system. Figure 21 shows the heat supply and the amount of heat going in and out of the storage.

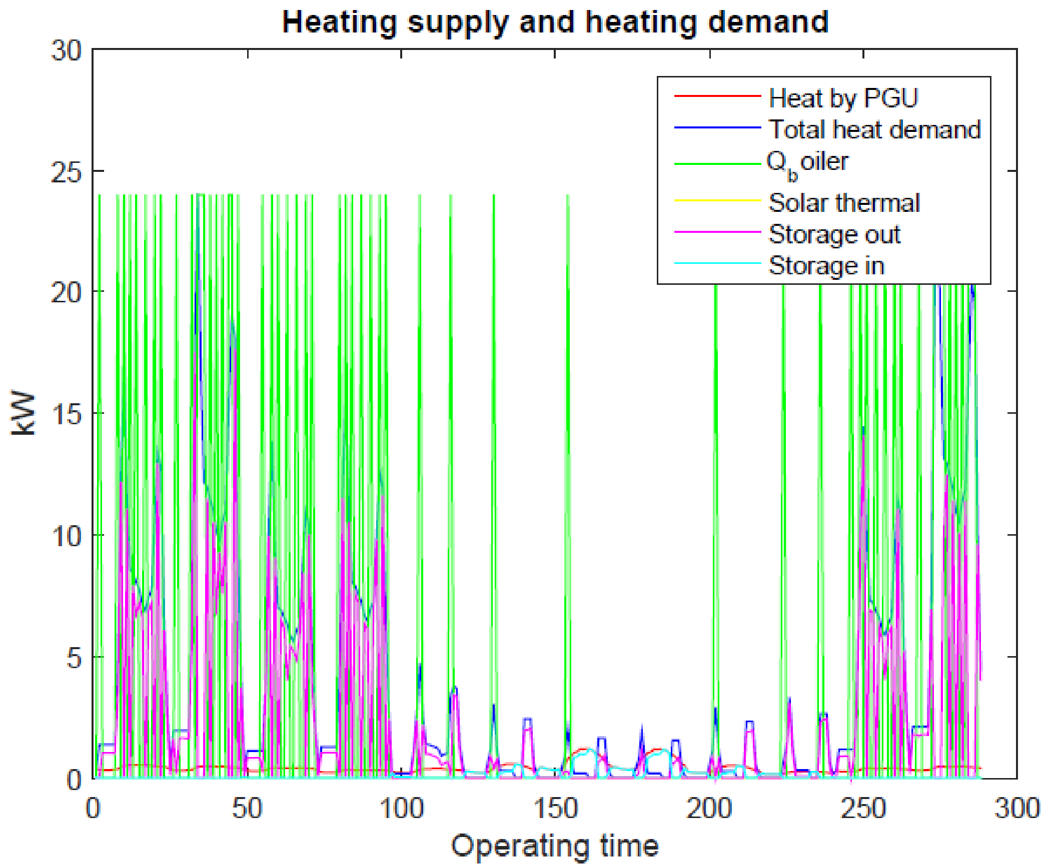


Figure 21: Heat supply in Case #4

As the excess from the storage is high, there is available heat in the storage that can considerably contribute to the supply. The amount of heat inside the storage is shown in Figure 22.

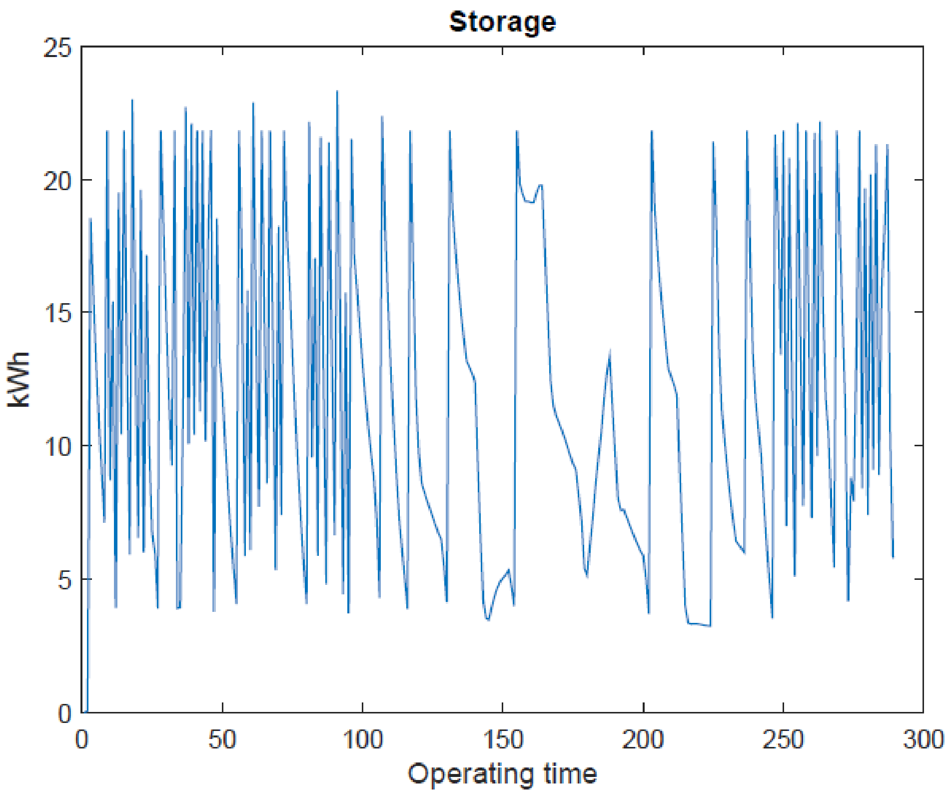


Figure 22: Amount of heat inside the storage in Case #4

After getting the heat supply from the PGU and the solar thermal modules, the storage is checked for available heat and heat flows out if the PGU and solar thermal modules were not sufficient to meet the demand, which generally is the case for this case study due to the demand profile of the household. This helps decreasing the capacity of the boiler. During the summer months, since there is no space heating demand, there is no excess from the boiler. However, a heat flow going in the storage is still present from the solar thermal modules.

Case #5 is separated into 2 sub cases. In Case #5a, the PGU and the boiler is operated at full load whereas the VCR runs on part load. The excess electricity may be sold to the grid and the excess in heating can be stored in the storage. The results are in Table 15.

Table 15: Optimized values of the variables in Case #5b

Variable	**Optimized size**
Capacity of PGU	0 kW
Capacity of boiler	24 kW
Capacity of VCR	6 kW
Capacity of storage	30 kWh
Number of solar thermal collectors	0

The total annual cost is 740.94 €. This case can be evaluated as a separate production case with storage since the capacity of the PGU and the solar thermal modules are 0. Compared to other cases that has been analyzed, this is the case with the least cost due to the absence of the capital cost of the PGU. The excess from the boiler is stored in the storage as the previous case and the available heat in the storage is used to contribute to the heat supply as seen in Figure 23.

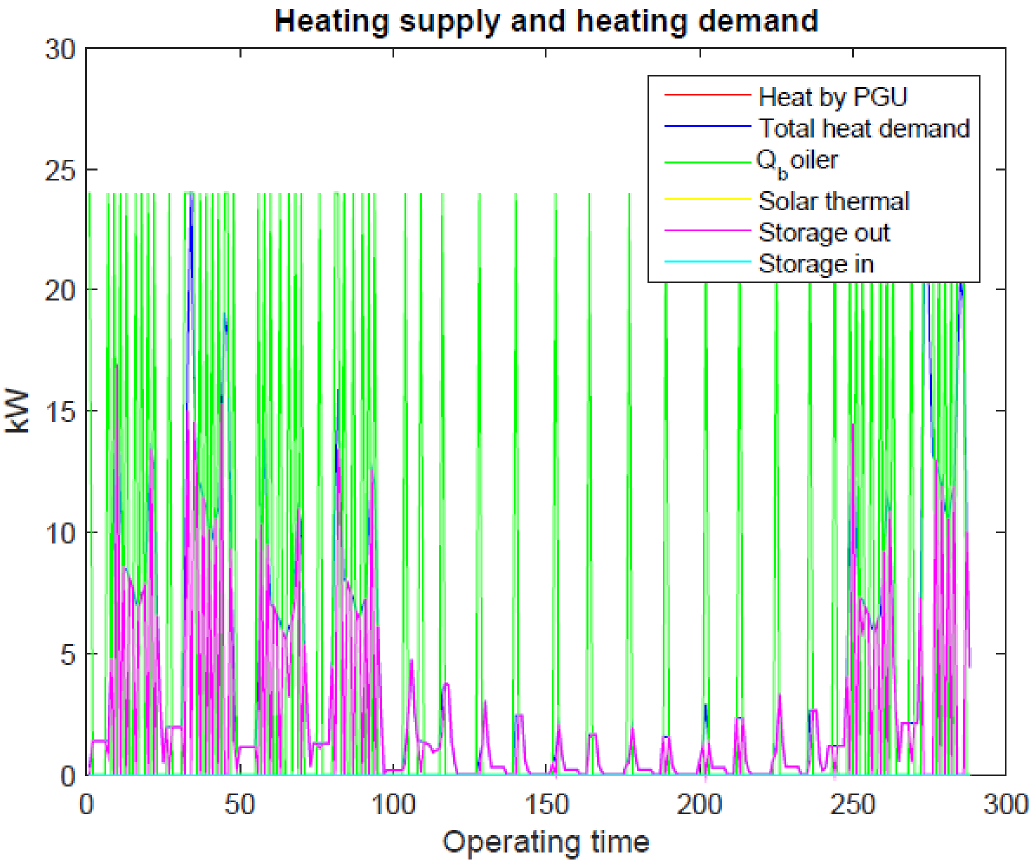


Figure 23: Heat supply in Case #5a

During summer, only the domestic hot water demand is present which is mostly met by the storage. However, at the peak hours during the day in summer months, the storage is not sufficient and the boiler is turned on.

As the size of the PGU is zero, the electricity demand is met by buying electricity from the grid as shown in Figure 24.

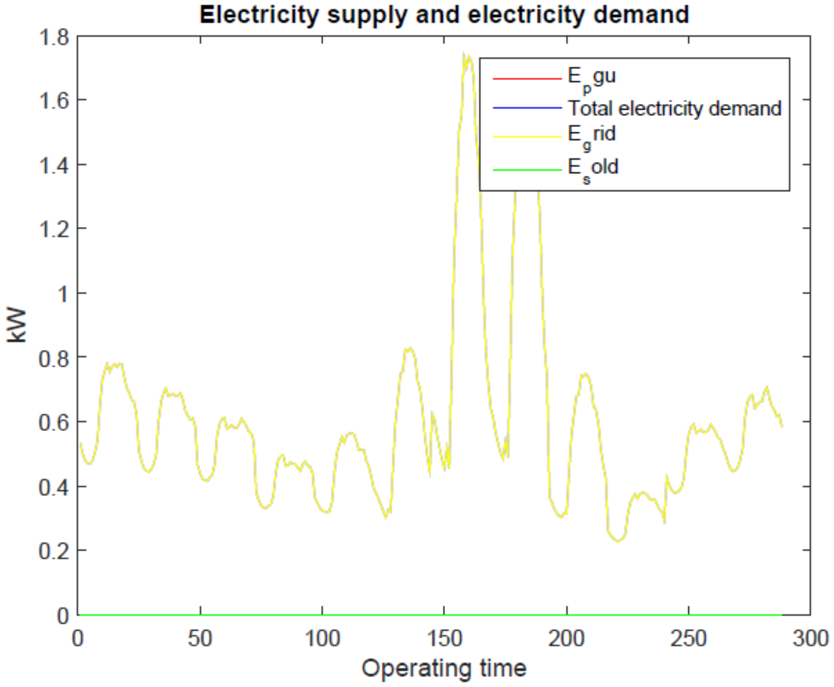


Figure 24: Electricity supply in Case #5a

Case #5b represents the separate production case with no storage. In this case, electricity is bought from the grid, heat is only produced by a boiler and cooling is supplied by a VCR, i.e. electrical chiller. The values of the variables in this case are as follows, shown in Table 16.

Table 16: Values of variables in Case #5b

Variable	**Size**
Capacity of PGU	0 kW
Capacity of boiler	26 kW
Capacity of VCR	6 kW
Capacity of storage	0 kWh
Number of solar thermal collectors	0

The total annual cost is 1353.20 €. This results indicates that having a storage contributes a lot to cost savings. This is due to high heating demand, thus larger size of boiler.

For Case #6, the PGU is set to operate at load factors between 0.4 and 1. The PGU is turned off if the load factor is less than 0.4. As the relationship between the efficiency of the PGU and the load factor is of second degree, using the PGU at lower efficiencies cause it to operate at lower efficiencies. The aim to construct this case is to comprehend the effect of the load factor on the overall system. The results are shown in Table 17.

Table 17: Optimized values of the variables in Case #6

Variable	**Optimized size**
Capacity of PGU	1 kW

Capacity of boiler	22 kW
Capacity of VCR	6 kW
Capacity of storage	40 kWh
Number of solar thermal collectors	3

The total annual cost is 862.50 €. The capacity of the PGU is 1 kW, thus the electricity demand is met by both operating the PGU and buying electricity form the grid as shown in Figure 25. The reasoning behind this is that the PGU is turned off for load factors lower than 0.4. In this case, for time spans that the PGU is turned off, electricity is bought from the grid to meet the demand.

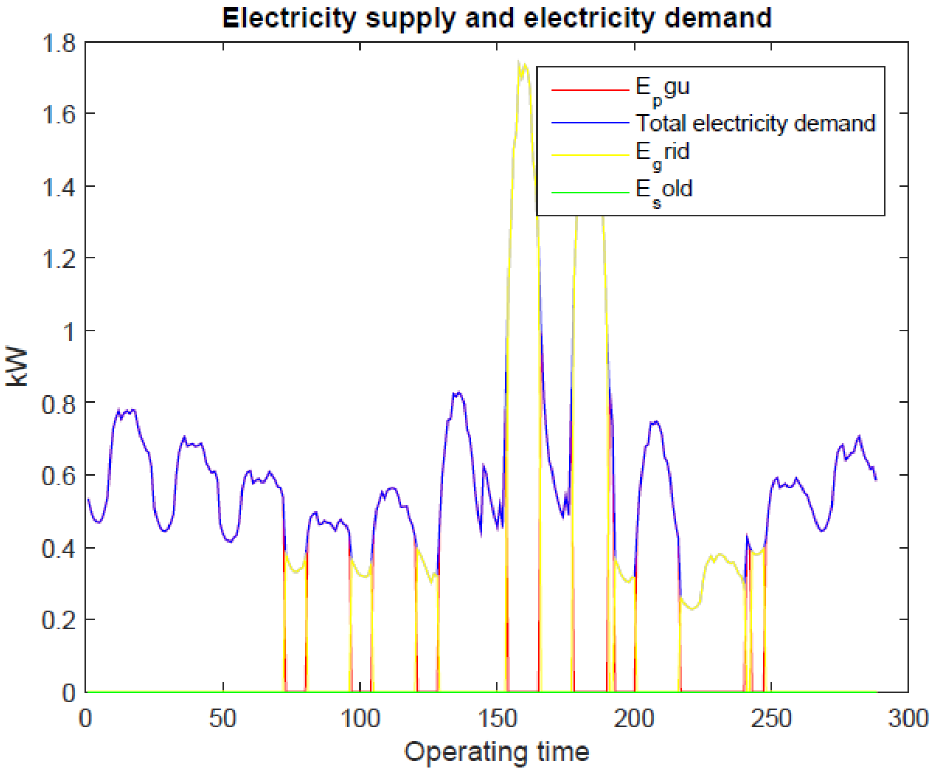


Figure 25: Electricity supply in Case #6

The fact that the capacity of the PGU also affects the heating supply. However, as the boiler is running at full load and the excess in supply is high, the storage is used effectively to meet the demand as seen in Figure 26. The yield from solar thermal modules is also high as suggested by the number of modules suggested by the results. Thus, even though the size of the PGU is lower, a lower capacity for the boiler is also achieved.

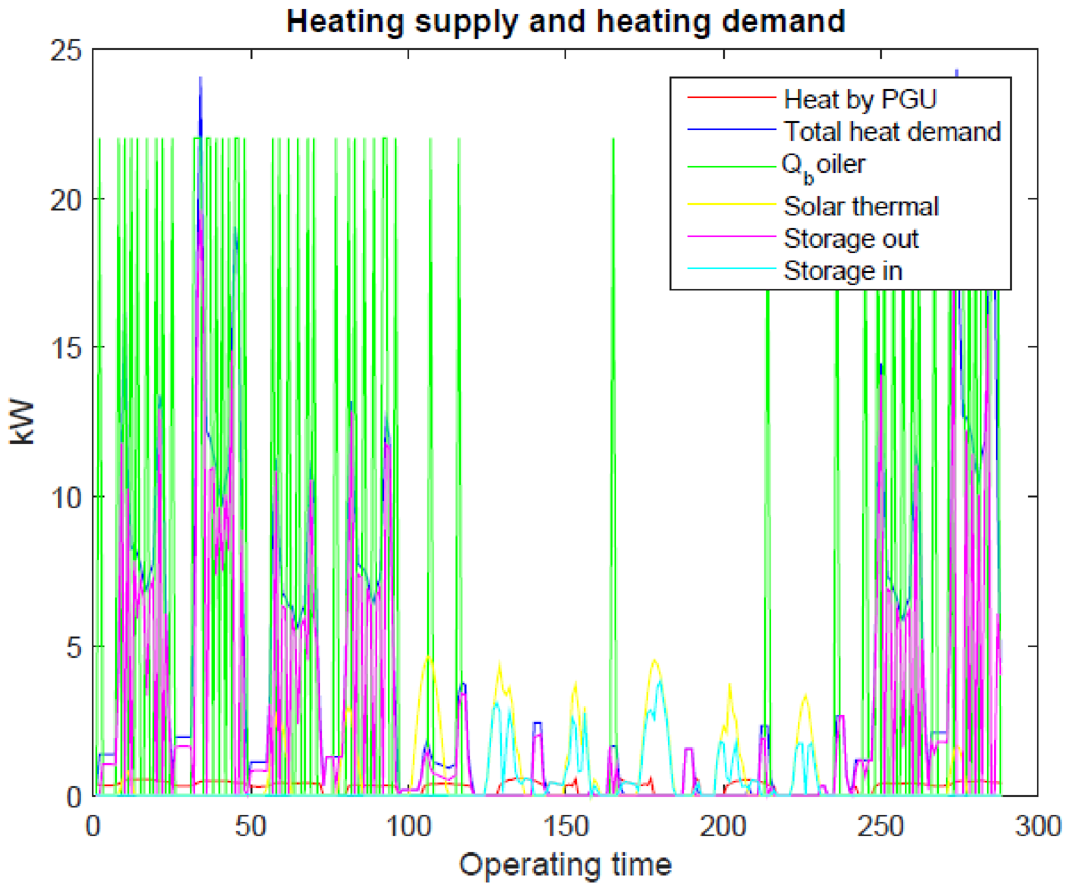


Figure 26: Heat supply in Case #6

Case #7 tests the effect of having solar thermal collectors on the system. It is the same as Case #6, except there are no solar thermal collectors in this case. Table 18 presents the results.

Table 18: Optimized values of the variables in Case #7

Variable	**Optimized size**
Capacity of PGU	1 kW
Capacity of boiler	24 kW
Capacity of VCR	6 kW
Capacity of storage	28 kWh
Number of solar thermal collectors	0

The total annual cost is 872.01 €. This strongly suggests that integrating solar thermal modules is the better choice as the cost is lower compared to the previous case. The reason behind this is the increase in boiler size. The size of the storage is also lower due to the absence of the excess heat from the solar thermal modules. The heating supply is shown in Figure 27. The electricity supply is the same as the previous case.

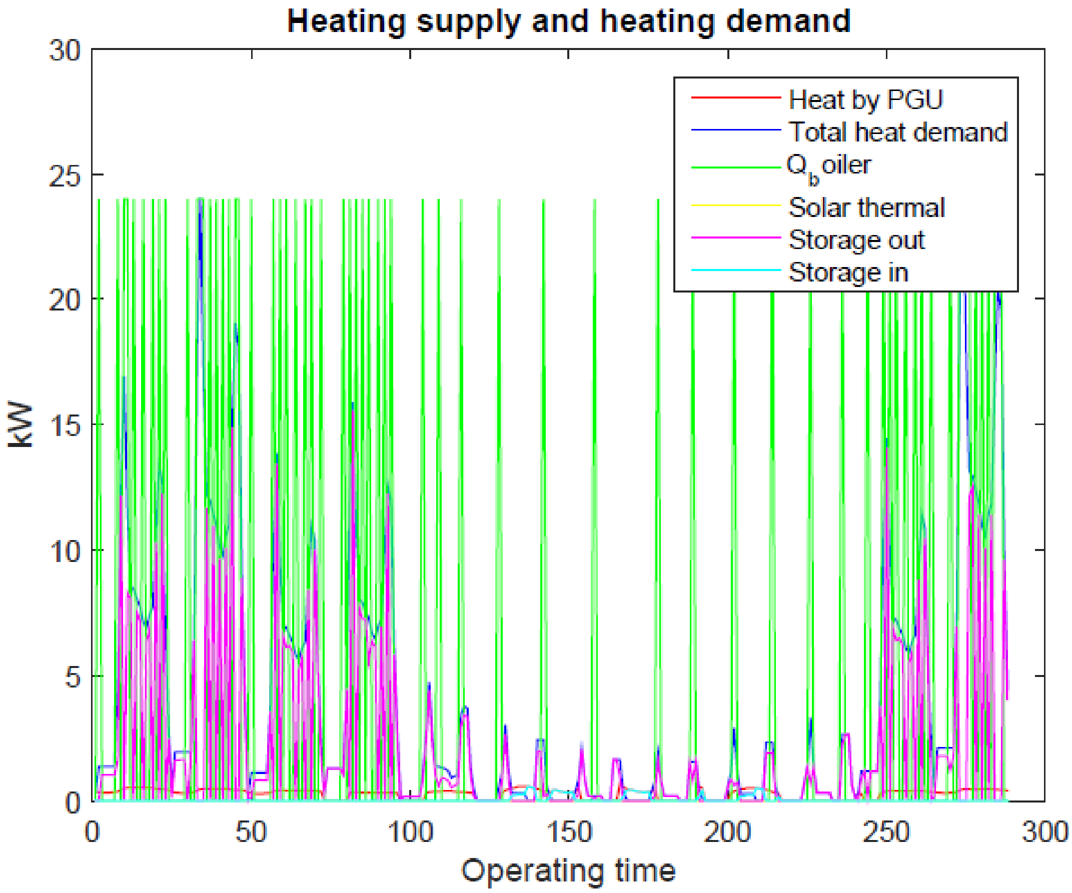


Figure 27: Heating supply in Case #7

The total annual costs of all case are listed below in Table 19 for an economic comparison.

Table 19: Total annual costs for all cases

Case #	**Total annual cost**
1	3787.40 €
2	1299.10 €
3	935.40 €
4	1005.30 €
5a	740.94 €
5b	1353.20 €
6	862.50 €
7	872.01 €

From all the cases, Case 5a is the one with the least cost. This indicates that having a storage to store the excess heat from the boiler significantly contributes to cost savings. Since the electricity demand is relatively much lower compared to the heat demand in Ankara, when electricity demand following operation is chosen, the size of the PGU is low. Thus, the share of heat that the PGU supplies compared to the boiler is small. Therefore, the case where a storage is integrated with separate production has a lower cost even though separate production is more expensive than any case with a CHP unit running on electrical load following operation.

From the cases with a CHP unit, the best choice, economically, is Case 6. This is due to the lower boiler size achieved by the PGU, solar thermal collectors and the storage. This results point out to the significance of utilizing waste heat as the boiler size has a considerable effect on annual total cost of the system. However, the effect of the capital and O&M sizes of the components should also be emphasized.

As for the operational strategy selection, electrical load following operation is the winner as the case with thermal demand following operation has the highest total annual cost among all cases. This is due to the selling price of electricity to the grid. Since the gain from selling excess electricity is not that high, thermal load following operation is not the best choice even for households having a much higher heat load than the electricity load.

7 Conclusion

The energy profile in the world is going through a transition for a cleaner and more sustainable energy system and the role of polygeneration systems are quite significant for this change to happen. Due to the large share of residential consumption, this study focused on small-scale polygeneration systems, particularly cogeneration and trigeneration systems as they are commonly used. System configuration, component sizes and operational strategy are very important for these systems. In order to provide a guidance for people who want to invest in CHP or CCHP units, decision making criteria were determined for selecting the prime mover as it is the most crucial component of such systems. Internal combustion engines, Stirling engines, micro turbines and fuel cells were evaluated by these criteria. However, apart from these criteria, the importance of market conditions and weather conditions, thus energy demand profile are emphasized.

In this study, a system where a CHP unit coupled with solar thermal collectors, a thermal energy storage, an auxiliary boiler and a vapor compression chiller. In order to define the best operational strategy and component sizes, an optimization model was created on MATLAB and solved by genetic algorithm. The model is applied to a case study featuring a single-family household in Ankara, Turkey. Due to market conditions and the results from the component selection process, the prime mover was determined to be an internal combustion engine powered with natural gas. Following this, different cases with different operational strategies were constructed. The models were solved by genetic algorithm due to its advantages in finding the global optimum. The object for the optimization was minimizing the total annual cost. The results suggest several crucial points for system design which are listed as follows:

- Even though thermal load following operation has been recommended for households with high thermal demands and where grid connection, thus electricity being sold to the grid, is possible, the energy policies in that region must be carefully reviewed since the revenue that can be gained by selling excess electricity to the grid is a determinant in total annual cost.
- For household with high thermal demands, the boiler has a significant influence on system cost. Reduction in the size of the boiler may achieve significant drops in annual cost. Therefore, decreasing the size of the boiler is important.
- Solar thermal collectors contribute to decreasing the size of the boiler in a system, thus enabling cost savings.
- Having a storage is crucial in the system as it also enables size reduction for the boiler, therefore achieving cost savings.

As solar thermal collectors and the usage of electrical chillers are very common in Turkey, implementing the system that is proposed in this study can be relatively simple.

Future work can be done by analyzing different types of fuels, e.g. using biogas instead of natural gas. The usage of solar thermal collectors may be widened by using the modules for space heating as well as domestic how water demand.

8 References

[1] M. Liu, Y. Shi, and F. Fang, “Combined cooling, heating and power systems: A survey,” *Renew. Sustain. Energy Rev.*, vol. 35, pp. 1–22, 2014.

[2] D. W. Wu and R. Z. Wang, “Combined cooling, heating and power: A review,” *Prog. Energy Combust. Sci.*, vol. 32, no. 5–6, pp. 459–495, 2006.

[3] S. Murugan and B. Horák, “Tri and polygeneration systems - A review,” *Renew. Sustain. Energy Rev.*, vol. 60, pp. 1032–1051, 2016.

[4] H. Cho, A. D. Smith, and P. Mago, “Combined cooling, heating and power: A review of performance improvement and optimization,” *Appl. Energy*, vol. 136, pp. 168–185, 2014.

[5] M. Jradi and S. Riffat, “Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies,” *Renew. Sustain. Energy Rev.*, vol. 32, pp. 396–415, 2014.

[6] IEA, “How has electricity consumption evolved in OECD countries?,” 2016. [Online]. Available: https://www.iea.org/newsroomandevents/graphics/oecd-total-final-electricity-consumption-by-sectoral-share-1971-2013.html. [Accessed: 21-Sep-2016].

[7] H. Ren, W. Gao, and Y. Ruan, “Optimal sizing for residential CHP system,” *Appl. Therm. Eng.*, vol. 28, no. 5–6, pp. 514–523, 2008.

[8] J. J. Wang, Y. Y. Jing, and C. F. Zhang, “Optimization of capacity and operation for CCHP system by genetic algorithm,” *Appl. Energy*, vol. 87, no. 4, pp. 1325–1335, 2010.

[9] M. Ebrahimi and A. Keshavarz, “Prime mover selection for a residential micro-CCHP by using two multi-criteria decision-making methods,” *Energy Build.*, vol. 55, pp. 322–331, 2012.

[10] J. J. Wang, Y. Y. Jing, C. F. Zhang, and J. H. Zhao, “Review on multi-criteria decision analysis aid in sustainable energy decision-making,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2263–2278, 2009.

[11] F. A. Al-Sulaiman, F. Hamdullahpur, and I. Dincer, “Trigeneration: A comprehensive review based on prime movers,” *Int. J. Energy Res.*, vol. 35, no. 3, pp. 233–258, Mar. 2011.

[12] M. Bianchi, A. De Pascale, and P. R. Spina, “Guidelines for residential micro-CHP systems design,” *Appl. Energy*, vol. 97, pp. 673–685, 2012.

[13] L. Li, H. Mu, W. Gao, and M. Li, “Optimization and analysis of CCHP system based on energy loads coupling of residential and office buildings,” *Appl. Energy*, vol. 136, pp. 206–216, 2014.

[14] H. I. Onovwiona and V. I. Ugursal, “Residential cogeneration systems: Review of the current technology,” *Renew. Sustain. Energy Rev.*, vol. 10, no. 5, pp. 389–431,

2006.

[15] M. Sasso, “Methodologies for the Performance Assessment of Micro Hybrid Polygeneration Systems Energy in Buildings and Communities Programme October 2014 A Report of Annex 54 “ Integration of Micro - Generation and Related Energy Technologies in,” no. October, 2014.

[16] D. Sonar, S. L. Soni, and D. Sharma, “Micro-trigeneration for energy sustainability: Technologies, tools and trends,” *Appl. Therm. Eng.*, vol. 71, no. 2, pp. 790–796, 2014.

[17] M. M. Maghanki, B. Ghobadian, G. Najafi, and R. J. Galogah, “Micro combined heat and power (MCHP) technologies and applications,” *Renew. Sustain. Energy Rev.*, vol. 28, pp. 510–524, 2013.

[18] J. J. Wang, Y. Y. Jing, C. F. Zhang, G. H. Shi, and X. T. Zhang, “A fuzzy multi-criteria decision-making model for trigeneration system,” *Energy Policy*, vol. 36, no. 10, pp. 3823–3832, 2008.

[19] M-Trigen, “PowerAire.” M-Trigen, Houston, TX.

[20] A. Piacentino and F. Cardona, “An original multi-objective criterion for the design of small-scale polygeneration systems based on realistic operating conditions,” *Appl. Therm. Eng.*, vol. 28, no. 17–18, pp. 2391–2404, 2008.

[21] G. Angrisani, C. Roselli, and M. Sasso, “Distributed microtrigeneration systems,” *Prog. Energy Combust. Sci.*, vol. 38, no. 4, pp. 502–521, 2012.

[22] O. A. Shaneb, P. C. Taylor, and G. Coates, “Optimal online operation of residential µcHP systems using linear programming,” *Energy Build.*, vol. 44, no. 1, pp. 17–25, 2012.

[23] K. K. Roman and J. B. Alvey, “Selection of prime mover for combined cooling, heating, and power systems based on energy savings, life cycle analysis and environmental consideration,” *Energy Build.*, vol. 110, pp. 170–181, 2016.

[24] W. Jiang-Jiang, Z. Chun-Fa, and J. You-Yin, “Multi-criteria analysis of combined cooling, heating and power systems in different climate zones in China,” *Appl. Energy*, vol. 87, no. 4, pp. 1247–1259, 2010.

[25] W. Gu, Z. Wu, R. Bo, W. Liu, G. Zhou, W. Chen, and Z. Wu, “Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review,” *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 26–37, 2014.

[26] A. Nadi, G. Kayakutlu, and S. Ercan, “An application of multiple criteria decision making on selecting the prime mover for trigeneration systems,” *J. Aeronaut. Sp. Technol.*, vol. 9, no. 1, 2016.

[27] M. Velasquez and P. Hester, “An Analysis of Multi-Criteria Decision Making Methods,” *Int. J. Oper. Res.*, vol. 10, no. 2, pp. 55–56, 2013.

[28] K. Darrow, R. Tidball, J. Wang, and A. Hampson, “Catolog of CHP Technologies - U. S. Environmental Protection Agency Combined Heat and Power Partnership,”

no. March, 2015.

[29] J. D. Nixon, P. K. Dey, and P. A. Davies, "Design of a novel solar thermal collector using a multi-criteria decision-making methodology," *J. Clean. Prod.*, vol. 59, pp. 150–159, 2013.

[30] S. Burge, "Pugh Matrix (PM)," *Syst. Eng. Tool Box*, pp. 1–15, 2009.

[31] Cogen Europe, "Vaillant EcoPOWER 1.0," no. February, p. 2010, 2010.

[32] Senertec, "Dachs Stirling SE," 2013.

[33] Hexis, "Galileo 1000 N," 2013.

[34] MTT Micro Turbine Technology, "EnerTwin," 2016.

[35] B. Wu and L. Wang, "Comparable analysis methodology of CCHP based on distributed energy system," *Energy Convers. Manag.*, vol. 88, pp. 863–871, 2014.

[36] N. Eskin and H. Türkmen, "Analysis of annual heating and cooling energy requirements for office buildings in different climates in Turkey," *Energy Build.*, vol. 40, no. 5, pp. 763–773, 2008.

[37] IEA, *Integration of Microgeneration and Related Technologies in Building Energy in Buildings and Communities Programme October 2014 Final Report of Annex 54*, no. October. 2014.

[38] K. C. Kavvadias, A. P. Tosios, and Z. B. Maroulis, "Design of a combined heating, cooling and power system: Sizing, operation strategy selection and parametric analysis," *Energy Convers. Manag.*, vol. 51, no. 4, pp. 833–845, 2010.

[39] M. Renzi and C. Brandoni, "Study and application of a regenerative Stirling cogeneration device based on biomass combustion," *Appl. Therm. Eng.*, vol. 67, no. 1–2, pp. 341–351, 2014.

[40] D. Maraver, A. Sin, J. Royo, and F. Sebasti??n, "Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters," *Appl. Energy*, vol. 102, pp. 1303–1313, 2013.

[41] V. Kuhn, J. Klemeš, and I. Bulatov, "MicroCHP: Overview of selected technologies, products and field test results," *Appl. Therm. Eng.*, vol. 28, no. 16, pp. 2039–2048, 2008.

[42] W. L. Becker, R. J. Braun, M. Penev, and M. Melaina, "Design and technoeconomic performance analysis of a 1 MW solid oxide fuel cell polygeneration system for combined production of heat, hydrogen, and power," *J. Power Sources*, vol. 200, pp. 34–44, 2012.

[43] J. Deng, R. Z. Wang, and G. Y. Han, "A review of thermally activated cooling technologies for combined cooling, heating and power systems," *Prog. Energy Combust. Sci.*, vol. 37, no. 2, pp. 172–203, 2011.

[44] A. Lowenstein, "Review of Liquid Dessciant Technology for HVAC applications,"

HVAC&R Res., vol. 9669, no. June, p. 22, 2008.

[45] J. Wang, Z. J. Zhai, Y. Jing, and C. Zhang, “Particle swarm optimization for redundant building cooling heating and power system,” *Appl. Energy*, vol. 87, no. 12, pp. 3668–3679, 2010.

[46] IEA, “Energy Storage Technology Roadmap,” *Technol. Annex*, no. March, pp. 1–31, 2014.

[47] Y. Kalinci, A. Hepbasli, and I. Dincer, “Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options,” *Int. J. Hydrogen Energy*, vol. 40, no. 24, pp. 7652–7664, 2015.

[48] A. Hepbasli, “A key review on exergetic analysis and assessment of renewable energy resources for a sustainable future,” *Renew. Sustain. Energy Rev.*, vol. 12, no. 3, pp. 593–661, 2008.

[49] R. Luna-Rubio, M. Trejo-Perea, D. Vargas-Vázquez, and G. J. Ríos-Moreno, “Optimal sizing of renewable hybrids energy systems: A review of methodologies,” *Sol. Energy*, vol. 86, no. 4, pp. 1077–1088, 2012.

[50] W. Zhou, C. Lou, Z. Li, L. Lu, and H. Yang, “Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems,” *Appl. Energy*, vol. 87, no. 2, pp. 380–389, 2010.

[51] O. Erdinc and M. Uzunoglu, “Optimum design of hybrid renewable energy systems: Overview of different approaches,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 3, pp. 1412–1425, 2012.

[52] P. Liu, D. I. Gerogiorgis, and E. N. Pistikopoulos, “Modeling and optimization of polygeneration energy systems,” *Catal. Today*, vol. 127, no. 1–4, pp. 347–359, 2007.

[53] M. Ebrahimi and A. Keshavarz, “Sizing the prime mover of a residential micro-combined cooling heating and power (CCHP) system by multi-criteria sizing method for different climates,” *Energy*, vol. 54, pp. 291–301, 2013.

[54] O. A. Shaneb, G. Coates, and P. C. Taylor, “Sizing of residential micro-CHP systems,” *Energy Build.*, vol. 43, no. 8, pp. 1991–2001, 2011.

[55] C. Qin, J. Tang, and Y. Zhang, “An efficient algorithm for CCHP system sizing and an operational optimization model based on LP,” *J. Nat. Gas Sci. Eng.*, vol. 25, pp. 189–196, 2015.

[56] European Committee for Standardization CEN, “Heating systems in buildings — Method for calculation of system energy requirements and system efficiencies — Part 4-3 Space heating generation systems , thermal solar systems,” *Bs En 15316-4-32007*, pp. 1–40, 2007.

[57] E. Cardona and A. Piacentino, “A methodology for sizing a trigeneration plant in mediterranean areas,” *Appl. Therm. Eng.*, vol. 23, no. 13, pp. 1665–1680, 2003.

[58] C. Brandoni and M. Renzi, “Optimal sizing of hybrid solar micro-CHP systems for

the household sector," *Appl. Therm. Eng.*, vol. 75, pp. 896–907, 2015.

[59] S. F. Fux, M. J. Benz, and L. Guzzella, "Economic and environmental aspects of the component sizing for a stand-alone building energy system: A case study," *Renew. Energy*, vol. 55, pp. 438–447, 2013.

[60] R. Viral and D. K. Khatod, "Optimal planning of distributed generation systems in distribution system: A review," *Renew. Sustain. Energy Rev.*, vol. 16, no. 7, pp. 5146–5165, 2012.

[61] Mathworks, "Global Optimization Toolbox User's Guide," 2016.

[62] Meteotest, "Meteonorm." Bern, 2016.

[63] SoDa, "Time series of solar irradiation data," 2016. [Online]. Available: http://www.soda-is.com/eng/index.html. [Accessed: 01-Aug-2016].

[64] Turkish State Electricity Transmission Company, "Load Dispatch Information System," 2016. [Online]. Available: http://ytbs.teias.gov.tr/ytbs/frm_login.jsf. [Accessed: 07-Jul-2016].

[65] M. Bianchi, A. De Pascale, and F. Melino, "Performance analysis of an integrated CHP system with thermal and Electric Energy Storage for residential application," *Appl. Energy*, vol. 112, pp. 928–938, 2013.

[66] E. Filoglu, "Micro-cogeneration in Turkey," *Turkish Cogener. Clean Energy Technol. Assoc.*, 2011.

[67] Ener-G, "Cogeneration Brochure," 2011.

[68] Teksan, "Cogeneration Units Brochure," 2016.

[69] U. Stritih, E. Osterman, H. Evliya, V. Butala, and H. Paksoy, "Exploiting solar energy potential through thermal energy storage in Slovenia and Turkey," *Renew. Sustain. Energy Rev.*, vol. 25, pp. 442–461, 2013.

[70] EPDK, "Regulation regarding unlicensed electricity generation in energy markets," *Off. Gaz.*, vol. 28559, 2013.

[71] Ministry of Energy and Natural Resources, "Statement on calculation of efficiencies of cogeneration and microcogeneration systems," *Off. Gaz.*, vol. 1, no. 1, 2014.

[72] EPDK, "Law for electricity production from renewable energy soruces," *Off. Gaz.*, vol. 44, no. 25819, 2005.

[73] Ministry of Environment, "Regulation regarding the control of GHG emissions caused by the industry," vol. 3, no. May, pp. 1–74, 2011.

[74] Trading Economics, "Turkey- interest rate," 2016. .

[75] IRENA, "IRENA-IEA-ETSAP Technology Brief 4: Thermal Storage," no. January, 2013.

[76] Arcelik A.S., "Arcelik Air-conditioner manual," Istanbul, 2016.

[77] Ezinc A.S., “Product Specifications,” no. November. 2012.