CRANFIELD UNIVERSITY

M. SYMEONIDOU

AN OPTIMIZATION TOOL FOR THE MANAGEMENT OF SMART MICRO-GRIDS

SCHOOL OF WATER ENERGY AND ENVIRONMENT
Energy Systems and Thermal Processes

MSc Thesis
Academic Year: 2016 - 2017

Supervisor: G. Kopanos
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This thesis is submitted in partial fulfilment of the requirements for the degree of MSc

Η παρούσα Διπλωματική εργασία πραγματοποιήθηκε στο πλαίσιο του προγράμματος ERASMUS+, με χρηματοδότηση της Ε.Ε.

Abstract

This project deals with the promising technology of micro-generation and the energy supply chain network in residential scale by proposing an optimization tool for the management of smart micro-grids. Firstly, the problem is being demonstrated by examining a network of houses that can not only produce the demand heat and electricity but also, interchange electricity between them and with the main grid. Secondly, a mathematical framework is being created and used for the optimization of the operation and the energy supply of such a system. The objective function of the model is being demonstrated taking into account the submission of all costs involving in the system, aiming in minimizing the total cost of the micro-grid. Thirdly, two main case studies consisting of several instances are being presented so as to underline the importance of choosing the appropriate scope for the problem in question. As a second part of the project, a graphical user interface (GUI) has been created so for the user to be easy to formulate the problem as wanted by modifying all the input data based on the problem statement, and at the end to obtain all needed graphs, figures and tables scoping in understanding the result of the optimization. The analysis concludes with some outcomes and potential for future research.

Keywords:

Energy Production; Energy Planning; Supply Chain Network; Demand Side Management; Smart Grid; Micro Combined Generation; Optimization Tool; Cost Saving; Carbon Dioxide; Emission Saving; GAMS; AIMMS; Graphical User Interface.

Acknowledgements

First and foremost, I would like to thank my supervisor Dr. Giorgos Kopanos, for his continuing support during all those months and his unstoppable guidance that provided to me. I would like to express my happiness, being so lucky to collaborate with him. I feel grateful that he was always available and able to help me, no matter how many hours should we spend so as to find the solution to the problem. Also, that he suggested that intriguing topic to me to be my Thesis. Finally, I wanted to express my feeling of having learnt so many things under the Thesis conducting, that will absolutely be helpful for my future career.

Secondly, it is important for me to thank my professors in the University of Western Macedonia for their support to my double degree studies and especially, Dr. Tourlidakis Antonios for believing in me and giving this great opportunity to me so as to study in Cranfield University.

Thirdly, many thanks go also to my family, for helping me so many years, during my studies and not only, for them being always there for me and make every possible step so as to support me in all my dreams to come true.

Fourthly, I would also like to express my gratefulness to my friends, those being my friends for so many years and them that I met to Cranfield University.

Finally, the conducting of this Thesis would be much harder, without the facilities of the University and the helpful library and IT staff.

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List of Abbreviations

AIMMS	Advanced Interactive Multidimensional Modelling System
CO_2	Carbon Dioxide
DER	Decentralized Energy Resources
DHW	Domestic Hot Water
DSM	Definition of Demand-Side Management
FC	Fuel Cells
FIT	Feed-In-Tariff
GAMS	General Algebraic Modelling Systems
GUI	Graphical User Interface
HS	Heat Storage
ICE	Internal Combustion Engine
IEA	International Energy Agency
LP	Liner Programming
mGT	Micro-Gas Turbine
Micro-CHP	Micro Combined Heat and Power
MILP	Mixed Integer Liner Programming
MINLP	Mixed Integer Non Liner Programming
mRC	Micro Rankine Cycle
NLP	Non Liner Programming
OM	Operational Mode
PV	Photovoltaic
RES	Renewable Energy Technologies
SE	Stirling Engine

TPV	Thermo-Photovoltaic Generators

Chapter 1

Introduction

One of the most crucial and initial needs of the humanity is energy. The development of the world is inextricably linked to the energy progress. Because of the population's expansion and the increase of life's requirements, huge amounts of fossil fuels are being burnt globally so as to cover the human needs. Due to the environmental reasons, the economical aspects and the technical issues that exist, micro-grids seem to play a key role in solving those problems. For that reason, they are rapidly being adopted by the energy sector in order to improve the way the power is being efficiently produced.

More specific, micro-grids are a small scale distribution network that is usually connected to the main grid. Those grids are able to supply the power needed within the network and also transmit power from and to the main grid [1]. Cogeneration, which is actually the simultaneously generation of heat and electricity, seems to be one of the most efficient ways for small-scale units. One of the most important benefits of cogeneration is that the overall efficiency of the system is increased at 90% contrary to 40-45% that can be achieved when producing only electricity [9]. Furthermore, what seems to be of great importance is that the losses due to the transmission and distribution are being minimized [2]. Finally, significant decreases in cost, carbon emissions and increase of system's efficiency in domestic scale, can also be noticed when using a micro Combined Heat and Power unit (micro-CHP) [3].

Moreover, regarding the micro-CHP technologies a variety of them have already been developed. The two most basic technologies in which micro-CHP could be categorized are the combustion and electrochemical ones. Those two refer to the different way by which the chemical energy of the fuel is being converted into the beneficial forms of heat and power. Some instances of the combustion technologies could be the micro-turbine gas engines, the stirling engines and the reciprocating engines that deals with the combustion and the conversion of mechanical power. Also, fuel cells are one example regarding the electrochemical technologies that directly handle the chemical energy of the fuel [4]. Although the output of such systems seems to be a low one (around 5kW of electricity), it is ideal for use in a house-scale [8].

Finally, it is important to refer to the United Kingdom's status where one quarter of the greenhouse emission is an outcome of the energy for domestic use [5]. Therefore, it is essential to find a way for reducing those emissions and the United Kingdom government seems to encourage the costumers to manage it by providing the micro-generation. Actually, nowadays the Feed-In-Tariff (FIT) is one of the most significant motives to the householders. FIT is a pay-back way to the residents not only for every kW that they produced from a micro-CHP but also for each kW that they export. To conclude, the benefits and the significance of using a micro-generation technology are numerous and attention should be paid to that technology.

Based on the facts mentioned above and on the significance of the micro-grids, the objective of the project was firstly to formulate the proper mathematical equations so as to approach a problem based on micro-grids and optimise the total cost and energy demand of that and secondly to create a GUI so for the user to be easy to use it and obtain the final result in demonstrative ways.

Chapter 2

Literature Review

2.1 The micro-CHP system

Micro-generation technologies are advancing more and more, developing the ways in which households and utility providers cover the energy needs. Nowadays, energy supply chains that are based on micro-generation systems are gaining significant importance. What is new in micro-generation system compared to the conventional energy generation system is that the main grid does not play the main role for the energy production. Instead it is used only as a back-up solution for the micro-generation technology. Electricity sharing between houses is a possibility due to the smart micro-grid connection that exists between them. This technology is able to satisfy both social and energy policies; the decentralization of both the supply and energy production, the reduction in costs and carbon dioxide (CO_2) emissions, the minimization of the losses during the transmission and distribution could be referred as some of the main advantages of the technology mentioned above [21]. Additionally, one of the most significant improvements that micro combined heat and power system can offer is the reduction of energy regarding the electricity used, the domestic hot water consumption and the space heating [22]. During the last years, the important factor that made the market to turn to that sector is the efficient way in which the micro-CHP can change the electrical load so as to satisfy the thermal output needed by either minimize or maximize it [23], [24], [25].

2.2 Micro-CHP Technologies

As it was mentioned, micro-CHP is nowadays gaining a lot of importance. For that reason, many technologies have already been developed and they are going to be examined following. International Energy Agency (IEA) has confirmed the micro-CHP as the simplest and easiest way of cogeneration [26]. There are several types of micro-CHP available for residential operation such as the micro-Gas Turbine (mGT), Internal Combustion Engine (ICE), Fuel Cells (FC), Stirling Engine (SE), micro Rankine Cycle (mRC), Thermo-Photovoltaic Generators (TPV) [27], [28], [29], [30], [31].

Micro Gas Turbine (mGT)

The use of multiple fuel, the high efficiency and the minimum efficiencies are some of the main characteristics of that type. The thermal efficiency is around 30%. A turbine, a compressor, a generator and a combustor are the parts by which a mGT consists of. Also, two are the basic cycles of a mGT, either a simple cycle or a recuperated type [32]. Finally, the electrical efficiency in the recypated cycle is doubled because of the heat recovered from the boiler [33].

Internal Combustion Engine (ICE)

The electrical efficiency of an ICE is 20% to 26% whilst the overall system efficiency is up to 90% [22]. Based on the output demands, the type of fuel used and the constrains of the space, both the compression ignition and the spark ignition can be used. However, the durability of the engine, the power density per kWh and the emissions when using a ICE for a micro-CHP unit, are yet the challenges that need to be overcame.

Fuel Cells (FC)

The electrochemical reaction of the fuel between the anode and the cathode of a fuel cell is the main source causing the movement of the ions resulting in the electric current in the external circuit [34]. The use of fuel cells can exist in residential sector as referred in [35].

Stirling Engines (SE)

The SE are available to the market for residential use offering a thermal output around 5 to 25 kW and an electric one around 1 to 9 kW. They can offer an efficient alternative to the household boilers. The efficiency of them is around 13% to 26% while the overall efficiency of the micro-CHP system is equal or greater to 80% [36].

Micro Rankine cycles (mRC)

In this type of micro-CHP unit, a Rankine cycle is taking place and an organic fluid such as water is usually used as the working fluid. The electric power can be between 1 to 10 kW as the thermal output can vary between 8 to 44 kW respectively. The overall micro-CHP efficiency is most of the times even higher than 90% [22].

Thermo-Photovoltaic Generators (TPV)

Photovoltaic parts can be placed in the surface of the combustor so as to maximize the boiler efficiency. Similarly to the previous cases, the micro-CHP efficiency is also around 90% [22].

2.3 Micro-grids in residential scale

The common way of the production and the supply of the needed electricity is the production of that to the conventional power stations such as the coal, nuclear and the gas fired plants. After the production, the electricity is transmitted through the power lines to the costumers.

Generation, transmission, distribution and production are the four categories in which the power procedure could be categorized to. Based on the current balance between the demand and supply, the price of electricity is then being formed. It should be mentioned that the Distribution Network Operators that are responsible for estimating the demand, do not have access in real time data, thus, most of the times the expected demand is overestimated [21]. Therefore, the increase of the system's efficiency is always a target, scoping in better managing of power production complexity.

In the meantime, many ways have been improved so as to help in solving the problem mentioned above. Renewable Energy Technologies (RES) could be referred as one of those. However, the most recent and advancing technology is the smart grids or micro-grids that have already been tested with significant results [37].

A micro-grid is actually a smart grid that is based on a small area network scoping in exploiting mostly clean energy so as to produce the energy needed within the micro grid and be independent from the main grid. RES or micro-CHP are two of the main technologies used for the energy production. Even though, the purpose of the smart grid is not to purchase electricity from the main grid so as to reduce the costs and the transmission losses, sometimes this is not enough to cover the main needs. In that case, there is the possibility of purchasing the extra electricity needed. For that reason the smart grids are flexible because they can either use or not the electricity from the main grid. Furthermore, the flexibility of storing the excess electricity produced by the smart grid is an important parameter of this technology [38], [39]. This can be used for later use or be sold to the main grid. Last but not least, those technologies have the constant support of the government (most of the times in the way of money paying back tariffs) because of the advantages that they can offer, as mentioned above [40], [41].

2.4 Definition of Demand-Side Management (DSM)

One of the most difficult tasks and challenges that occur to the energy supply, is the management of its production. Essentially, for the case that the smart grid is supplied by Photovoltaic (PV) panels, wind turbines or generally RES, the prediction of the energy that they can offer is a challenge because of the difficult weather prediction, the unexpected factors that may occur and even in the case of well work of them, the difficulty in matching between the time of the production and the demands [42].

Demand-Side Management is one technique that can be used so as to solve the problem mentioned above. This term had the first application in 1970 [21] and its objective is the change in the habits of the consumers and the deal with the peak demands. The bills of electricity and also the energy used can be reduced efficiently. Several methods and strategies of DSM can be used so as to achieve the target. To name a few, the controllable loads, the energy consumption profile, the variable price of electricity, the day-ahead forecast may be some of them. Furthermore, the approach of the problem varies depending on the consumer, the provider, the loads, the prices, the devices used.

Finally, both the providers and the consumers can be benefit for the DSM. The profit of the provider can be maximised simultaneously with better welfare of the costumer's life [43], [44].

2.5 Main Decision Support Tools

The mathematical programming is one of the most important support tools that can be used so as to optimize the problem in scope. The definition of the objective function, the description of the problem through the different variables and the constrains needed to ideally formulate the problem, are the first steps that have to be formed so for the problem to be optimized [45]. Depending on the structure of the objective function, the computer solving can be Linear Programming (LP), Non-Linear Programming (NLP) or Mixed Integer Linear Programming (MILP), Mixed Integer Non-Linear Programming (MINLP) and others [46]. Some of the software that can be used to solve that type of problems are the reMIND, GAMS, AIMMS, AMPL, LINGO, HOMER, RETSCREEN etc. [47].

2.6 Previous works have been done

Over the last decades attention has been paid to developing optimization models. However, not that many have already been made for the networks based on the micro-generation. Mehleri et al. [6] developed an optimization model regarding the decentralized energy resources (DER) based on the heat load so as to meet the requirements in domestic level. This work was mostly based on the design and sizing of the heating pipeline of the system. Moreover, Collazos et al. [7] approached the maximization of the efficiency of a micro-CHP network by the use of mixed integer linear programming. What was considered in the last study was the exchange of electricity between the micro-grid, the storage heat levels within the tanks and the planning of the operation of the system. The most important point of that work was that the mass flow rate of the system and also the input and the output temperatures of the elements of installations were taken into account. Kopanos et al. in [8] developed a model similar to the previous approach and with the thought of installing heat storage tanks and micro-CHP units in every house. Additionally, back-up gas burner is added to the households so as to meet the high heat demands. The houses can also interchange electricity between them. That work focuses on the minimization of the total cost. Furthermore, capital cost was added to the objective function by Koltsaklis et al. [9]. External heat importation to the micro-grid was also an important improvement of the last work mentioned above. Similarly to the previous works, Zhang, Luo and Chen in [10] developed a model based on mixed integer non-linear programming that concentrates mostly on the utility optimization of the system, of the heat integration process and the integration of the site-scale steam.

Furthermore, Pipattanasomporn, Feroze, Rahman in [11] worked on the possibility of disconnecting the micro-grid form the macro-grid and make it independent, so as for the micro-grid system to be able to cover both critical and non-critical loads. In continuing, Logenthrian, Srinivaran and Khambadkone in [12] came up with a model to determine the cost of the system considering the local demand, the way to transfer the energy to the main grid and the planning of the micro-grid by the current demand and sales. Lee and Bahn [13] made an algorithm considering the real-time pricing and that led to a significant cut of the total cost.

It is important to notice that there is not any previous work in developing a model that emphasizes on the fixed or variable heat to electricity ratio and simultaneously taking into account such a complex micro-generation system (provided with renewable sources such as PV panel and wind turbine) so as to minimize the cost of it. Additionally, one important aspect that had not been taken into account in the previous works, is the carbon dioxide footprint and the influence of that on the total cost. Furthermore, the time intervals could be greater so that for the flexible power consumption of the appliances to be more accurate. The current approach aims to develop such a model and lead the research even further.

Chapter 3

Materials and Methods

3.1 Problem explanation

In the current study, a micro-grid of 60 houses is being developed. The needed heat and electricity are being produced by a micro-CHP system that every house is equipped with. That produced energy is being used directly to cover the needs of each house. Furthermore, all of the houses are connected between them by an electrical distribution system.

Considering a single house of the residential micro-grid, apart from the micro-CHP that it is equipped with, there is also a back-up gas burner and also two tanks for the heat storage and heat being used. The back-up gas burner is set to be used in case the heat demand of the house is greater than what is being generated by the micro-CHP. Respectively, the two tanks are for storing the heat for the domestic hot water or space heating and for later use of those. It should be mentioned that the use of the tanks is an important one because it helps in dealing with possible short running times or with intermittent switch on and off of the micro-CHP equipment that otherwise would lead to a negative performance of the system. Also, extra electricity is being produced from the solar photovoltaic panels that each house is provided with. Furthermore, a wind turbine is being considered for the whole network that can provide extra electricity needed. The majority amount of electricity will be consumed within the house or it will be shared between the houses in the micro-grid. If excess electricity exists it will be sold to the main grid or be saved to the battery for later use. A brief description of the model for each house is being presented in Figure 3.1.

It is important to mark that such a micro-grid network can offer a variety of alternatives for the efficient use of the energy between the residential system. For that reason, a micro-grid administrator is being considered so as to satisfy the needs in the most efficient way. Finally, a model based on computer aid and a tool to help in dealing with such a complex problem seems to be of great importance.

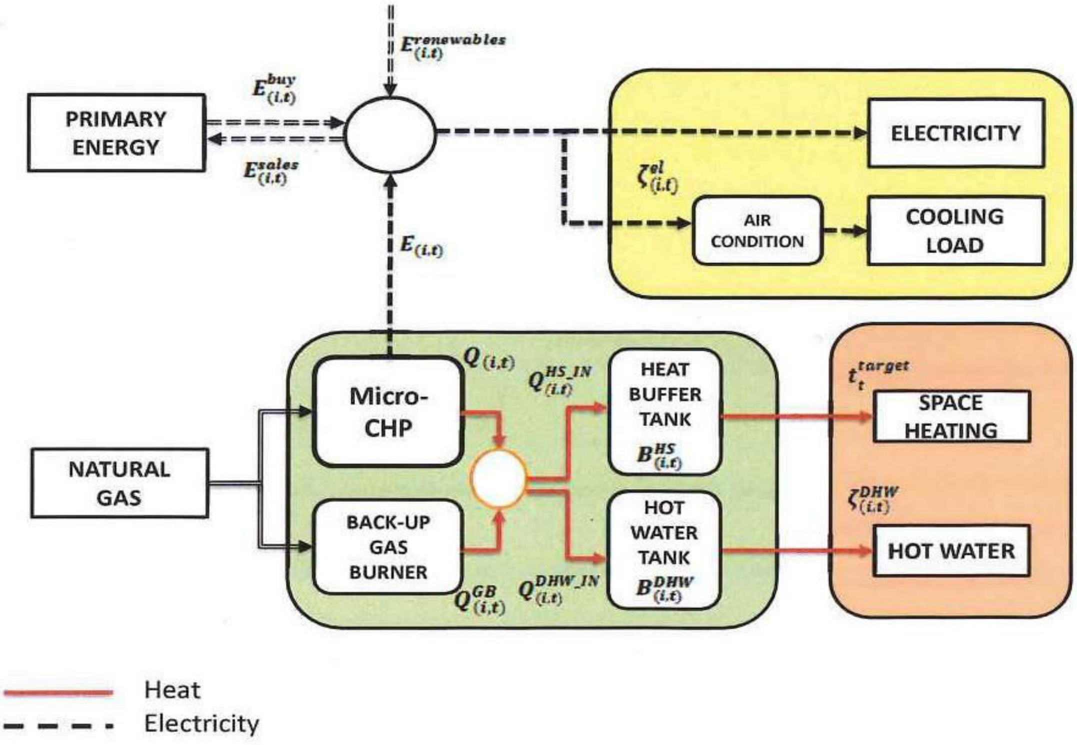


Figure 3.1: Structure of the micro-CHP system.

The produced electricity by either the PV panel or the wind turbine are being calculated as follows:

$$e^{PV}_{(i,t)} = rad_t a^{PV} \eta^{panel} \eta^{system} \eta^{temperatures} \eta^{reflection} \qquad [14] \qquad \forall i \in I, t \in T$$

$$e_t^{wind} = 0.5(v_t^{wind})^3 a^{wind} \delta^{air} c_p^{wind} \qquad [15] \qquad \forall t \in T$$

In Figure 3.2 it is demonstrated the usage of the wind turbine. One wind turbine is assumed for the whole system so the generation of that is being shared to the houses need excess of electricity. That excess could also be bought from the main grid but the scope of the wind turbine is to decrease the electricity bought due to its high cost and carbon dioxide emissions. Finally, the Figure mentioned above, represents the total electricity that could be sold to the main grid. That consists of the submission between the electricity that each house may sell.

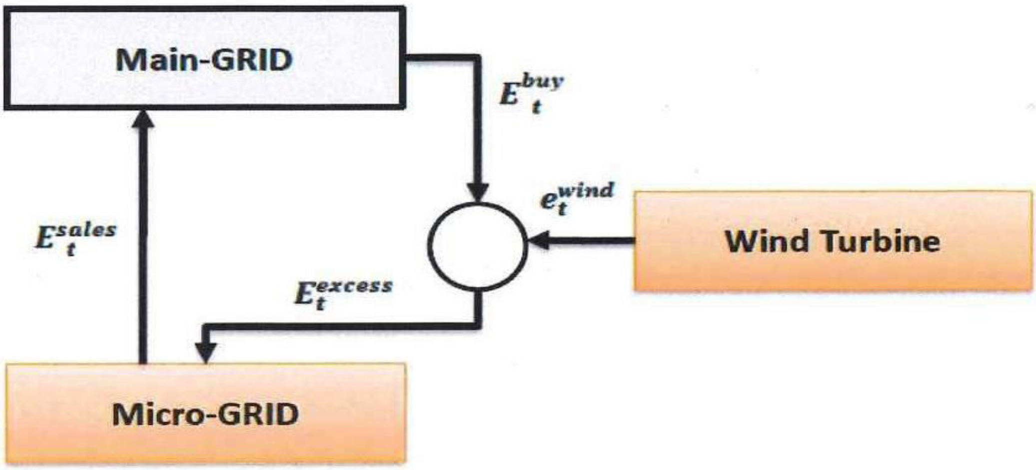


Figure 3.2: Total electricity bought and sold to the main grid-Wind turbine usage.

The main decisions to be made by the optimization model, for every time interval are the following:

- The operation or not of the micro-CHP for every household.
- The heat production load for every household.
- The gas burner for excess heat production.
- The supply of electricity from the PV panel, the wind turbine or from the

main grid.

- The selection of the timings for the appliances.

3.2 Mathematical Formulation

In this section, the expressions and equations that formed and used for the model will be presented. Those are a development of the approach made in [48]. The variables and parameters used for the problem will also be examined. Furthermore, a mixed linear programming framework is the one that is used for the production planning. Finally, capital Latin letters are being used to represent the variables and lower-case Greek or Latin letters represent the parameters of the problem.

Objective function

One of the most important step is the appropriate definition of the objective function that should be optimized. For that reason, all the elements that affect to the overall cost of the system should be integrated so as to be optimized. Specifically, the cost of the micro-CHP regarding the start-up and shut-down, the fuel of the back-up gas burner, the fuel of the micro- CHP depending on the type of heat and electricity production, the fact of buying electricity from the main grid, some more factors like the comfort penalties, and emission penalties are taken into account so as to calculate the total cost. However, there are some benefits that are added to the function such as the FIT, the fact that the production is an outcome of the micro-CHP, the production from PV and wind turbine and the possibility of selling electricity to the main grid. It should be noticed that the cost between the micro-CHP fuel and the back-up gas burner varies because it is divided by the efficiency of each one. Finally, the objective function that should be optimized is the following:

$$\begin{aligned}
&\sum_{i\in I}\sum_{t\in T}\theta_i^S\,S_{(i,t)}+\sum_{i\in I}\sum_{t\in T}\theta_i^F\,F_{(i,t)}+\sum_{i\in I}\sum_{t\in T}\xi_{(i,t)}^{GB}\,Q_{(i,t)}^{GB}\Delta t+\sum_{i\notin I^{OM3}}\sum_{t\in T}\xi_{(i,t)}\,Q_{(i,t)}^{S}\Delta t\\
&+\sum_{i\in I^{OM3}}\sum_{t\in T}\xi_{(i,t)}\,\rho_{(i)}^{max}E_{(i,t)}\Delta t+\sum_{i\in I}\sum_{t\in T}\xi_{(i,t)}\,cp_iT_{(i,t)}^{dev}\Delta t\\
&+\sum_{i\in I}\sum_{t\in T}\xi_{(i,t)}\,dp_iQ^{disp}(i,t)\Delta t+\sum_{i\in I}\sum_{t\in T}\psi_t\,E_{(i,t)}^{buy}\Delta t\\
&+\sum_{i\in I}\sum_{t\in T}\nu^{co2,c}\,E_{(i,t)}\Delta t+\sum_{i\in I}\sum_{t\in T}\nu^{co2,b}\,Q_{(i,t)}^{GB}\Delta t+\sum_{i\in I}\sum_{t\in T}\nu^{co2,eb}\,E_{(i,t)}^{buy}\Delta t\\
&-\sum_{i\in I}\sum_{t\in T}\pi^{CHP}\,E_{(i,t)}\Delta t-\sum_{i\in I}\sum_{t\in T}\pi_t\,E_{(i,t)}^{sales}\Delta t-\sum_{i\in I}\sum_{t\in T}\pi^{PV}\,e_{(i,t)}^{PV}\Delta t-\sum_{t\in T}\pi^{wind}\,e_t^{wind}\\
&\forall i\in I,t\in T
\end{aligned} \tag{3.1}$$

Operational constrains of the micro-CHP generators

Some binary variables have been defined so as to avoid the starting-up or shutting-down of the equipment more times than one in the same time interval. Those constrains could lead to more realistic use of the micro-CHP because of the limited time that it should operate once it starts and also the minimum time it should work without efficiency losses before shutting-down.

The binary $X_{(i,t)}$ indicates the operation or not of the system at the time interval t, $S(i,t)$ is the start-up binary that describes the operation at the beginning of time t, $F(i,t)$ is the shut-down binary that is about the switching of at time t.

$$S_{(i,t)}-F_{(i,t)}=X_{(i,t)}-X_{(i,t-1)}\qquad\forall i\in I,t\in T \tag{3.2}$$

$$S_{(i,t)}+F_{(i,t)}\leq 1\qquad\forall i\in I,t\in T \tag{3.3}$$

$$\sum_{t'=t}^{t+\delta_i^{on}-1}X_{(i,t')}\geq\tilde{\delta}_{(i,t)}^{on}\,S_{(i,t)}\qquad\forall i\in I,t\in T \tag{3.4}$$

$$\sum_{t'=t}^{t+\delta_i^{off}-1} (1 - X_{(i,t')}) \geq \tilde{\delta}_{(i,t)}^{off} F_{(i,t)} \qquad \forall i \in I, t \in T \tag{3.5}$$

where

$$\tilde{\delta}_{(i,t)}^{on} = \begin{cases} \delta_i^{on} & \forall i \in I, t \leq |T| - \delta_i^{on} + 1 \\ |T| + 1 - t & \forall i \in I, t > |T| - \delta_i^{on} + 1 \end{cases}$$

and

$$\tilde{\delta}_{(i,t)}^{off} = \begin{cases} \delta_i^{off} & \forall i \in I, t \leq |T| - \delta_i^{off} + 1 \\ |T| + 1 - t & \forall i \in I, t > |T| - \delta_i^{off} + 1 \end{cases}$$

$$S_{(i,t)} - F_{(i,t)} = X_{(i,t)} - X_{(i,t-1)} \qquad \forall i \in I, t \in T \tag{3.6}$$

Furthermore, the energy ramp refers to the time needed for the micro-CHP so as to reach the demand and also the least it should operate once set into operation.

$$E_{(i,t)} - E_{(i,t-1)} \leq ramp_i^{up} \qquad \forall i \in I, t \in T \tag{3.7}$$

$$E_{(i,t-1)} - E_{(i,t)} - \leq ramp_i^{down} \qquad \forall i \in I, t \in T \tag{3.8}$$

The micro-CHP generators can operate within a limit. The constrains for the upper and lower range of that are illustrated in the following equation:

$$\theta_i^{min} X_{(i,t)} \leq Q_{(i,t)}^{s} \leq \theta_i^{max} X_{(i,t)} \qquad \forall i \in I, t \in T \tag{3.9}$$

Energy generation levels for micro-CHP units

The actual heat that can be used is the remaining of the generated heat subtracted the losses and adding the heat that is being produced even after the shutting-down of the system. Remaining heat that is not being used can be stored to the Heat Storage tank (HS) and the Domestic Hot Water tank (DHW).

$$Q_{(i,t)} = Q^s_{(i,t)} - \sum_{k=1}^{\alpha_i^-} \lambda^-_{(i,k)} \, S_{(i,t-k-1)} + \sum_{k=1}^{\alpha_i^+} \lambda^+_{(i,k)} \, F_{(i,t-k-1)} \qquad \forall i \in I, t \in T \tag{3.10}$$

Moreover, three operational modes are being analysed regarding the ratio between the heat and electricity production.

Operational Mode 1

The ratio between the produced heat and electricity is fixed.

$$Q^s_{(i,t)} = \rho_i E_{(i,t)} \qquad \forall i \in I^{OM1}, t \in T \tag{3.11}$$

Operational Mode 2

The ratio between the produced heat and electricity is variable.

$$X_{(i,t)} = \sum_{z \in Z_i} P_{(i,t,z)} \qquad \forall i \in I^{OM2}, t \in T, z \in Z \tag{3.12}$$

$$\rho_i^{min} \, X_{(i,t)} \le Q^s_{(i,t)} \le \rho_i^{max} \, X_{(i,t)} \qquad \forall i \in I^{OM2}, t \in T \tag{3.13}$$

$$\sum_{z \in Z_i} \varepsilon^{min}_{(i,z)} P_{(i,t,z)} \le E_{(i,t)} \le \sum_{z \in Z_i} \varepsilon^{min}_{(i,z)} P_{(i,t,z)} \qquad \forall i \in I^{OM2}, t \in T, z \in Z \tag{3.14}$$

$$Q^s_{(i,t)} \ge Q^{max}_{(i,z)} + \rho_{(i,z)}(E_{(i,t)} - \varepsilon^{min}_{(i,t)}) - \rho_i^{max}(1 - P_{(i,t,z)}) \qquad \forall i \in I^{OM2}, t \in T, z \in Z \tag{3.15}$$

$$Q^s_{(i,t)} \le Q^{max}_{(i,z)} + \rho_{(i,z)}(E_{(i,t)} - \varepsilon^{min}_{(i,t)}) + \rho_i^{max}(1 - P_{(i,t,z)}) \qquad \forall i \in I^{OM2}, t \in T, z \in Z \tag{3.16}$$

Figure 3.3 illustrates the ratio between heat and electricity from mode 2 that this is a variable one.

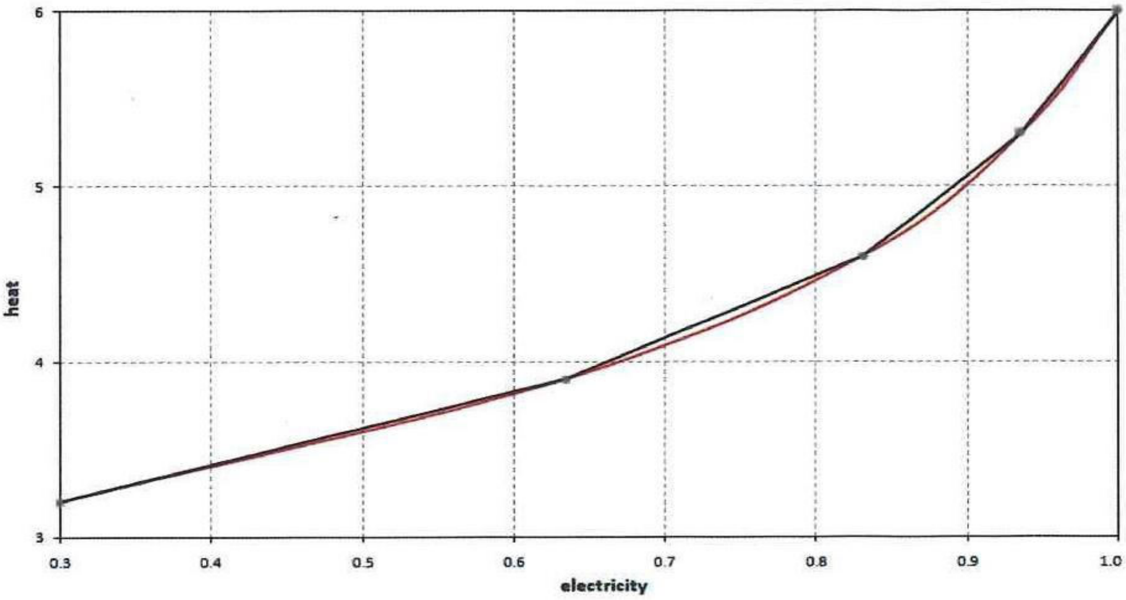


Figure 3.3: Heat to electricity ratio for operating mode 2.

In both previous modes the produced electricity is being constrained by the following equation:

$$\varepsilon_t^{min} \leq E_{(i,t)} \leq \varepsilon_t^{max} \qquad \forall i \in I^{OM2}, t \in T \tag{3.17}$$

Operational Mode 3

The heat is being calculated for stable electricity production.

$$\rho_i^{min} E_{(i,t)} \leq Q^s_{(i,t)} \leq \rho_i^{max} E_{(i,t)} \qquad \forall i \in I^{OM3}, t \in T \tag{3.18}$$

Heat losses and gains of the houses

The balance regarding the heat of the house involves the heat losses and the gains of the house, the heat that is required to achieve the desired house temperature and the heat from the storage tank. The last term of the following equation refers to the heat that is being disposed by a window opening. This action takes place if there is no other way to release the excess heat cost effectively but the optimization tries to avoid that fact.

$$Q^{HS_{out}}_{(i,t)} + q^{gains}_{(i,t)} = Q^{HOUSE_{loss}}_{(i,t)} + Q^{DT}_{(i,t)} + Q^{disp}_{(i,t)} \qquad \forall i \in I, t \in T \tag{3.19}$$

Also, the heat losses of the house are because of the ventilation and the house surfaces (roof, walls, floor, and windows).

$$Q^{HOUSE_{loss}}_{(i,t)} = q^{fabric_l}_{(i,t)} + q^{vent_l}_{(i,t)} = (\sum_{n} u_i^n a_i^n + c_p^{air} \delta_{air} v_i^{house} n_i)(T^{house}_{(i,t)} - t^{target}_{(i,t)}) \qquad \forall i \in I, t \in T \tag{3.20}$$

In the same logic, the heat gains are an outcome of the solar gains, the living people in the houses and the heat generated from the appliances.

$$q^{gains}_{(i,t)} = q^{fabric_g}_{(i,t)} + q^{solar_g}_{(i,t)} + q^{internal_g}_{(i,t)} \qquad \forall i \in I, t \in T \tag{3.21}$$

Finally, the heat that is required is used so as to warm the house up or to cool it down so for the temperature to be maintained at the target value.

$$Q^{DT}_{(i,t)} = c_p^{air} \delta^{air} v_i^{house} (T^{house}_{(i,t)} - T^{house}_{i,(t-1)}) \qquad \forall i \in I, t \in T \tag{3.22}$$

Comfort temperature penalty

Due to the fact that the final achieved temperature may be different from the target one, there is a penalty that is being added to the cost function. It is calculated as following:

$$t_t^{target} - t_i^{comf} \leq T^{house}_{(i,t)} \leq t_t^{target} - t_i^{comf} \qquad \forall i \in I, t \in T \tag{3.23}$$

$$T^{dev}_{(i,t)} \geq \mid T^{house}_{(i,t)} - t_t^{target} \mid \qquad \forall i \in I, t \in T \tag{3.24}$$

Back-up gas burner

The back-up gas burner will be set into operation only when the heat demand cannot be fully covered from the micro-CHP. The generation of the back-up gas burner ($Q^{GB}_{(i,t)}$) should be within the limits because of the operating capacity.

$$\gamma_i^{min} X^{GB}_{(i,t)} \leq Q^{GB}_{(i,t)} \leq \gamma_i^{max} X^{GB}_{(i,t)} \qquad \forall i \in I, t \in T \tag{3.25}$$

Heat storage system

DHW tank

The submission between the heat that was stored in the previous time interval and the heat that it produced in the current time minus the demand for the domestic hot water is the total heat of the DHW tank.

$$B^{DHW}_{(i,t)} = B^{DHW}_{(i,t-1)} + Q^{DHW_{in}}_{(i,t)} - Q^{DHW_{loss}}_{(i,t)} - \zeta^{DHW}_{(i,t)} \qquad \forall i \in I, t \in T \tag{3.26}$$

The losses from the DHW tank must be calculated and that is a result of the following equation. Furthermore, for that propose the temperature of the tank should also be calculated. Finally, the heat storage capacity has been measured considering the maximum and the minimum temperatures of the tank which is 80°C and 60°C respectively.

$$Q^{DHW_{loss}}_{(i,t)} = u_i^{DHW} a_i^{DHW} (T^{DHW}_{(i,t)} - T^{DHW_{room}}_{(i,t)}) \qquad \forall i \in I, t \in T \tag{3.27}$$

$$T^{DHW}_{(i,t)} = \frac{B^{DHW}_{(i,t)}}{c_p^{water} \delta^{water} v_i^{DHW}} + t_i^{DHW_{min}} \qquad \forall i \in I, t \in T \tag{3.28}$$

Moreover, the domestic hot water tank has a minimum and maximum heat storage capacity:

$$\beta_i^{DHW_{min}} \leq B_{(i,t)}^{DHW} \leq \beta_i^{DHW_{max}} \qquad \forall i \in I, t \in T \tag{3.29}$$

HST tank

The calculations for the heat storage tank have been made in the same logic as in the previous case.

$$B_{(i,t)}^{HST} = B_{(i,t-1)}^{HST} + Q_{(i,t)}^{HST_{in}} - Q_{(i,t)}^{HST_{loss}} - \zeta_{(i,t)}^{HST} \qquad \forall i \in I, t \in T \tag{3.30}$$

$$Q_{(i,t)}^{HST_{loss}} = u_i^{HST} a_i^{HST} (T_{(i,t)}^{HST} - T_{(i,t)}^{HST_{room}}) \qquad \forall i \in I, t \in T \tag{3.31}$$

$$T_{(i,t)}^{HST} = \frac{B_{(i,t)}^{HST}}{c_p^{water} \delta^{water} v_i^{HST}} + t_i^{HST_{min}} \qquad \forall i \in I, t \in T \tag{3.32}$$

$$\beta_i^{HST_{min}} \leq B_{(i,t)}^{HST} \leq \beta_i^{HST_{max}} \qquad \forall i \in I, t \in T \tag{3.33}$$

Sharing of electricity within the micro-grid

The produced electricity can be shared between the houses and in that case all the electricity should be consumed by the rest of the houses. The following equations show the balance between the electricity shared and also the constrain that one house that gives electricity cannot receive for the same time interval.

$$TMG_t^{in} = TMG_t^{out} \qquad \forall t \in T \tag{3.34}$$

$$MG_{(i,t)}^{out} \leq 1000 Y_{(i,t)}^{out} \qquad \forall t \in T, i \in I \tag{3.35}$$

$$MG^{in}_{(i,t)} \leq (1 - 1000)Y^{out}_{(i,t)} \qquad \forall t \in T, i \in I \tag{3.36}$$

$$TMG^{in}_{t} = \sum_{i} MG^{in}_{(i,t)} \qquad \forall t \in T, i \in I \tag{3.37}$$

$$TMG^{out}_{t} = \sum_{i} MG^{out}_{(i,t)} \qquad \forall t \in T, i \in I \tag{3.38}$$

Electricity Storage Systems, Batteries

There are some limitations regarding the battery such as the capacity of that and also the power that it can give. Those factors are being summarized in the following constrains.

Furthermore, the electricity that is stored to the battery is equal to the one being stored before and also the new one minus the amount being discharged.

$$EB_{(i,t)} = EB_{i,(t-1)} + EB^{in}_{(i,t)}\Delta t + EB^{out}_{(i,t)}\Delta t \qquad \forall t \in T, i \in I \tag{3.39}$$

$$\beta^{min}_{i} \leq EB_{(i,t)} \leq \beta^{max}_{i} \qquad \forall t \in T, i \in I \tag{3.40}$$

$$EB^{out}_{(i,t)} \leq c^{max}_{i} \qquad \forall t \in T, i \in I \tag{3.41}$$

$$EB^{in}_{(i,t)} \leq c^{min}_{i} \qquad \forall t \in T, i \in I \tag{3.42}$$

Energy balance

The electricity demand for each house is the submission of the schedulable and the constant electricity demand. More specific:

$$DE_{(i,t)} = el^{con}_{(i,t)} + cons_{(i,t)} * W_{(i,j,t)} \qquad \forall i \in I, t \in T, j \in J \tag{3.43}$$

The electricity being produced with the submission of the electricity produced by the PV panels and wind turbine should match with the demand of the house and also the energy storage to the battery.

$$E_{(i,t)} + e^{PV}_{(i,t)} + E^{WINDI}_{(i,t)} = E^{DEM}_{(i,t)} + EB^{in}_{(i,t)} + MG^{in}_{(i,t)} \qquad \forall t \in T, i \in I \tag{3.44}$$

In the same logic, the produced electricity from the house, the electricity from the batteries and the electricity that is bought should be equal to the demand and the electricity sold to the main grid.

$$MG^{out}_{(i,t)} + E^{DEM}_{(i,t)} + EB^{out}_{(i,t)} + E^{buy}_{(i,t)} = DE_{(i,t)} + E^{sales}_{(i,t)} \qquad \forall t \in T, i \in I \tag{3.45}$$

Finally, the generated heat from the micro-CHP unit and the back-up gas burner should be equal to the demand for heat and DHW.

$$Q_{(i,t)} + Q^{GB}_{(i,t)} = Q^{DHW_{in}}_{(i,t)} + Q^{HS_{in}}_{(i,t)} \qquad \forall t \in T, i \in I \tag{3.46}$$

All mentioned above are being synthesized and aiming to minimizing the total cost of the system by examining the factors of start-up and shut-down of the micro-CHP, the operation of the back-up gas burner, the electricity selling or purchasing, the use of the PV panel and the wind turbine. The problem aligned with the equations developed and an excel file that contains the main input data, has been translated into GAMS and two main case studies consisting of several examples each, have been solved so as to minimize the total cost and obtain representative results scoping in examining the way the optimization tool works.

3.3 Graphical User Interface (GUI) Creation

As a second step, a graphical user interface was developed, scoping in adjustment of the problem structure in user's needs and obtaining of representative results of the optimization.

Firstly, the problem was translated from GAMS to AIMMS as the second software offers much more options for the GUI creation.

AIMMS offers a direct model translation for models coming from GAMS, however, this is not always reliable for complex model structures as syntax errors may occur. For that reason, every translated variable or equation has been checked separately so as to avoid possible errors. The input data were imported to the system by using the same excel file used also for GAMS. At the end of this translation, four same case studies with GAMS were solved using AIMMS so as to verify the proper translation of the model.

The aim of the GUI creation was for that to be flexible regarding the problem statement. More specific, the design of that was made so for the user to be able to choose the number of houses considered into the optimization, the type of them, the use or not of the renewable sources (PV panels and wind turbine), the number and type of smart appliances, the micro-CHP operation, the demands (heat and electricity) per house and per day. Moreover, the objective function should also be flexible depending on either taking into account or not, the costs as a result of the carbon dioxide emissions.

Finally, the last target of the GUI creation, was the development of analytical and demonstrative results so for the user to be easy to understand the result of the optimization, save the taken data or upload existing already solved case studies.

Chapter 4

Results and Discussion

4.1 Case studies

Description of the main case studies and basic results

In this study, two representative main case studies consisting of many problem instances considering alternative structures have been selected to be analysed. The main data needed for the operation and economic aspects are shown in Table 4.1. The data for the electricity and heat demand of the houses have been gathered from the Milton Keynes Energy Park provided by the UK Energy Research Centre [16]. Each house is considered to be provided with a number of electrical appliances. The power consumption of them and some more characteristics are shown in Table 4.2 [20]. For case study II it is assumed that not all of the houses have the same number and time window for the appliances. Moreover, Figure 4.1 demonstrates an average energy demand during the day. It should be noticed that this is assumed to be the same between the houses for case study I while it varies for case study II because of the different seasons. Figure 4.2 illustrates the comparison between the target temperature and the outside temperature and Figure 4.3 the average domestic hot water demand for winter. Furthermore, the number of houses for which the case studies are being solved is 15 for case study I and problem instances 1 to 20 and 20 or 40 for case study II, the time intervals is 30 minutes for all studies, 15 minutes for the last instance (20) of case study I and the season is winter for case study I but it varies for case study II. Note that the first time interval is supposed to correspond to 8:00 am. Also, for case study II not all the houses are assumed to be provided by PV panel. The initial constrains for the tanks and the battery are half full. The terminal constrains of them are to the maximum stage.

Additionally, the micro-CHP unit is chosen to be similar to a stirling engine type due to the fact that most of the UK houses use that type of engines. The maximum output of that is chosen to be 1kW as this is the limit for taking advantage of the Feed in Tariff. The technical characteristic of the micro-CHP and the back-up gas burner have been taken from [17]. Regarding the PV panel, the type of that is monocrystalline due to its high efficiency and durability. The area of each panel is assumed to be $7m^2$. Finally, for the case that the wind turbine is added to the system , the type is chosen to be the Skystream 3.7 [18] and the wind speed that operates it, was taken for the Milton Keynes region by the weather forecast for each season [19]. For case study I the wind speed is supposed to be constant through the day, contrary to the wind speed for case study II that varies through the hours of the day. Finally, due to the technical characteristics of the wind turbine, that does not operate for wind speed lower than 3.5 m/s.

Tables 4.3 and 4.4 depict the description that corresponds to every number for the instances. All case studies were solved using GAMS/CPLEX12.7 in an Intel(R) Core(Tm) i5 under standard configurations and zero optimal gab. The time needed for the optimal solutions to be found was from some seconds to twenty minutes depended on the case study. However for the last two instances the time was around 8 hours because of the big house number.

Table 4.1: Main operational and economic data.

α_i^-	1	θ_i^S	£0.01/kWh
α_i^+	1	θ_i^F	£0.001/kWh
β_i^{min}	0 kWh	$\lambda_{(i,k)}^-$	0.6 kW
β_i^{max}	4.8 kWh	$\lambda_{(i,k)}^+$	0.3 kW
β_i^{DHWmin}	2 kW	$\xi_{(i,t)}$	£0.0225 /kWh
β_i^{DHWmax}	6 kW	π^{CHP}	£0.1395 / kWh
β_i^{HSmin}	2.5 kW	π^{PV}	£0.0035 / kWh
β_i^{HSmax}	10.5 kW	π^{W}	£0.0889 / kWh
γ_i^{min}	1 kW	π_t	£0.0485 / kWh
γ_i^{max}	6 kW	$\nu^{co2,b}$	£0.0151 / kWh
$\delta_{(i,t)}^{on}$	1	$\nu^{co2,c}$	£0.0047 / kWh
$\delta_{(i,t)}^{off}$	1	$\nu^{co2,eb}$	£0.0091 / kWh
$\epsilon_{(t)}^{min}$	6 kWh	ψ_t	£0.1558 /kWh
$\epsilon_{(t)}^{max}$	3.2kWh		

Table 4.2: Characteristics of the appliances for the first 18 cases [20].

	Tasks	**Power (kW)**	**t^{ls} (h)**	**t^{lf}(h)**	**t^{dur} (h)**
1	Dish washer	-	9	17	2
2	Washing Machine	-	9	12	1.5
3	Spin dryer	2.5	13	18	1
4	Cooker hob	3	8	9	0.5
5	Cooker oven	5	18	19	0.5
6	Microwave	1.7	8	9	0.5
7	Interior lighting	0.84	18	24	6
8	Laptop	0.1	18	24	2
9	Desktop	0.3	18	24	3
10	Vacuum cleaner	1.2	9	17	0.5
11	Fridge	0.3	8	32	24
12	Electrical car	3.5	18	32	3

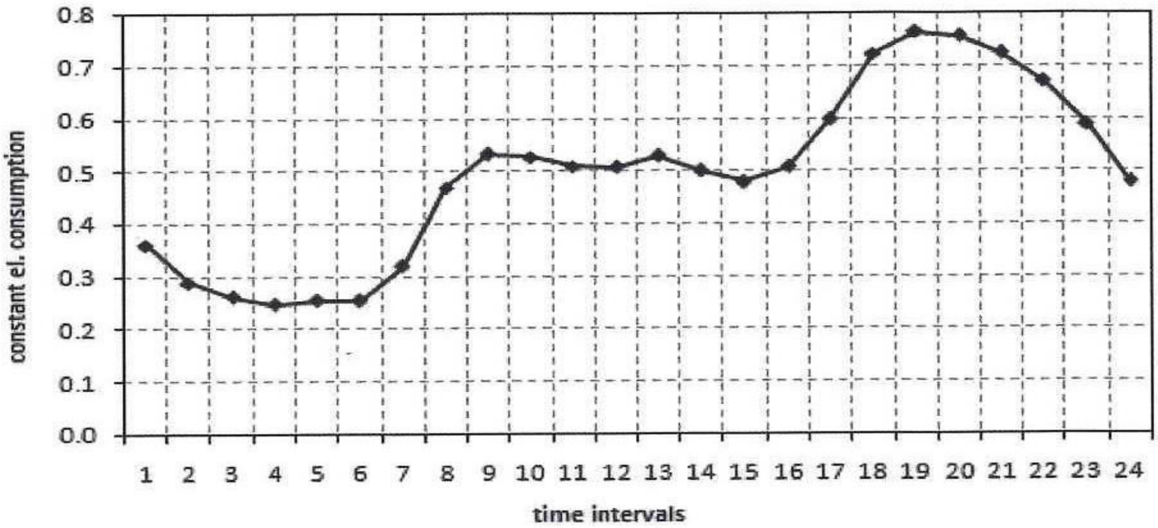


Figure 4.1: Average of constant electricity consumption for winter (kWh).

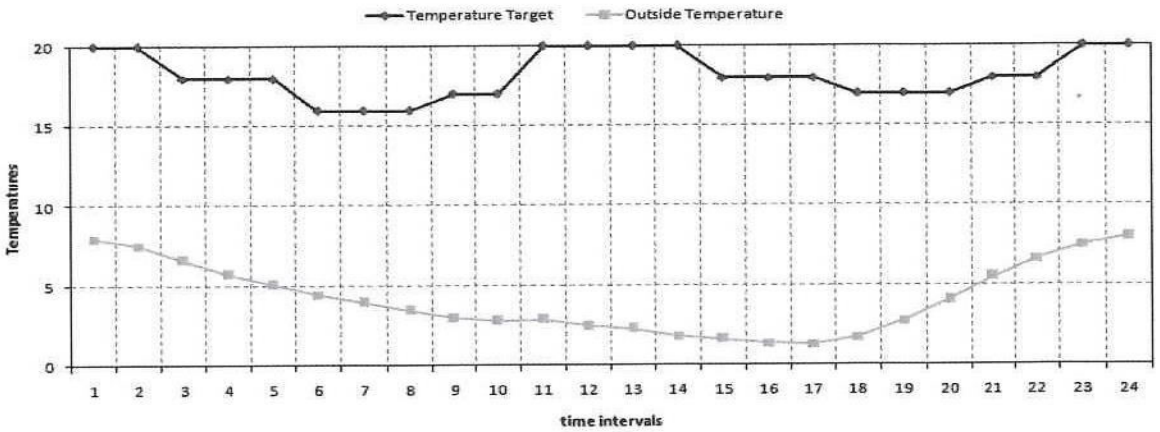


Figure 4.2: Average of target and outside temperature for winter (°C).

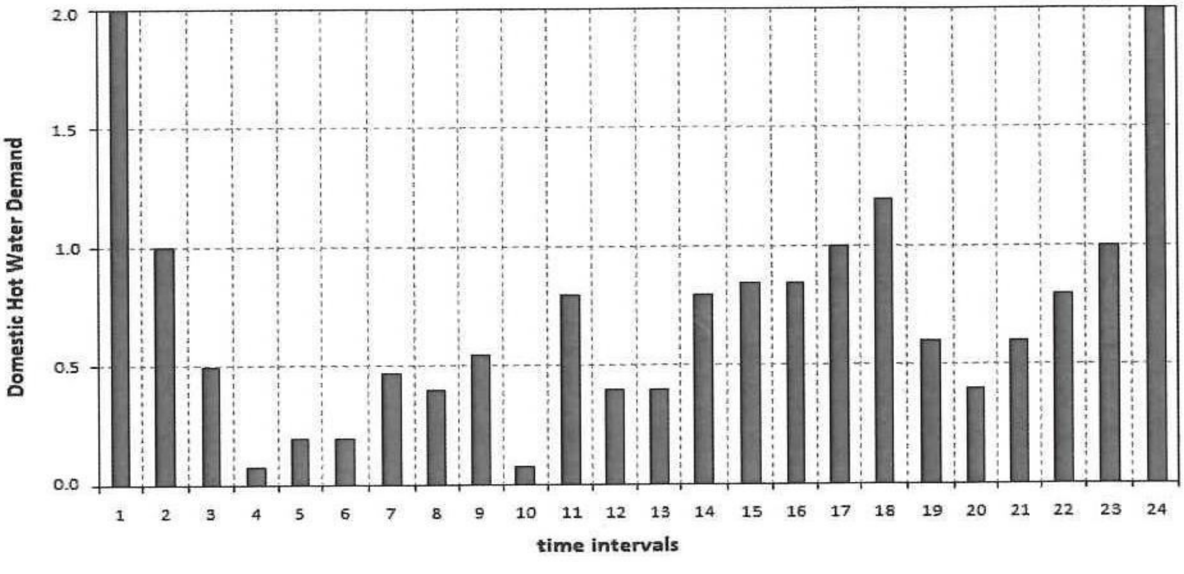


Figure 4.3: Average Domestic Hot Water Demand (kWh).

Table 4.3: Description of case study I.

	NETWORK STRUCTURE		CHP OPERATIONAL MODE							OBJECTIVE FUNCTION	
CASE STUDY I	Number of Houses	Electricity Share	OM-1	OM-3	PV	WT	SEASON	DAY TYPE	Dt	Only costs optimization	CO2 costs optimization
1	15	X	X		15		WINTER	WEEKDAY	48	X	
2	15	X		X	15		WINTER	WEEKDAY	48	X	
3	15		X		15		WINTER	WEEKDAY	48	X	
4	15			X	15		WINTER	WEEKDAY	48	X	
5	15	X			15		WINTER	WEEKDAY	48	X	
6	15				15		WINTER	WEEKDAY	48	X	
7	15	X	X		15		WINTER	WEEKDAY	48		X
8	15	X		X	15		WINTER	WEEKDAY	48		X
9	15		X		15		WINTER	WEEKDAY	48		X
10	15			X	15		WINTER	WEEKDAY	48		X
11	15	X			15		WINTER	WEEKDAY	48		X
12	15				15		WINTER	WEEKDAY	48		X
13	15	X	X		15		WINTER	WEEKDAY	48	X	X
14	15	X		X	15		WINTER	WEEKDAY	48	X	X
15	15		X		15		WINTER	WEEKDAY	48	X	X
16	15			X	15		WINTER	WEEKDAY	48	X	X
17	15	X			15		WINTER	WEEKDAY	48	X	X
18	15				15		WINTER	WEEKDAY	48	X	X
19	15	X	X		15	X	WINTER	WEEKDAY	96	X	X
20	15		X		15	X	WINTER	WEEKDAY	96	X	X

Table 4.4: Description of case study II.

	NETWORK STRUCTURE		CHP OPERATIONAL MODE							OBJECTIVE FUNCTION	
CASE STUDY II	Number of Houses	Electricity Share	OM-1	OM-3	PV	WT	SEASON	DAY TYPE	Dt	Only costs optimization	CO2 costs optimization
21	20	X	X		12		WINTER	WEEKDAY	48	X	X
22	20	X	X		12		SPRING	WEEKDAY	48	X	X
23	20	X	X		12		AUTUMN	WEEKDAY	48	X	X
24	40	X	23	17	24	X	SPRING	WEEKDAY	48	X	X
25	40		23	17	24	X	SPRING	WEEKEN	48	X	X

Table 4.5: Results of case study I.

Case Study	Total Cost	Electricity(kWh)							Micro-CHP	Micro-CHP/GB	CPUs times
I	(£)	Demand	micro-CHP	PV	WT	Purchased	Sales	Gas Burner	Start-ups	Fuel Cost	
1	44.4	809.4	184.1	75.8	0.00	549.5	0.0	0.0	14.0	13.8	7.0
2	33.6	809.4	344.0	75.8	0.00	389.6	0.0	0.0	60.0	25.8	600.0
3	45.1	809.4	177.1	75.8	0.00	558.4	0.0	0.0	20.0	13.3	326.0
4	35.4	809.4	336.0	75.8	0.00	408.2	0.0	0.0	130.0	25.2	600.0
5	73.5	809.4	0.0	75.8	0.00	736.5	0.0	1000.8	0.0	16.0	7.0
6	72.8	809.4	0.0	75.8	0.00	736.2	0.0	959.6	0.0	15.4	6.0
7	63.7	809.4	715.0	75.8	0.00	29.6	0.0	0.0	0.0	53.0	3.0
8	63.9	809.4	714.9	75.8	0.00	28.9	0.0	0.0	5.0	53.6	3.0
9	125.1	809.4	619.0	75.8	0.00	145.3	0.0	0.0	5.0	47.0	600.0
10	132.1	809.4	626.8	75.8	0.00	136.1	0.0	0.0	0.0	46.4	178.0
11	465.4	809.4	0.0	75.8	0.00	736.5	0.0	1000.8	0.0	16.0	6.0
12	464.9	809.4	0.0	75.8	0.00	736.2	0.0	959.6	0.0	15.4	7.0
13	46.1	809.4	184.5	75.8	0.00	549.1	0.0	0.0	22.0	13.8	6.0
14	35.3	809.4	347.0	75.8	0.00	386.2	0.0	0.0	95.0	26.0	600.0
15	46.7	809.4	176.9	75.8	0.00	558.6	0.0	0.0	19.0	13.3	147.0
16	36.8	809.4	335.0	75.8	0.00	408.4	0.0	0.0	80.0	25.1	600.0
17	79.8	809.4	0.0	75.8	0.00	736.5	0.0	1000.8	0.0	16.0	8.0
18	78.9	809.4	0.0	75.8	0.00	736.2	0.0	959.6	0.0	15.4	7.0
19	11.8	788.8	408.0	75.8	40.1	265.2	0.0	0.0	0.0	13.8	600.0
20	12.3	788.8	408.8	75.8	40.1	273.0	0.0	0.0	9.0	13.8	1200.0

Table 4.6: Results of case study II.

Case Study	Total Cost	Electricity (kWh)							Micro-CHP	Micro-CHP/GB	CPUs times
II	(£)	Demand	micro-CHP	PV	WT	Purchased	Sales	Gas Burner	Start up cost	Fuel Cost	
21	10.5	525.8	388.0	60.7	0.0	77.2	6.0	0.0	13.0	29.1	33.0
22	15.7	449.6	214.1	73.9	0.0	161.5	12.6	0.0	19.0	16.1	685.0
23	8.2	428.9	298.8	71.3	0.0	59.1	4.6	0.0	10.0	22.4	28.0
24	18.1	926.7	519.8	147.8	114.8	144.3	11.2	0.0	69.0	39.0	3764.0
25	17.5	975.5	512.9	147.8	114.8	245.0	11.0	19.7	47.0	38.5	25231.0

Discussion based on results for : Case Study I

In the first 6 instances of case study I, the objective function is based only on the costs optimization. Considering the data in Table 4.5, it can be noticed that the cost increases by 1.46% when there is not electricity share between the houses but the most noticeable increase in cost is 63.2% for no use of the micro-CHP as all the electricity needed should be bought from the main grid and the demands for heat are being covered by using only the back-up gas burner. Furthermore, the cost for operating mode 3 (OM3) seems generally to be lower than the one for operating mode 1 (OM1). That is a result of the better flexibility for finding the best solution for heat requirements as in mode 3 the electricity is stable to the maximum electricity generation whilst in mode 1 the model has to optimize simultaneously both the heat and electricity. Moreover, it should be noticed that for the mode 3 the start-ups and shut-downs of the micro-CHP are more than those at mode 1 but, the cost for that is really low so the total cost for mode 3 is lower.

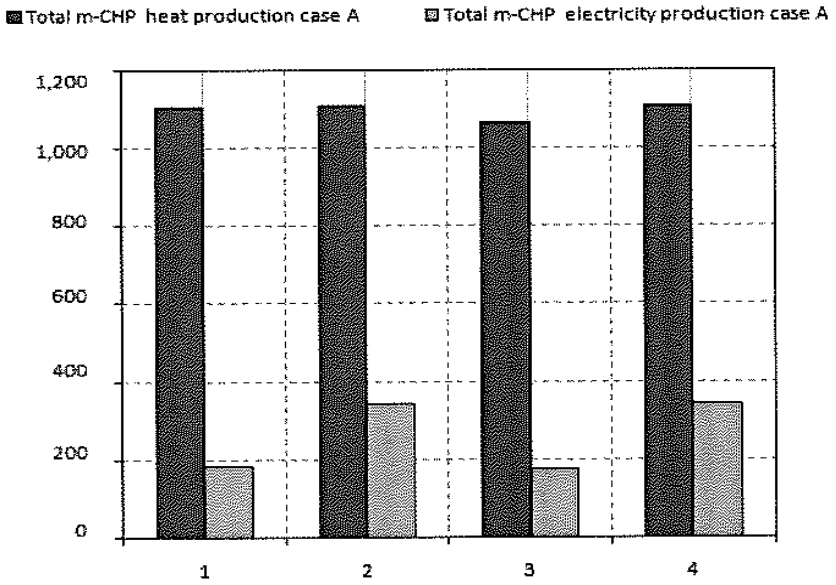


Figure 4.4: Case study I: Total Heat and Electricity production of micro-CHP (kWh).

As it is shown is Figure 4.4, the electricity production of the micro-CHP varies the most between the different cases compared to the heat production, as for the mode 3 the electricity is taken to be the maximum as mentioned before. The difference between the heat productions does not vary a lot as the needs are being covered and no excess heat is required from the back up gas burner. However, electricity should be bought from the main grid for all cases as the electricity demand is not being covered. It should be mentioned that a part of electricity demand is being covered by the PV production that is equal to 75.8 kWh for all the cases. Taking that into account, the electricity demand seems to be covered mostly by the main grid rather than the micro-CHP or the PV panel due to the high demand. Specifically, for the instances that the operating mode is equal to 1, around 68% of the total demand is being purchased from the main grid while the remaining is produced within the micro-grid. That number is 48% for the operating mode to be equal to 3 as more electricity is being produced by the micro-CHP in that instance. Additionally, it seems that there is not a great increase at the cost between the instances of electricity share and the instances without. That increase for all the instances varies between 0.9-5%, so the impact of the electricity share is not a great one.

In the next 6 instances (7-12), the optimization deals only with the carbon dioxide costs. Apparently, the carbon dioxide emission increases for the instance that micro-CHP does not operate. The cause that leads to that result is the fact of the total heat generation by the back-up gas burner and the majority of electricity purchased by the main grid taking into account that both of them are the worse choice regarding the carbon dioxide emissions. A huge cost increase is the result for the instances that only the back-up gas burner is being used.

Furthermore, the electricity produced by the micro-CHP is the possible higher so as to decrease the electricity purchased from the main grid. That happens because the operation of the micro-CHP is the best solution that can lead to carbon dioxide emissions. For the same reason, the fuel cost, it is almost the double for the instances that micro-CHP operates as it consumes a lot of fuel. Moreover, the start-up cost is really low because of the almost continues operation of the micro-CHP. Similarities are being noticed between the instances as the initial scope of the optimization in the less possible carbon dioxide cost, so as it is expected that solution is almost the same for similar instances. Also, in that instance, the fact of the electricity share seems to play an important role as every house produces as much possible electricity but in the instance that the needs are not being covered, electricity should be bought from the main grid as it cannot be taken from a house that may had excess. Hence, the total cost increases due to the tariff for the electricity purchased.

Finally, Figure 4.5 illustrates the difference between the cost and carbon dioxide cost that result regarding the different instances numbering from 7 to 18. For instances 7 to 12 the total cost has been calculated taking into account the results that the optimization has found as it is shown in Table 4.5. In the current instances, the total cost is higher because of the greater micro-CHP operation. Also, excess fuel for its operation is burnt. As it is shown the solution is total different between those two different aspects of cost or carbon dioxide saving.

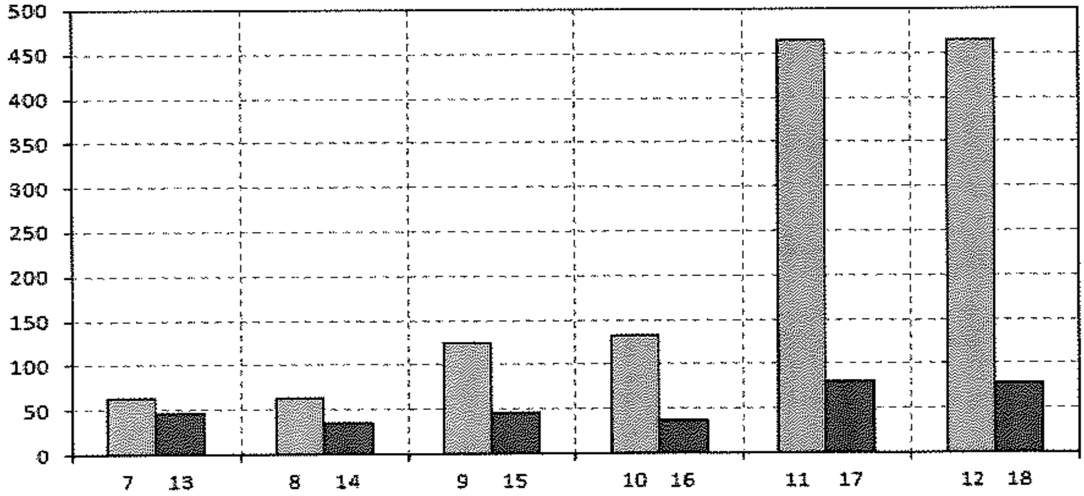


Figure 4.5: Case study I: Total cost comparison between instances 7 to 18.

The next 6 instances (13-18) deal with the total cost including both the cost and the carbon dioxide emission cost. That extra cost could be the cost due to the use of the back-up gas burner, the electricity production by the micro-CHP or the electricity purchased by the main grid. Taking into account the data in Table 4.5, it could be mentioned that the increase of the cost is around 3% for cases 13,14,15 and 16. For cases 17 and 18 it is apparently higher, around 7% as the carbon dioxide emissions of the back-up gas burner are increased. However, the difference that is noticed regarding the energy production is that it does not change significantly. A small increase of the electricity production by the micro-CHP is the change with the scope of reducing the electricity purchased from the main grid. That increase did not happen to the previous instances (1-6) as the start-up cost would increase but in that case it is more efficient to avoid both the purchased cost and the cost because of the carbon dioxide due to the purchases. However, in that instances it is preferable that to happen, otherwise there would be an increase due to the emissions emitted. Also, for more electricity production by the micro-CHP the advantage of the Feed-In Tariff increases.

To the following 2 instances (19,20), a wind turbine is added to the system scoping in decreasing the electricity bought from the main grid and as a result of that to reduce the total cost. Furthermore, the time interval is set to 0.25 so for the optimization to be more accurate and the electricity demand to be decreased. The operating duration of some appliances changes as now it is possible to have more accurate duration including quarter of time. For that reason, the duration of the washing machine is 1h and 45m (7 time intervals), for the dish-washer 1h and 15m (5 time intervals), for the spin-dryer 45m (3 time intervals), for the cooker-hob 15m (1 time interval).

The total cost seems to decrease enough (around 70%) compared to the first 12 instances. That reduction is an outcome of the less electricity bought from the main grid. Furthermore, due to the time interval the optimization can be more accurate and finally the total cost to be reduced. Figure 4.6 describes the different sources from which the electricity demand is covered. The main difference seems to be for the purchases as electricity cannot be share between the houses and some of them should buy the excess so as to cover the needs.

Additionally, Figure 4.7 represents the comparison between the average storage level in the heat storage tank. This seems to be smoother for instance 19 due to

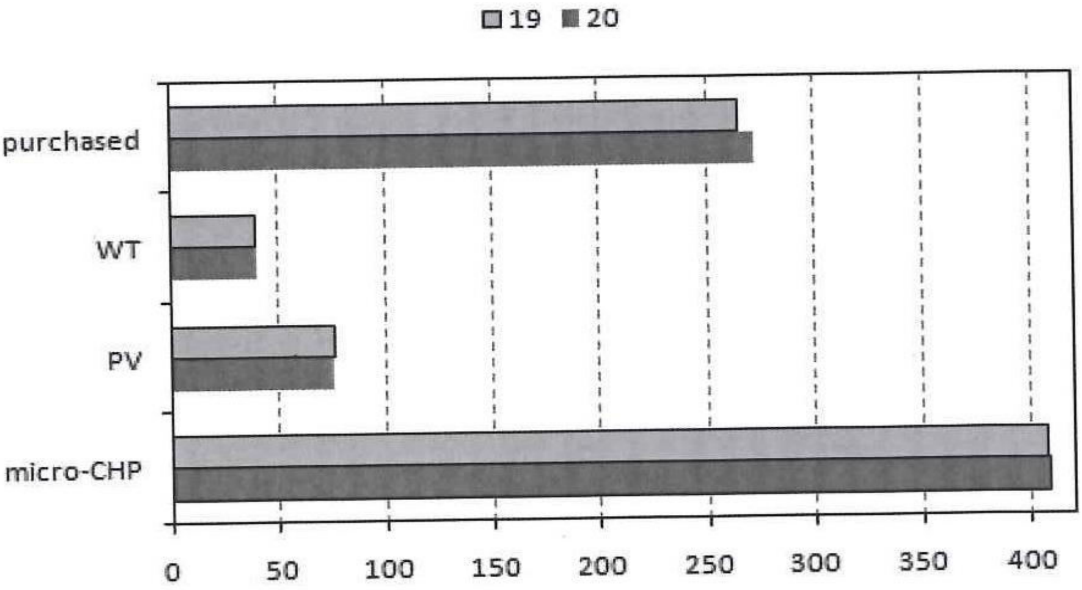


Figure 4.6: Case study I: Distribution of electricity used for instances 19 and 20 (kWh).

better flexibility regarding the electricity needed as for that case it can be shared within the micro-grid between the houses. For the same reason, for instance 20 there can be noticed some peaks depending on the demand at the corresponding time interval.

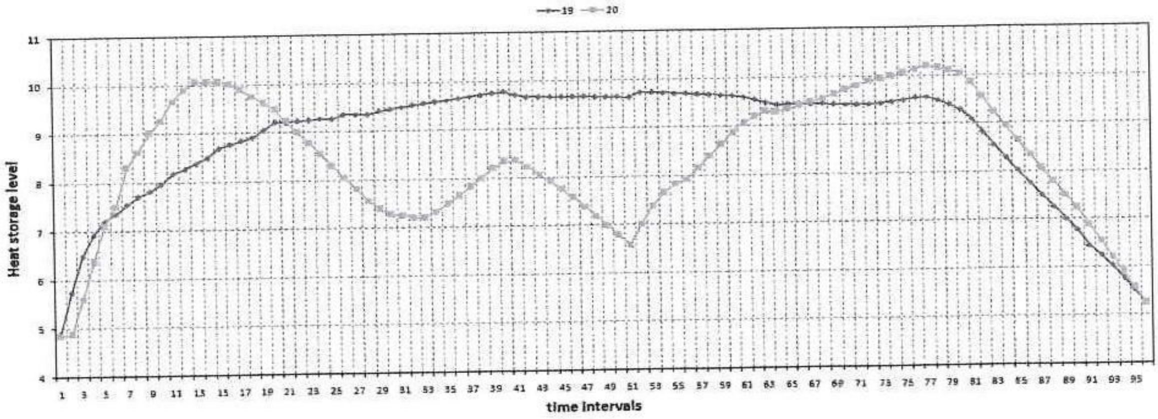


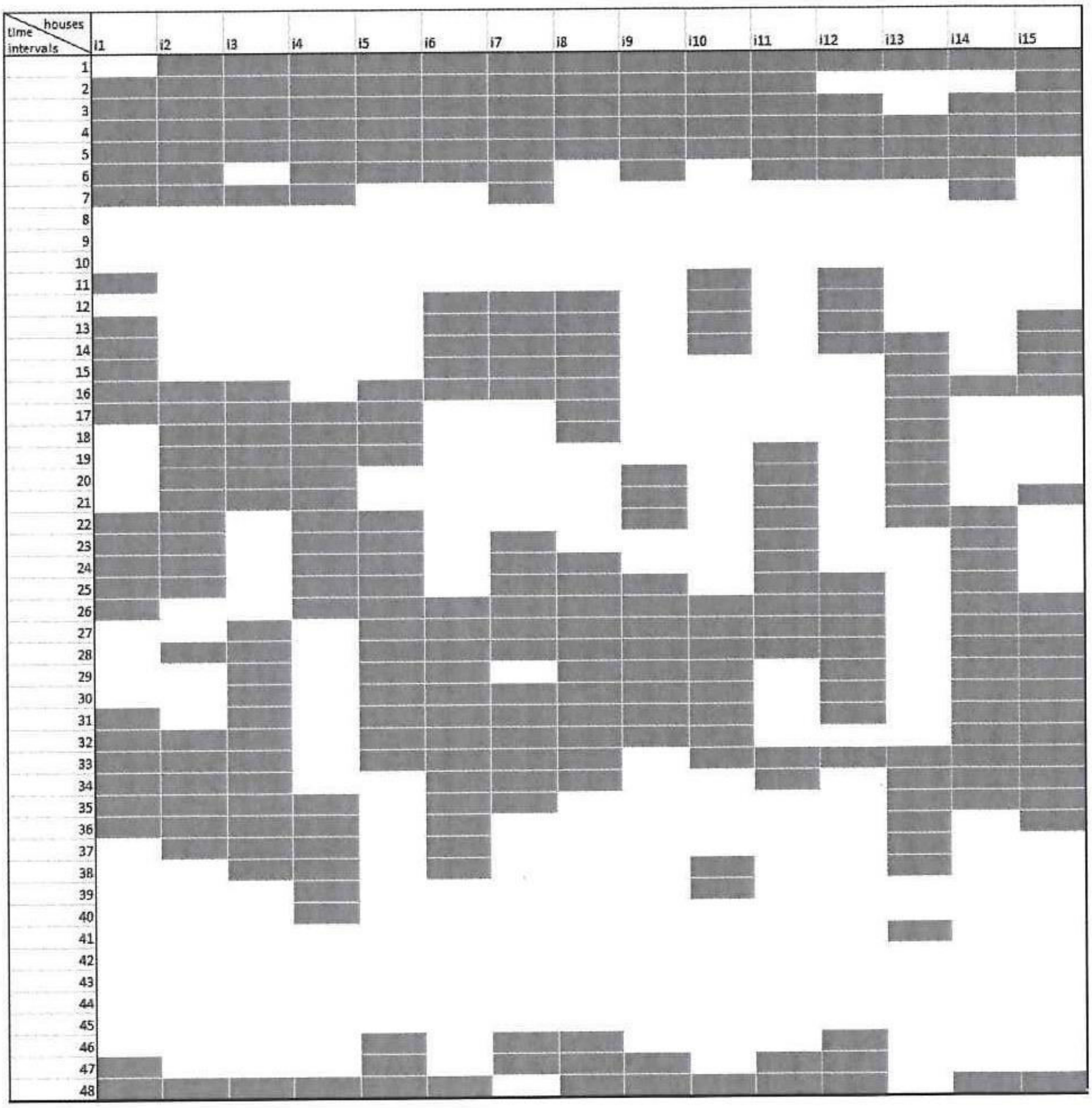
Figure 4.7: Case study I: Average heat storage level for instances 19 and 20 per time interval (kWh).

General Remarks

As it is noticed generally between the cases, the start-up and fuel cost of the micro-CHP is greater for the cases that there is no electricity share. That is an outcome of more electricity needed as it cannot be supplied from a house that could have excess.

Table 4.7 demonstrates the operation of micro-CHP for instance 2. The dark grey boxes, indicate that the micro-CHP operates for this time interval. As it shown, most of the times the micro-CHP operates, as the operating mode is equal to 3 and that works for maximum electricity output, so as much possible electricity demand to be covered by that. Additionally, for some time intervals that the electricity demand is not really high, the micro-CHP does not operate at all but even for the cases that the electricity demand is noticeable, it does not operate due to the fact that the heat requirements are not that high so as to avoid the heat disposal. Especially, for those time intervals, the temperature in the heat storage tank is nearly to the maximum possible as it it shown in Figure 4.8 for instance 2 and for the first house. Furthermore, Table 4.8 represents the operation of the smart-appliances for the same instance and house. It is important to notice the result of the micro-CHP operation mainly for covering the highest electrical needs and maybe do not operate for covering the lowest such as the laptop charging (j6). As it can be resulted from the comparison of those two Tables, the optimization combined the heat requirements with the operation of micro-CHP and simultaneously the covering of the needs for the more power consumed smart appliances.

Table 4.7: Case study I: Micro-CHP operation for instance 2.



houses time intervals	i1	i2	i3	i4	i5	i6	i7	i8	i9	i10	i11	i12	i13	i14	i15
1		■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	■	■	■	■	■	■	■	■	■	■	■				■
3	■	■	■	■	■	■	■	■	■	■	■	■		■	■
4	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
5	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
6	■	■		■	■	■	■		■		■	■	■	■	
7	■	■	■	■			■							■	
8															
9															
10															
11	■									■		■			
12						■	■	■		■		■			
13	■					■	■	■		■		■			■
14	■					■	■	■		■		■	■		■
15	■					■	■	■					■		■
16	■	■	■		■	■	■	■					■	■	■
17	■	■	■	■	■			■					■		
18		■	■	■	■			■					■		
19		■	■	■	■						■		■		
20		■	■	■					■		■		■		
21		■	■	■					■		■		■		■
22	■	■		■	■				■		■		■	■	
23	■	■		■	■		■				■			■	
24	■	■		■	■		■	■			■			■	
25	■	■		■	■		■	■	■		■	■		■	
26	■			■	■	■	■	■	■	■	■	■		■	■
27			■		■	■	■	■	■	■	■	■		■	■
28		■	■		■	■	■	■	■	■	■	■		■	■
29			■		■	■		■	■	■		■		■	■
30			■		■	■	■	■	■	■		■		■	■
31	■		■		■	■	■	■	■	■		■		■	■
32	■	■	■		■	■	■	■	■	■				■	■
33	■	■	■		■	■	■	■		■	■	■	■	■	■
34	■	■	■			■	■	■			■		■	■	■
35	■	■	■	■		■	■						■	■	■
36	■	■	■	■		■							■		■
37		■	■	■		■							■		
38			■	■		■				■			■		
39				■						■					
40				■											
41													■		
42															
43															
44															
45															
46					■		■	■				■			
47	■				■		■	■	■		■	■			
48	■	■	■	■	■	■		■	■	■	■	■		■	■

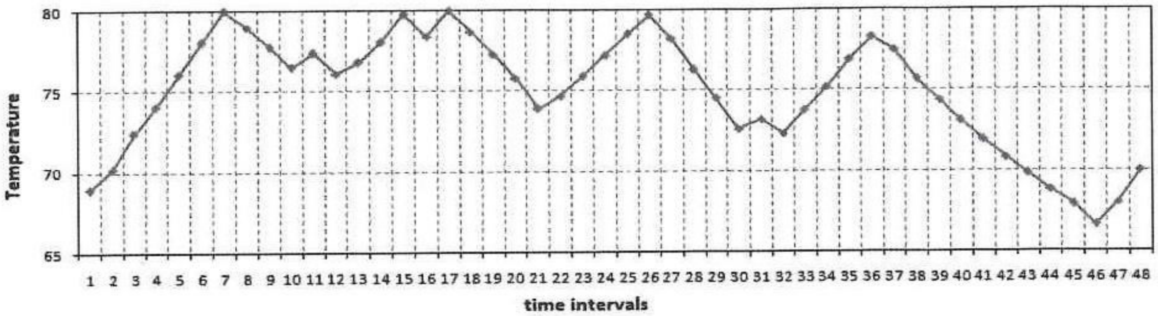


Figure 4.8: Case study I: Temperature distribution in the heat storage tank for instance 2 and i1 (^oC).

Also, it should be mentioned that for the instances that micro-CHP does not operate, the electricity purchased and the heat produced from the back-up gas burner are equal between all instances.The reason for that is that no matter the objective function, the needs should be covered so at least the needed amount of energy is being purchased and produced.

Table 4.8: Case study I: Operation of the smart appliances for instance 2 and i1.

appliances time intervals	j1	j2	j3	j4	j5	j6	j7	j8
1				▨				
2								
3							▨	
4		▨						
5	▨	▨						
6	▨	▨						
7	▨	▨						
8	▨	▨						
9	▨							
10								
11								
12			▨					
13			▨					
14								
15								
16								
17								
18								
19								
20								
21								
22					▨			▨
23								▨
24								▨
25								▨
26						▨		▨
27						▨		▨
28						▨		
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48								

Discussion based on results for : Case Study II

In the first part of the current case study, a comparison between the different impacts of the seasons is being examined for 20 houses, whereas the second part concentrates on different type of days (Weekdays or Weekends) but for the same season, on the role that a varied electricity purchased profile may play, combined with either electricity share or not and the adding of wind turbine for 40 houses.

Regarding the total cost for the three different seasons, it is noticed that this is higher for spring while nor the electricity demand or the heat requirements are the highest compared to winter. Also, compared to autumn the electricity demand is slightly bigger but the heat demand remains lower. The total cost seems to be around 33-44% higher compared to other two seasons. The reason that leads to that effect is that due the lower heat requirements for spring, the micro-CHP does not operate a lot to cover the electricity demands. In case that would happen, then heat should be disposed to the environment. This is a fact that the optimization model tries to avoid as in that case the total cost would increase and energy would be spend for no reason. Considering that fact, electricity have to be bought from the main grid, so for the needs to be covered. Moreover, the PV panels produce 4-19% more electricity than the other seasons but this is obviously not enough as it can cover only the 17% of the electricity demand. Due to that fact, the purchased electricity for spring is 52% more than the one in winter and 63% more compared to autumn. Finally, Figure 4.9 demonstrates the total cost from the micro-CHP during the day for winter and spring. As it is shown that is higher for winter so the main source that cause a higher total cost for spring is the purchased electricity as it was mentioned above.

Furthermore, Figure 4.10 illustrates a general cost comparison between all the instances. As it is demonstrated, the total cost for the second part of cases (spring and 40 houses) has an important reduction compared to spring case for 20 houses, even if the total electricity demand is almost the double. That is happening because

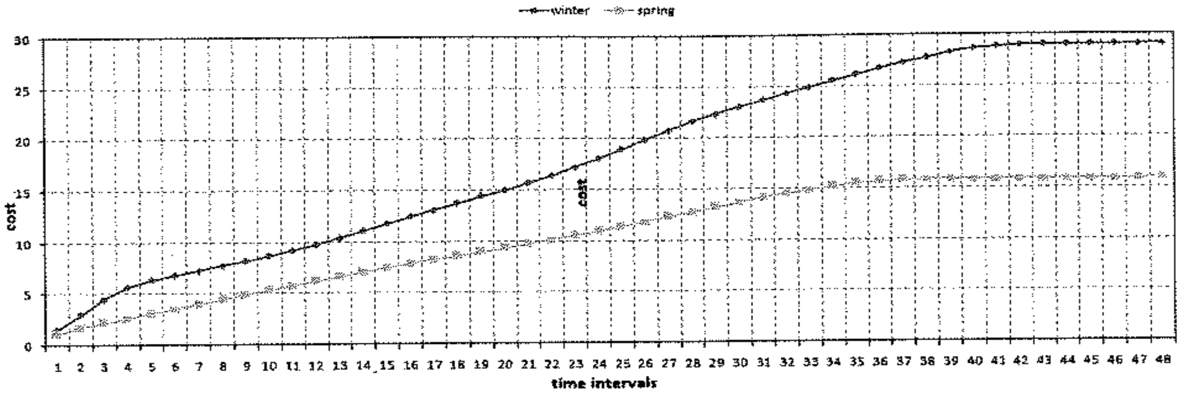


Figure 4.9: Case study II: Micro-CHP cost comparison between winter and spring.

of the wind turbine usage that produces almost the 13% of the electricity needed. Because of that fact, even if the electricity demand has been doubled, the electricity purchased has not. It is also significant that for instance 24 the purchased electricity is 10% less than instance 22.

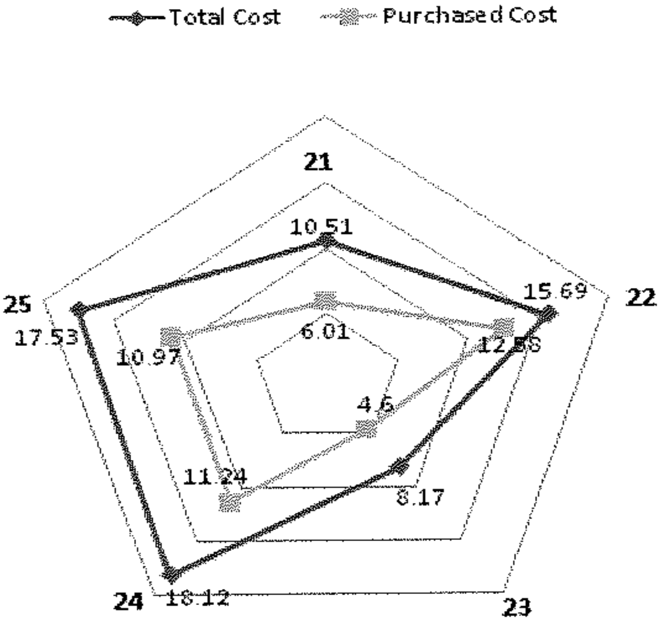


Figure 4.10: Case study II: Different cost comparisons between the instances.

Moreover, what is interesting is that the total cost for instance 25 is less than the one for instance 24 even if the demand for weekends is greater and there is not electricity share between the houses. However, the micro-CHP cost is less because greater amount of electricity is purchased from the main grid (41% more). No matter that fact, the total cost remains less because electricity is mainly purchased during the night as the price of that varies for this case and is lower than the one during the day, so the increase in that cost is only 2.4%. For that reason, the optimization found that is more costly efficient to purchase electricity during that period of the day and sell it. The amount of electricity sold is 19.78 kWh and leads to a slightly lower cost for that instance.

Also, the total fuel cost seems to be greater than the total cost. However, that is possible as at the end, cost is being deducted from the total cost due to the use of the micro-CHP. That amount consists around the 85-90% of the fuel cost.

Additionally, Figure 4.11 demonstrates the comparison between the constant electricity demand and the demand after the optimization, for Autumn and i1. As it is shown, for some time intervals the final demand is higher due to the demand from the smart appliances.

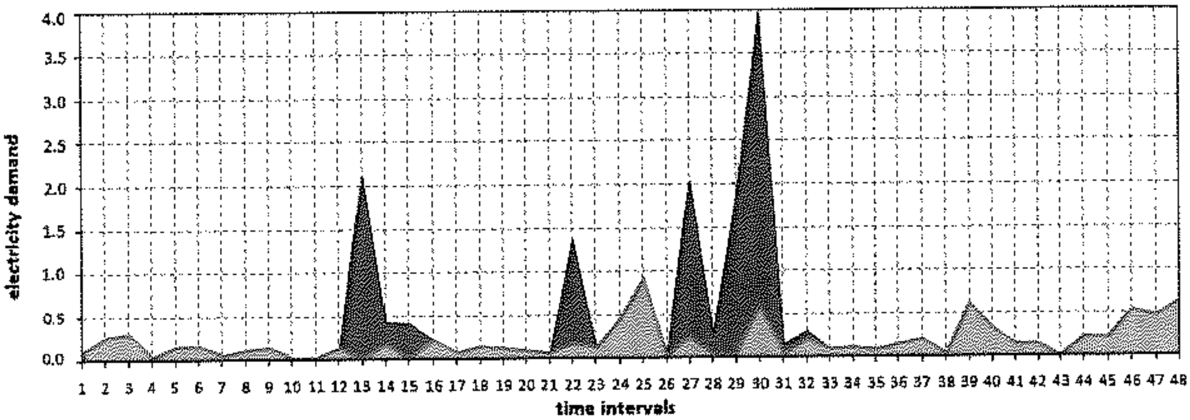
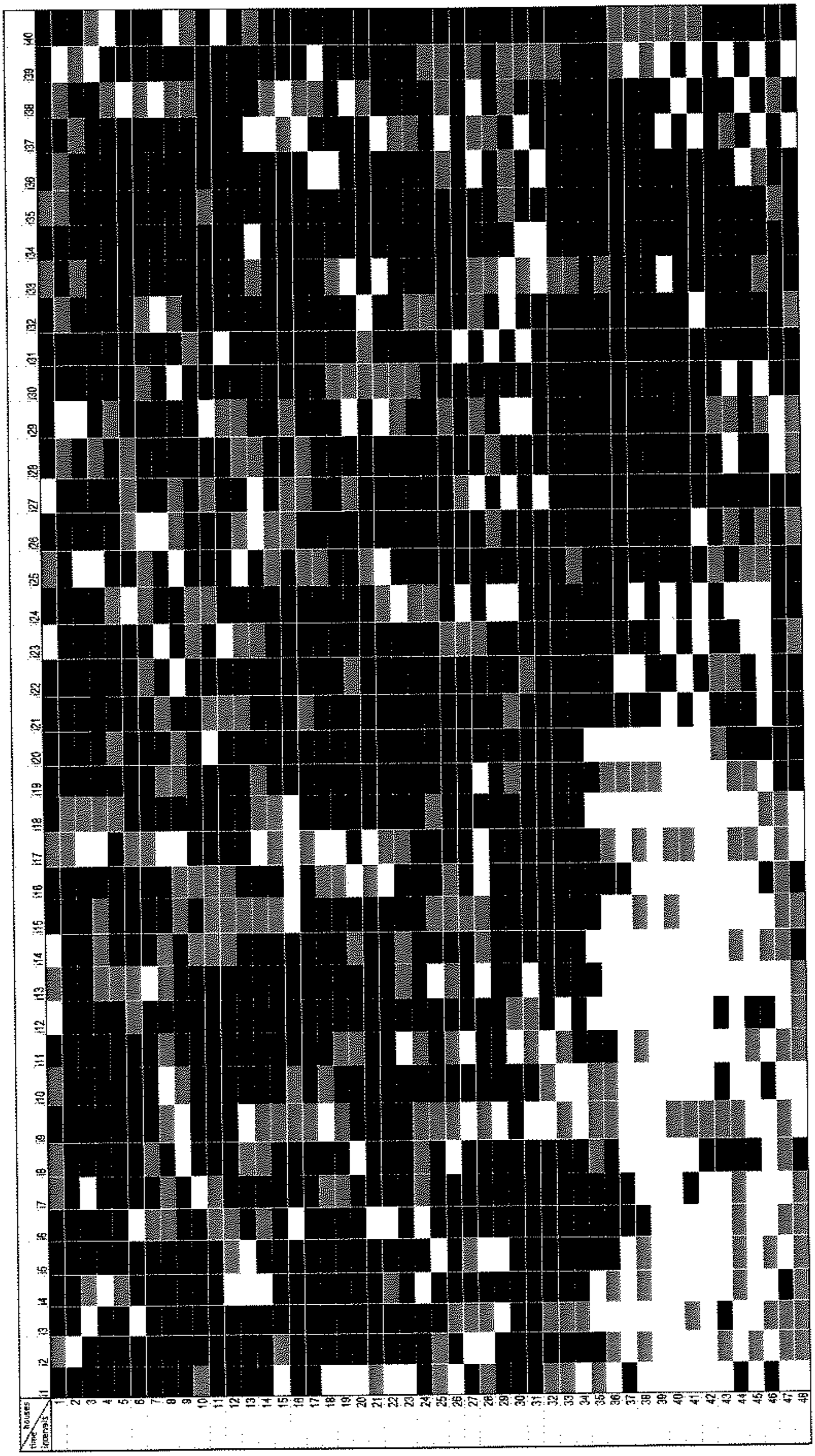


Figure 4.11: Case study II: Difference between the constant and the final electricity demand for instances 23 and i1.

Finally, in Table 4.9, it can be noticed which house gives (grey boxes) and which house receives (black boxes) electricity at each time interval. That information could be useful in case that those houses were receiving an amount as profit for that electricity that they share.

Table 4.9: Case study II: Houses that give and receive electricity at the specific time interval for instance 23.



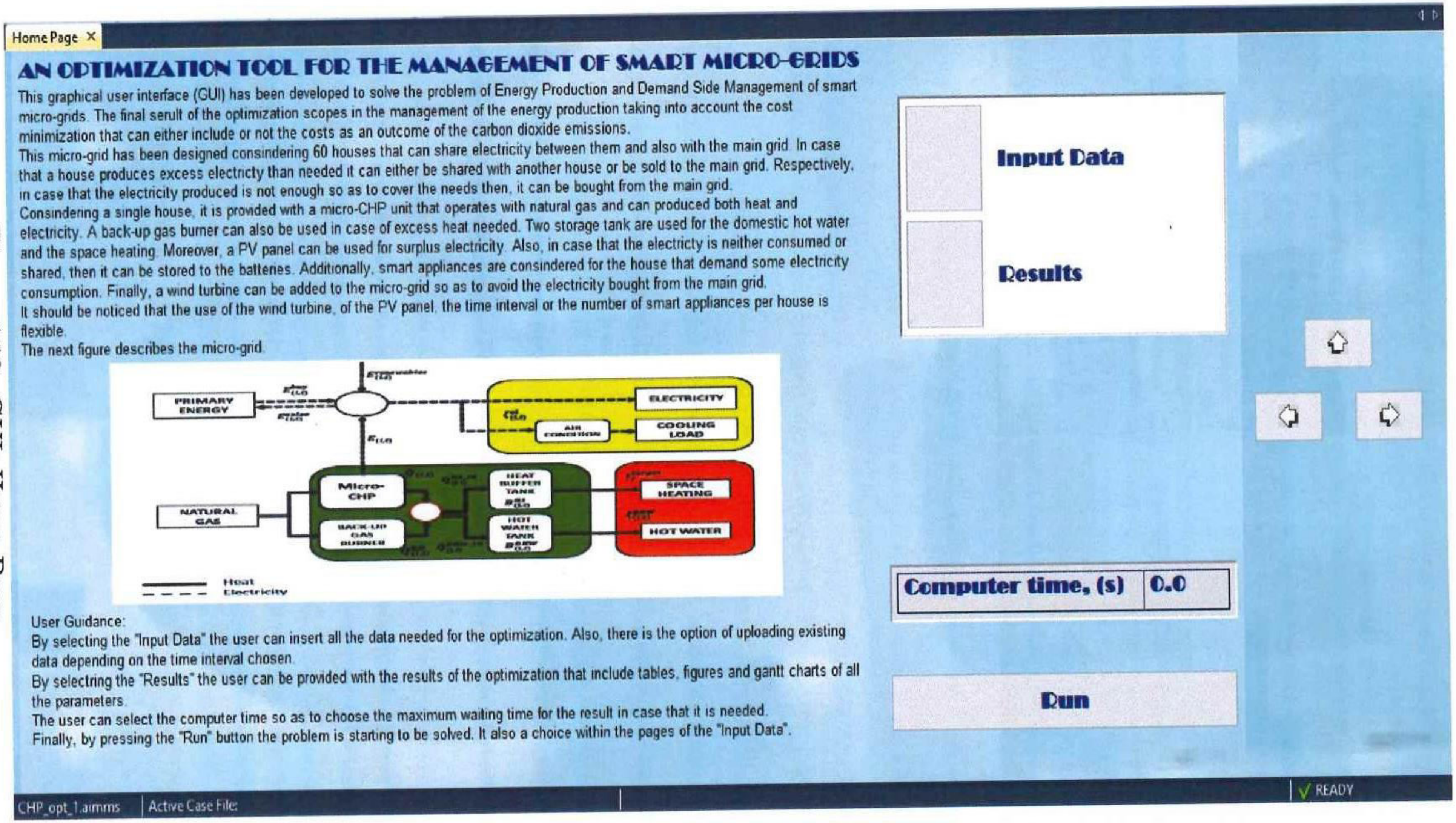
4.2 Grafical User Interface (GUI)

In this section, the GUI that has been created is going to be presented. A detailed analysis of the GUI can also be demonstrated at [55] where a video has been created so as to show all the parts of the GUI, the steps should be made for the result to be taken and at the end the output demonstration. However, the basic pages of that will also be presented following. Even more detailed information can be found in Appendices. By turning the mode to 'user' at the AIMMS, the GUI opens and is ready to be used.

Home Page-Input

In Figure 4.12 it is shown the Home Page of the GUI. As it can be noticed, this begins with a description of the model and with some guidance for the user so to be easy to be used. The user is getting informed that by pressing the corresponding bottoms of input and output, the pages referred to those data opens, respectively.

By pressing the input bottom, the user can see the list that contains all the categories of the input data available to be changed. The data are categorized in that way so for the user to be easy to get lead on the corresponding category of the data wanted to be changed. The GUI has been designed scoping in the possible demonstration of the problem from scratch. That way, every input data used for the optimization can be changed. Figure 4.13, illustrates the page that appears after pressing the 'Input' bottom and the main categories in which the data are categorized to.



AN OPTIMIZATION TOOL FOR THE MANAGEMENT OF SMART MICRO-GRIDS

This graphical user interface (GUI) has been developed to solve the problem of Energy Production and Demand Side Management of smart micro-grids. The final serult of the optimization scopes in the management of the energy production taking into account the cost minimization that can either include or not the costs as an outcome of the carbon dioxide emissions.

This micro-grid has been designed consindering 60 houses that can share electricity between them and also with the main grid. In case that a house produces excess electricty than needed it can either be shared with another house or be sold to the main grid. Respectively, in case that the electricity produced is not enough so as to cover the needs then, it can be bought from the main grid.

Consindering a single house, it is provided with a micro-CHP unit that operates with natural gas and can produced both heat and electricity. A back-up gas burner can also be used in case of excess heat needed. Two storage tank are used for the domestic hot water and the space heating. Moreover, a PV panel can be used for surplus electricity. Also, in case that the electricty is neither consumed or shared, then it can be stored to the batteries. Additionally, smart appliances are consindered for the house that demand some electricity consumption. Finally, a wind turbine can be added to the micro-grid so as to avoid the electricity bought from the main grid.

It should be noticed that the use of the wind turbine, of the PV panel, the time interval or the number of smart appliances per house is flexible.

The next figure describes the micro-grid.

User Guidance:

By selecting the "Input Data" the user can insert all the data needed for the optimization. Also, there is the option of uploading existing data depending on the time interval chosen.

By selectring the "Results" the user can be provided with the results of the optimization that include tables, figures and gantt charts of all the parameters.

The user can select the computer time so as to choose the maximum waiting time for the result in case that it is needed.

Finally, by pressing the "Run" button the problem is starting to be solved. It also a choice within the pages of the "Input Data".

Computer time, (s): 0.0

Figure 4.12: GUI: Home Page.

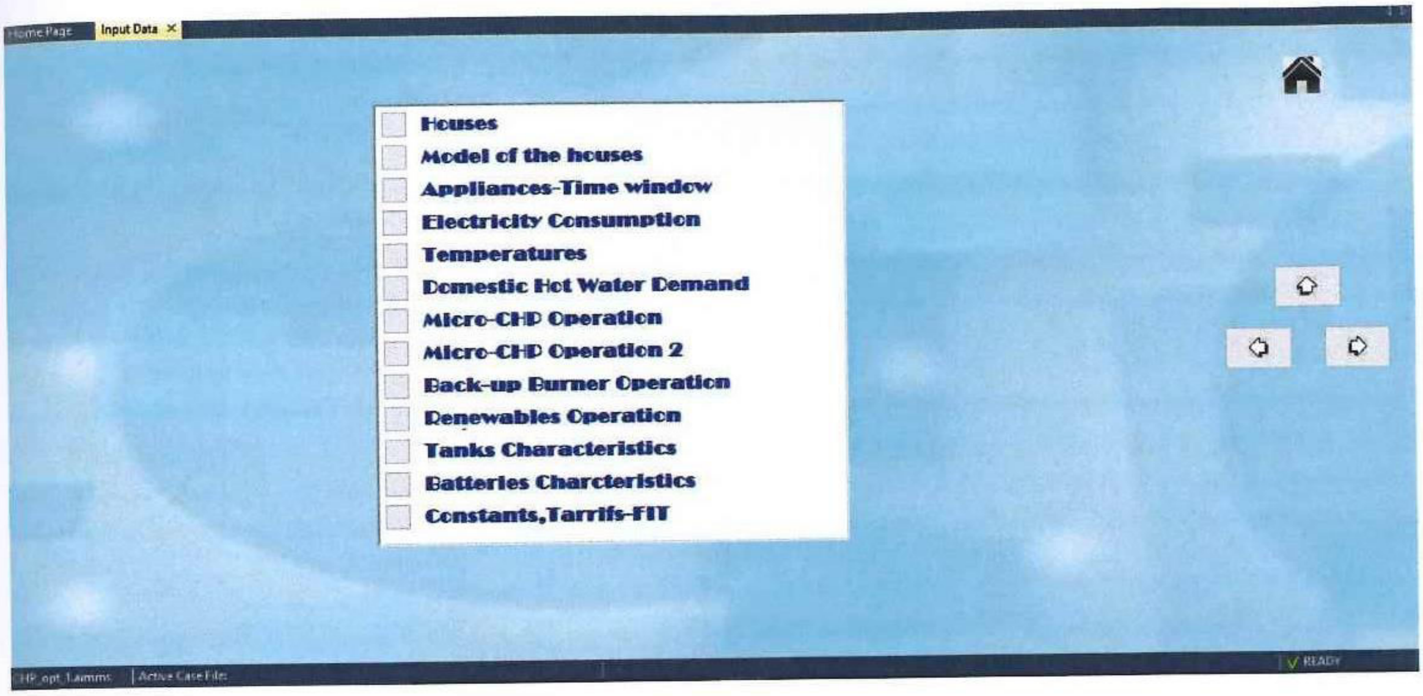
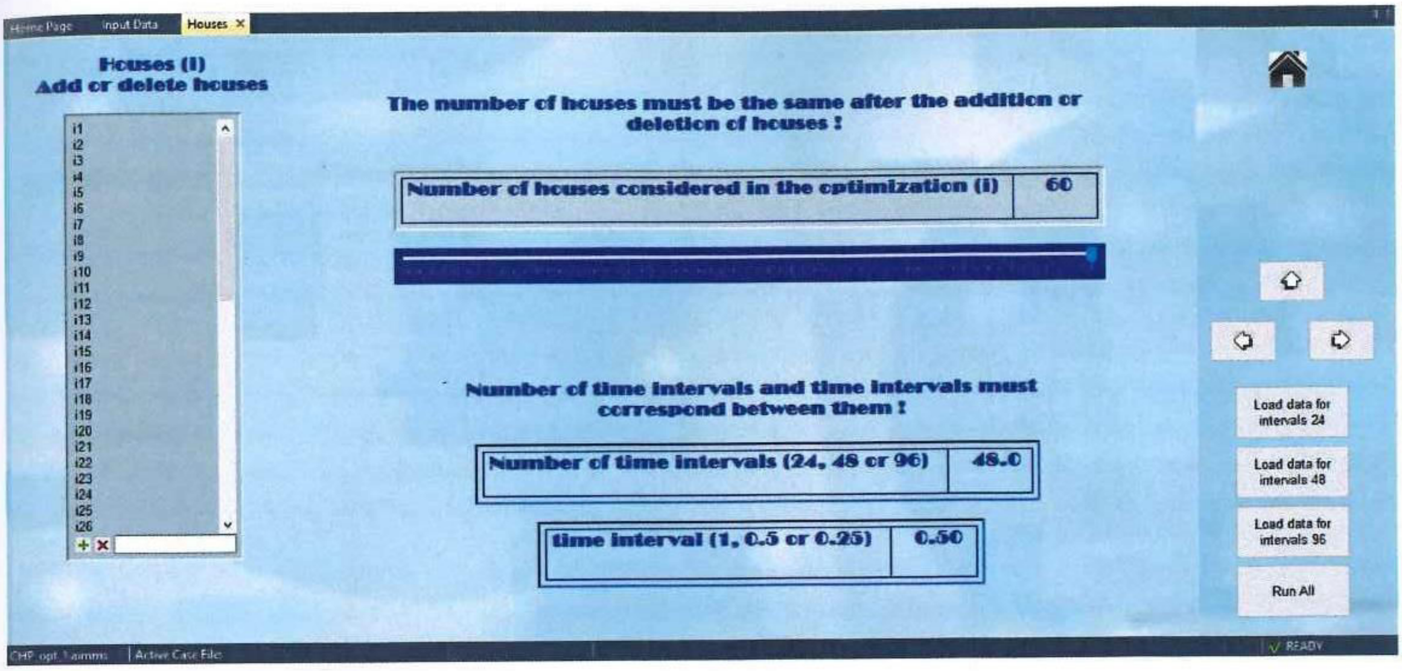


Figure 4.13: GUI: Input Page.

Houses

The first input page is the one regarding the Houses. In Figure 4.14, all the data regarding the houses are being presented. As it is shown, by using the left table, the user is able to add new houses or delete existing ones. It is important to notice that the name of the houses has selected to be illustrated by the letter 'i' and the number of them. However, the user has the advantage to name the new added house as he wish. The upper right figure, is the one by which the number of houses considered into the optimization is selected. The slider down of that, indicates that existing data can be added directly to the GUI and that this is possible for a number of houses up to 60. Continuing, down of that figure, there are the data regarding the time interval chosen as that can vary between 24, 48 or 96. Finally, the user can select to upload the existing data regarding the time interval chosen by pressing the corresponding bottom depending on that number. Extra comment have been added to each figure so for the user to be easy to understand how they operate and to avoid any mistakes.



Houses (I)
Add or delete houses

The number of houses must be the same after the addition or deletion of houses !

Number of houses considered in the optimization (i): 60

Number of time intervals and time intervals must correspond between them !

Number of time intervals (24, 48 or 96): 48.0

time interval (1, 0.5 or 0.25): 0.50

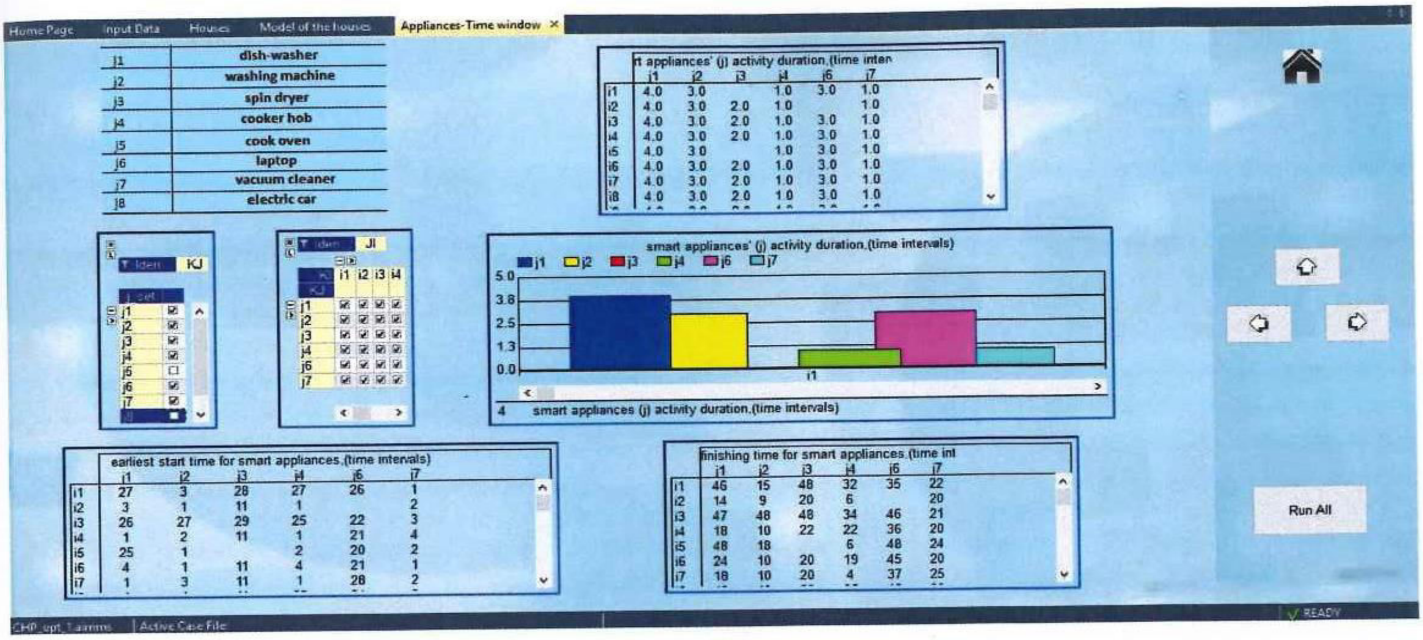
Figure 4.14: GUI: Input, Houses.

Model of the house

In that page, all the data regarding the areas of the parts of houses, the volume of them, the heat transfer coefficients of all the parts and the heat gains and losses can be formed.

Appliances-Time Window

From that page that is shown in Figure 4.15, all the data regarding the smart appliances can be added. In the upper left side of the page there is a table explaining the type of smart appliances corresponding to every 'j'. Down of that there are two tables from which the user can select not to consider some appliances either from all the houses (first table), or from every house separately (second table). The time needed for them in time intervals, can be changed by using either the table or the figure with the bars (upper right in Figure 4.15). Finally, as it is shown in the down part of the Figure 4.15, the earliest starting and the latest finishing time of the smart appliances can be formed. That allows the model to have a time window and optimize the time of the operation of the appliances aligned with the user's wiling.



j1	dish-washer
j2	washing machine
j3	spin dryer
j4	cooker hob
j5	cook oven
j6	laptop
j7	vacuum cleaner
j8	electric car

smart appliances' (j) activity duration,(time intervals)

	j1	j2	j3	j4	j6	j7
i1	4.0	3.0		1.0	3.0	1.0
i2	4.0	3.0	2.0	1.0		1.0
i3	4.0	3.0	2.0	1.0	3.0	1.0
i4	4.0	3.0	2.0	1.0	3.0	1.0
i5	4.0	3.0		1.0	3.0	1.0
i6	4.0	3.0	2.0	1.0	3.0	1.0
i7	4.0	3.0	2.0	1.0	3.0	1.0
i8	4.0	3.0	2.0	1.0	3.0	1.0

earliest start time for smart appliances,(time intervals)

	j1	j2	j3	j4	j6	j7
i1	27	3	28	27	26	1
i2	3	1	11	1		2
i3	26	27	29	25	22	3
i4	1	2	11	1	21	4
i5	25	1		2	20	2
i6	4	1	11	4	21	1
i7	1	3	11	1	28	2

finishing time for smart appliances,(time int

	j1	j2	j3	j4	j6	j7
i1	46	15	48	32	35	22
i2	14	9	20	6		20
i3	47	48	48	34	46	21
i4	18	10	22	22	36	20
i5	48	18		6	48	24
i6	24	10	20	19	45	20
i7	18	10	20	4	37	25

Figure 4.15: GUI: Input, Appliances-Time Window.

Electricity Consumption

Continuing, the Electricity consumption page follows. This regards the constant consumption that cannot be scheduled as it is and outcome from the appliances used within the houses and they are not smart ones or the interior lighting.

Temperatures

The Temperatures page, summarizes all the data about the temperatures, starting with the target temperature wanted to be achieved within the houses at every time interval. It also contains the outside temperature of the environment and the temperature allowance.

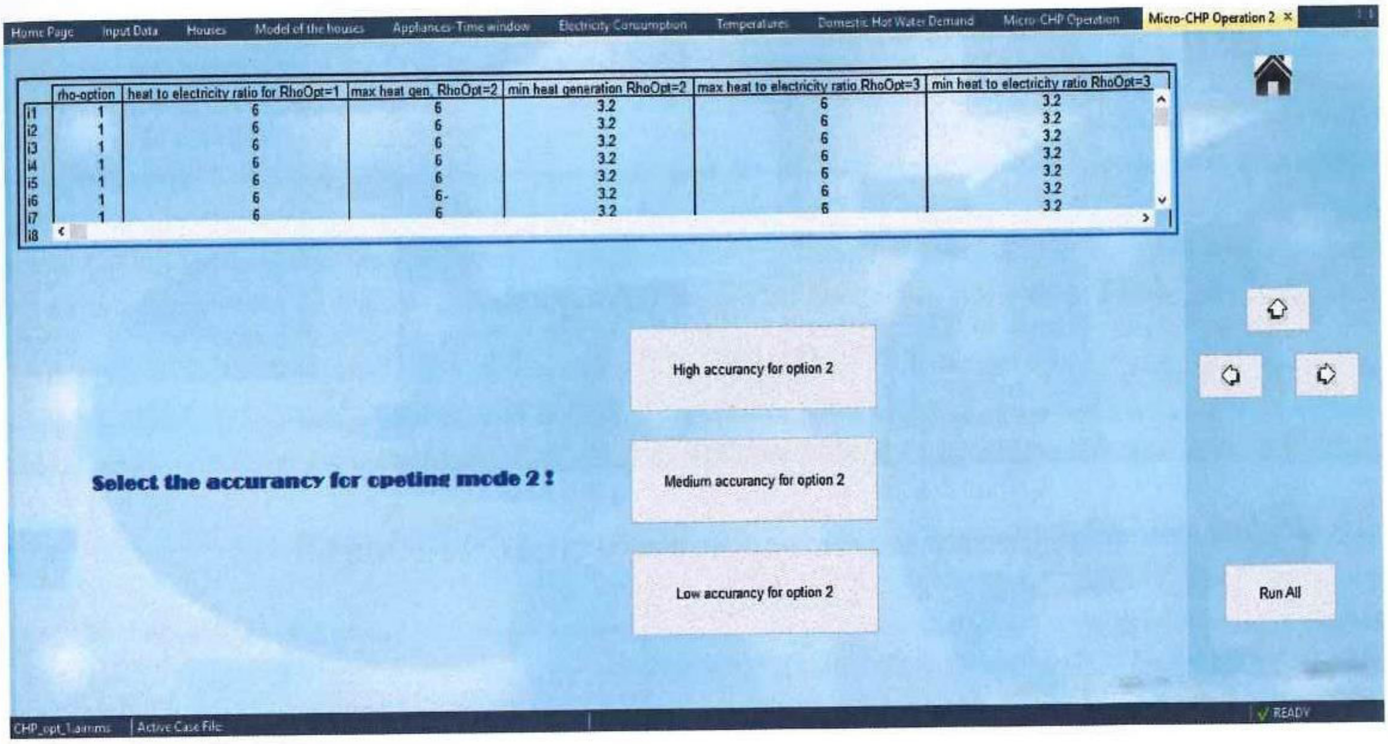
Domestic Hot Water Demand

The Domestic Hot Water Demand page, includes the demand of the hot water that every house wants to have at every time interval.

Micro-CHP Operation

The two following pages are about the micro-CHP. In them there are all the characteristics of the micro-CHP and that way the type, the efficiency, the initial operation and all the characteristics of that can be chosen. Figure 4.16, illustrates the second page of the micro-CHP where the operational mode of that can be chosen.

It is significant that the user can select the type of the accuracy wanted for OM2. It can be high, medium or low depending on the lines used to approach the slope that can respectively be four, three or two.



	rho-option	heat to electricity ratio for RhoOpt=1	max heat gen. RhoOpt=2	min heat generation RhoOpt=2	max heat to electricity ratio RhoOpt=3	min heat to electricity ratio RhoOpt=3
i1	1	6	6	3.2	6	3.2
i2	1	6	6	3.2	6	3.2
i3	1	6	6	3.2	6	3.2
i4	1	6	6	3.2	6	3.2
i5	1	6	6	3.2	6	3.2
i6	1	6	6-	3.2	6	3.2
i7	1	6	6	3.2	6	3.2
i8						

Select the accurancy for opeting mode 2 !

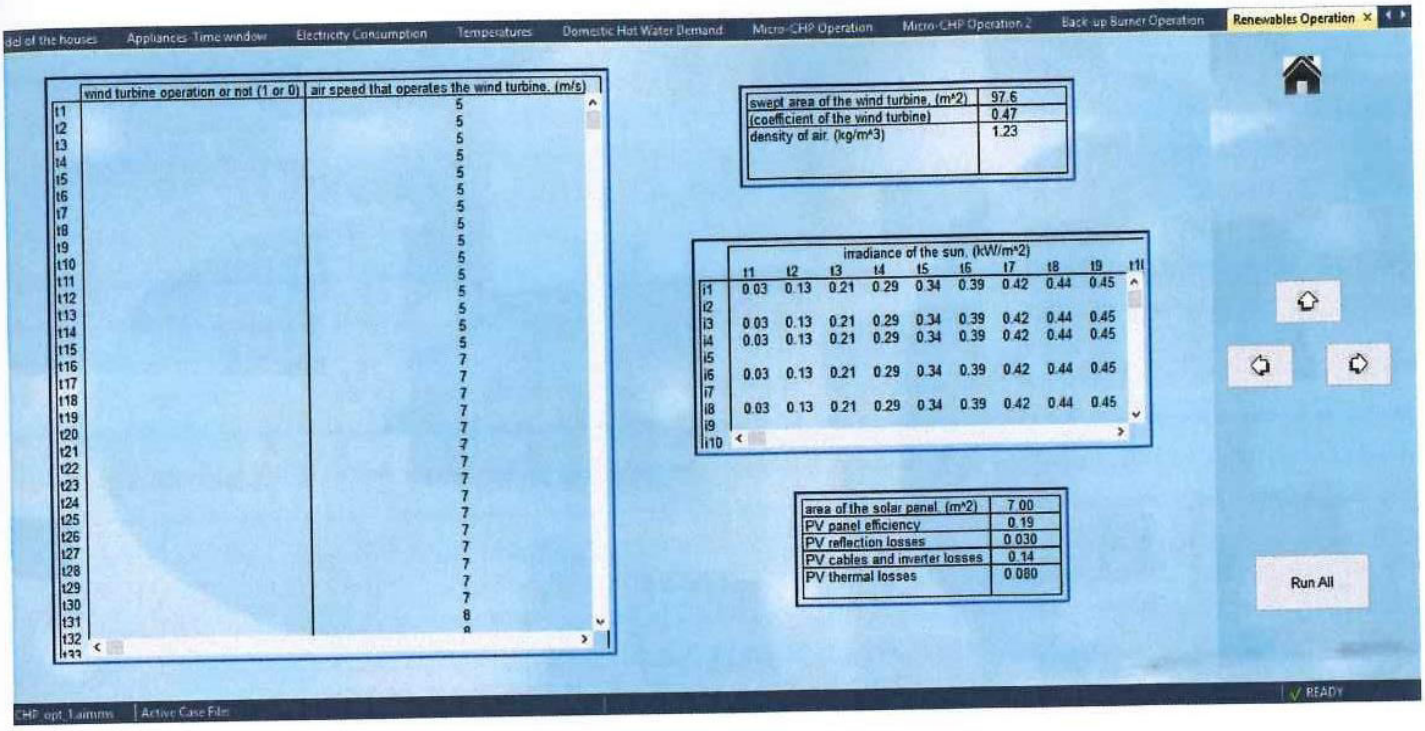
Figure 4.16: GUI: Input, Micro-CHP Operation.

Back-up Burner Operation

The characteristics of the back-up burner can also be chosen and they can refer to the efficiency of that, the maximum and minimum heat generation capacity.

Renewables Operation

The use or not of the renewable sources (Wind Turbine, PV panels), can be selected from this page. Furthermore, the characteristics of each one can also be given as shown in Figure 4.17. In case that the PV panel should not be used for one house, that information can be given indirectly by setting the radiation level equal to zero.



	wind turbine operation or not (1 or 0)	air speed that operates the wind turbine. (m/s)
t1		5
t2		5
t3		5
t4		5
t5		5
t6		5
t7		5
t8		5
t9		5
t10		5
t11		5
t12		5
t13		5
t14		5
t15		5
t16		7
t17		7
t18		7
t19		7
t20		7
t21		7
t22		7
t23		7
t24		7
t25		7
t26		7
t27		7
t28		7
t29		7
t30		7
t31		8
t32		

swept area of the wind turbine, (m^2)	97.6
(coefficient of the wind turbine)	0.47
density of air. (kg/m^3)	1.23

	irradiance of the sun. (kW/m^2)								
	t1	t2	t3	t4	t5	t6	t7	t8	t9
i1	0.03	0.13	0.21	0.29	0.34	0.39	0.42	0.44	0.45
i2									
i3	0.03	0.13	0.21	0.29	0.34	0.39	0.42	0.44	0.45
i4	0.03	0.13	0.21	0.29	0.34	0.39	0.42	0.44	0.45
i5									
i6	0.03	0.13	0.21	0.29	0.34	0.39	0.42	0.44	0.45
i7									
i8	0.03	0.13	0.21	0.29	0.34	0.39	0.42	0.44	0.45
i9									
i10									

area of the solar panel. (m^2)	7.00
PV panel efficiency	0.19
PV reflection losses	0.030
PV cables and inverter losses	0.14
PV thermal losses	0.080

Figure 4.17: GUI: Input, Renewables Operation.

Tanks Characteristics

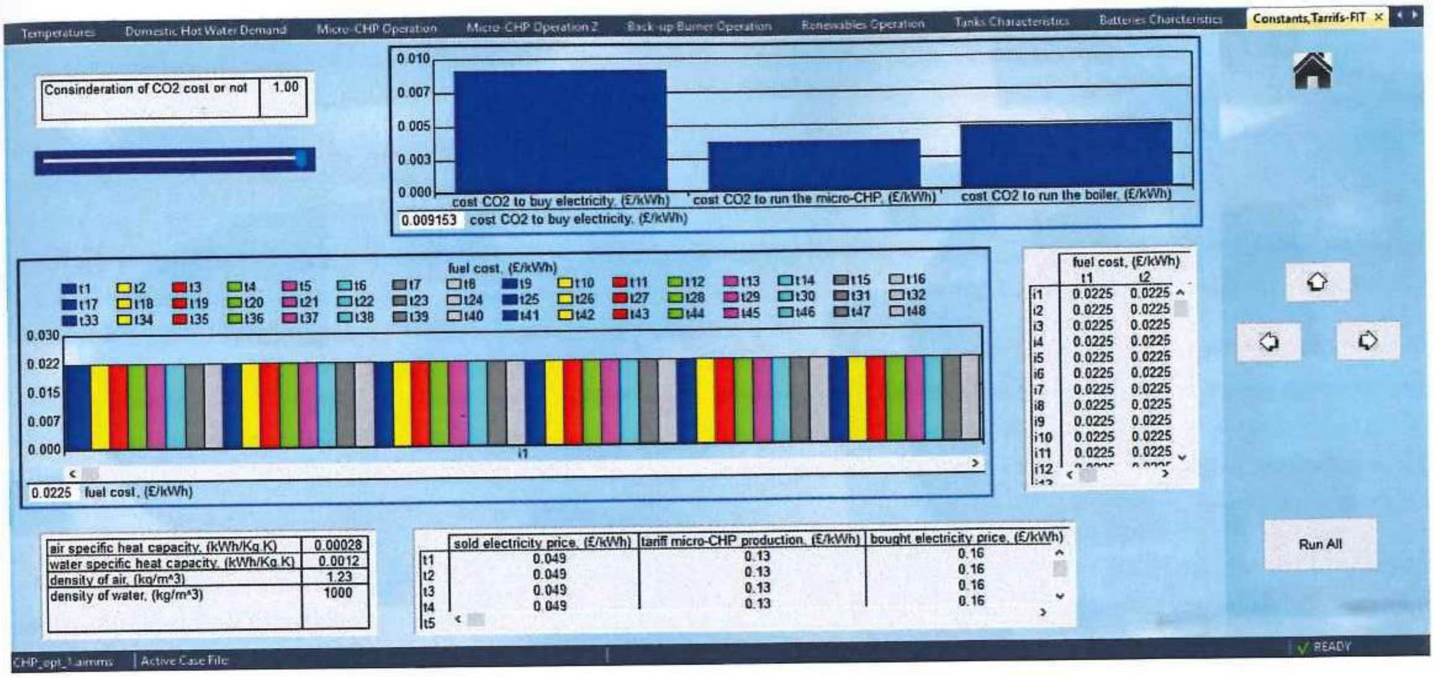
By this page, the tanks characteristics can be imported to the model. Those can refer to the area of the DHW or the HS tank, the capacity of them, the maximum and minimum operating temperature etc.

Batteries Characteristics

This page has been designed so as to add all the batteries details such as the efficiency of them, the capacity, the initial and terminal operation and the discharged rate.

Constants, Tariffs-FIT

The last page of the input sector, is about the constant values (eg. densities, coefficient), the prices (fuel price, purchased price etc.), or the FIT. There is also the choice of choosing the type of the objective function by either taking into consideration the CO_2 emissions or not. Figure 4.18 indicates that page.



Consinderation of CO2 cost or not 1.00

0.009153 cost CO2 to buy electricity, (£/kWh)

0.0225 fuel cost, (£/kWh)

	fuel cost, (£/kWh)	
	t1	t2
i1	0.0225	0.0225
i2	0.0225	0.0225
i3	0.0225	0.0225
i4	0.0225	0.0225
i5	0.0225	0.0225
i6	0.0225	0.0225
i7	0.0225	0.0225
i8	0.0225	0.0225
i9	0.0225	0.0225
i10	0.0225	0.0225
i11	0.0225	0.0225

air specific heat capacity, (kWh/Kg.K)	0.00028
water specific heat capacity, (kWh/Kg.K)	0.0012
density of air, (kg/m^3)	1.23
density of water, (kg/m^3)	1000

	sold electricity price, (£/kWh)	tariff micro-CHP production, (£/kWh)	bought electricity price, (£/kWh)
t1	0.049	0.13	0.16
t2	0.049	0.13	0.16
t3	0.049	0.13	0.16
t4	0.049	0.13	0.16

Figure 4.18: GUI: Input, Constants, Tariffs-FIT.

Running of the Optimization

Having inserted all the input data the user can go back to the home page by selecting the home icon that is available in every page. Then as it is shown in Figure 4.14 above, the user can select the computer running time so as to set the maximum waiting time for the optimization to find the result. Then, pressing the 'Run' bottom, the simulation starts to run. It should be noticed that this is also available from every input page as this is easier in case that the user wish to change some details of a specific page without being necessary to go back to the home page. In the current stage, the instance 23 has been solved again so as to verify the proper use of the GUI and compare the results taken.

Results

As the last step, by pressing the 'Results' bottom, the user can see the list shown in Figure 4.19 and obtain the corresponding results.

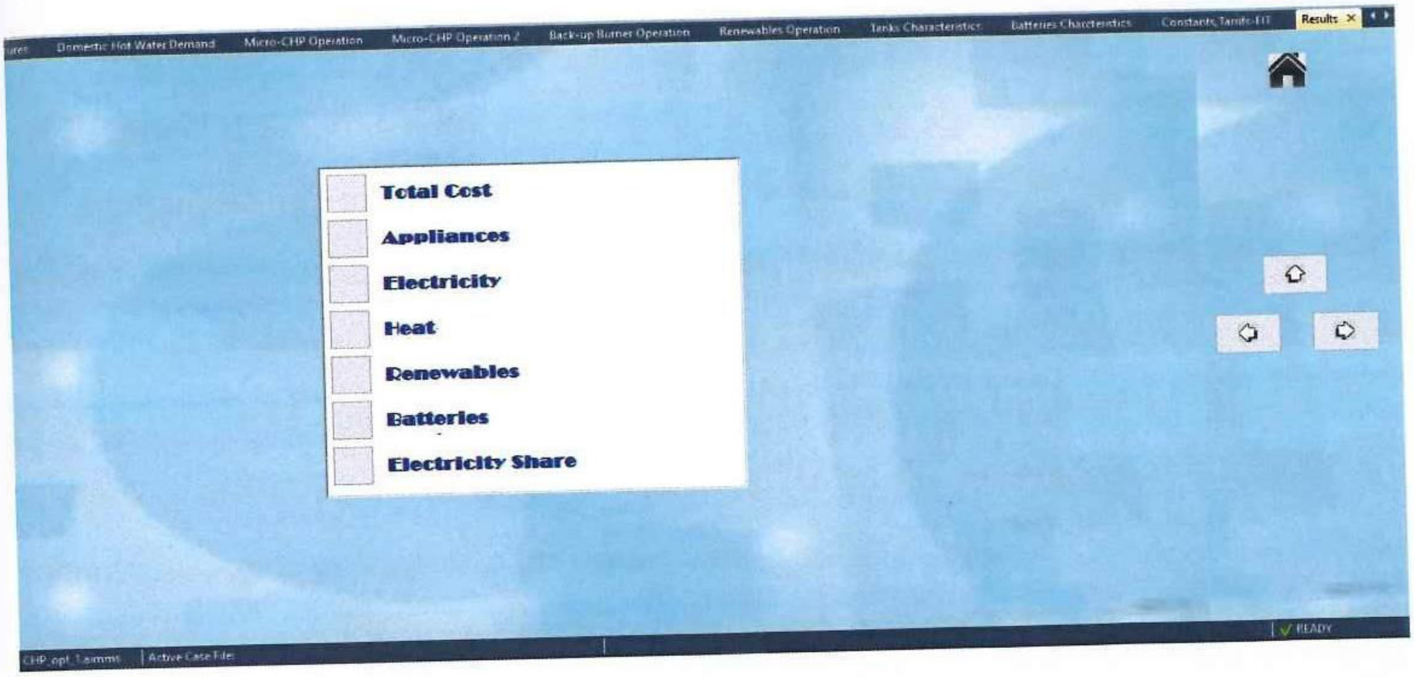
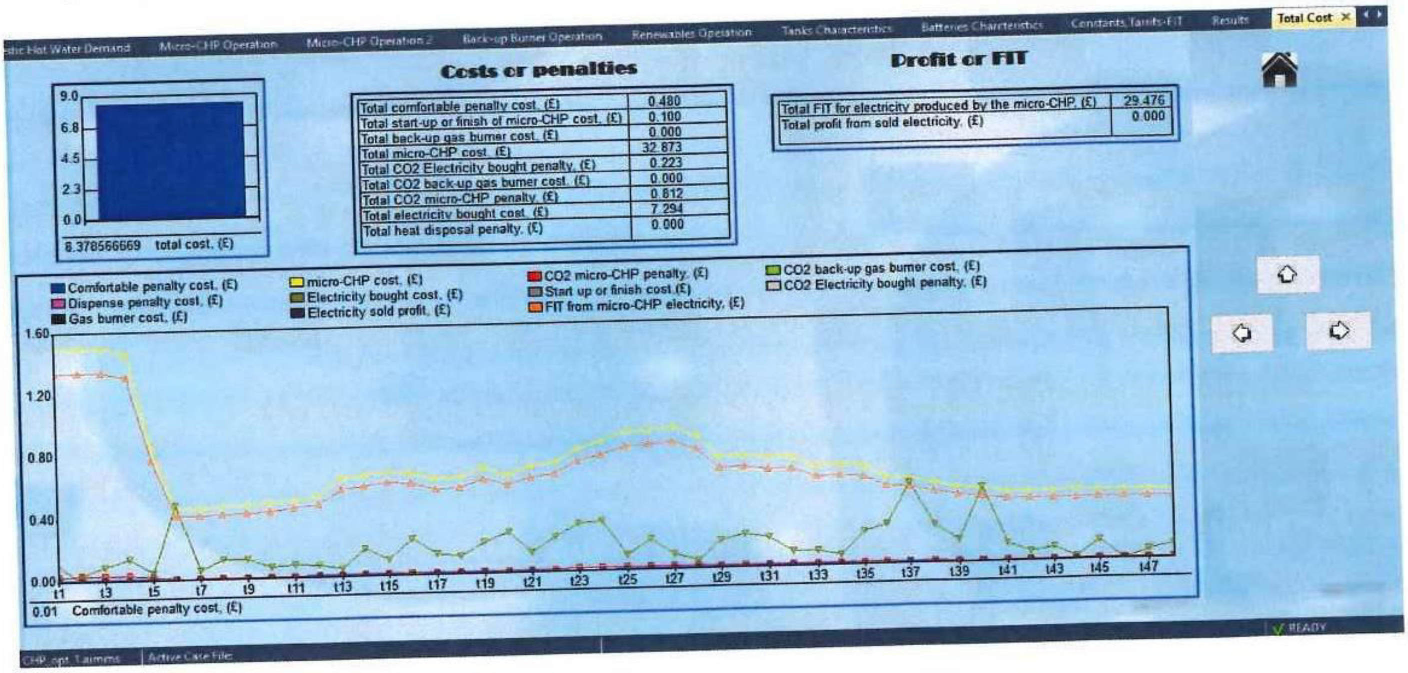


Figure 4.19: GUI: Results.

Total Cost

The total cost that was taken as result for the current case is equal to £8.38 and as it can be noticed it is equal to the one taken as result of the GAMS optimization for the same instance. Figure 4.20, demonstrates the Total Cost page and as it is shown, all the results related to the cost can be summarised in it, such as the costs, the profits and the change of them over the time intervals.



Costs or penalties

Total comfortable penalty cost, (£)	0.480
Total start-up or finish of micro-CHP cost, (£)	0.100
Total back-up gas burner cost, (£)	0.000
Total micro-CHP cost, (£)	32.873
Total CO2 Electricity bought penalty, (£)	0.223
Total CO2 back-up gas burner cost, (£)	0.000
Total CO2 micro-CHP penalty, (£)	0.812
Total electricity bought cost, (£)	7.294
Total heat disposal penalty, (£)	0.000

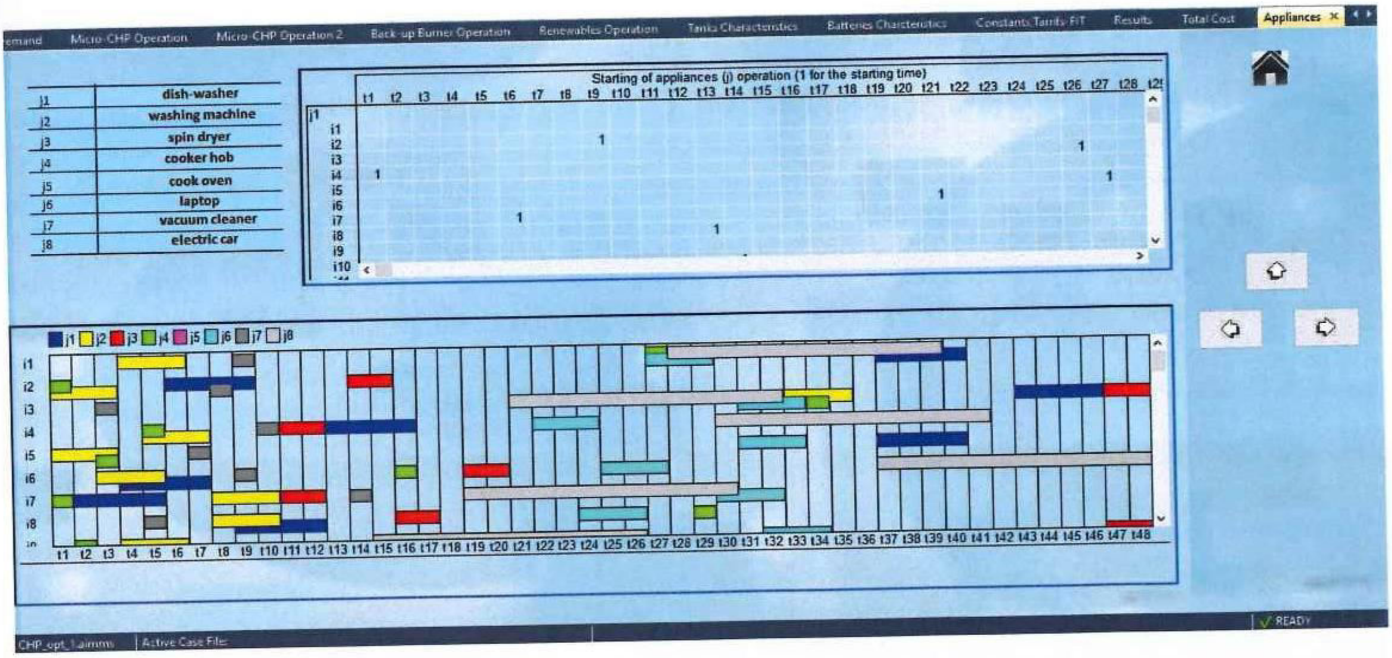
Profit or FIT

Total FIT for electricity produced by the micro-CHP, (£)	29.476
Total profit from sold electricity, (£)	0.000

Figure 4.20: GUI: Results, Total Cost.

Appliances

Figure 4.21 illustrates the result taken for the smart appliances. The starting of the appliances' operation and a gantt chart showing the specific operation of them are two of the most useful results for the user. Once again, those aligned with the initial GAMS result with slightly differences. One detail that should be noticed, is that the gantt chart has been designed that way that in case of two or more appliances operating at the same time interval, them the bars moves above or down so as there is not overlapping between them (eg.i3).



j1	dish-washer
j2	washing machine
j3	spin dryer
j4	cooker hob
j5	cook oven
j6	laptop
j7	vacuum cleaner
j8	electric car

Starting of appliances (j) operation (1 for the starting time)

j1	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24	t25	t26	t27	t28
i1																												
i2									1																	1		
i3																												
i4	1																										1	
i5																					1							
i6																												
i7						1																						
i8													1															
i9																												
i10																												

Figure 4.21: GUI: Results, Appliances.

Electricity

The electricity page consists of some tables showing the total electricity bought or produced by the micro-CHP. The difference of that result with the GAMS is around 0.4%. Also, a gantt chart is provided regarding the micro-CHP operation.

Heat

In this page, tables regarding the heat produced either by the micro-CHP or the back-up gas burner are being included. Once again, the difference with the previous solved same instance is really small, around 0.6%. Furthermore, tables about the level in storage tanks are provided for every house and each time interval.

Renewables

The current page consists of both tables and figures for every house illustrating the total electricity produced by the PV panel or the Wind Turbine. Regarding the Wind Turbine, the result shows the electricity that could have been produced and the optimization either takes it into account if the user wish so or not. It has to be mentioned that for the PV production the result is exactly the same as all the possible production from the PV panels is used to both of the results.

Batteries

The Batteries page, indicates the usage of the batteries and also provides tables showing the charge or discharge for every time interval.

Electricity Share

The last page of the 'Results' section, included a gantt chart shown in Figure 4.22, that indicates either the coming in or out of electricity for every house at every time interval. This is also approximately the same as the one shown in Table 4.6.

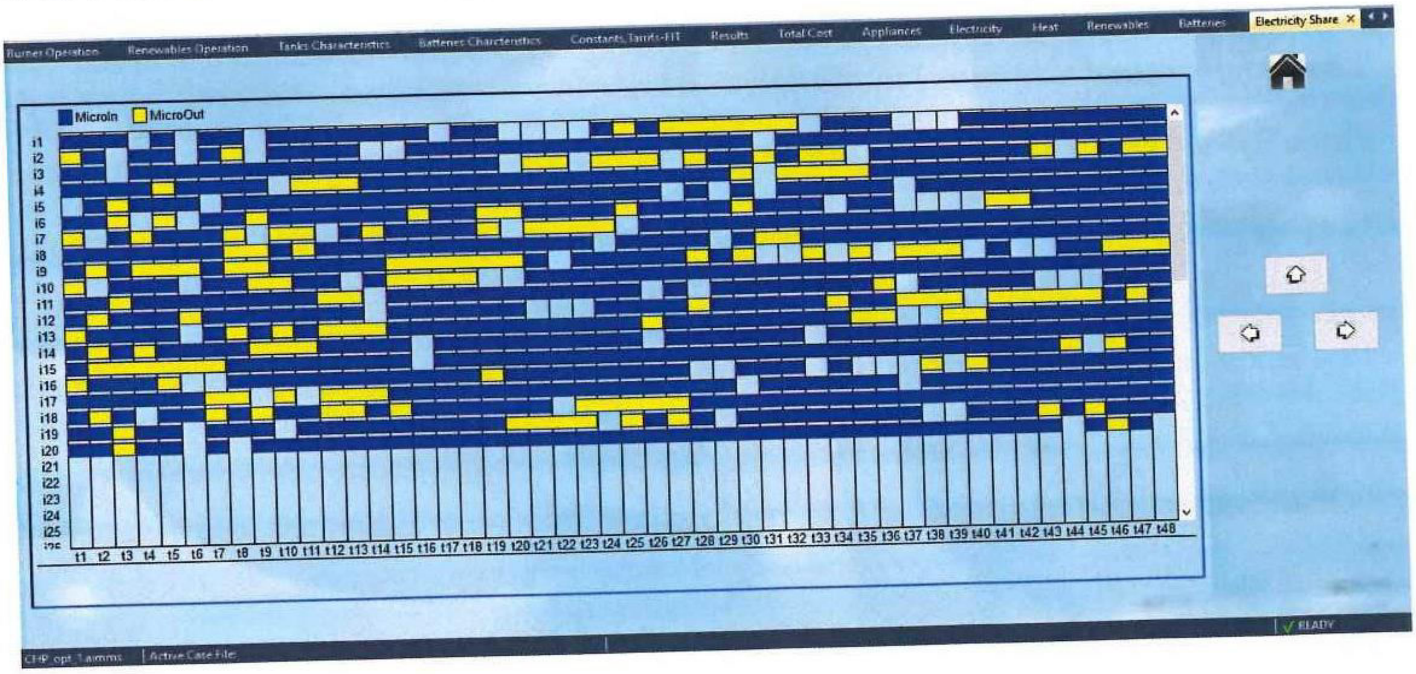


Figure 4.22: GUI: Results, Electricity Share.

Last but not lest, after having finished with the result taken, the user has the option of saving the current case by using the 'Menu Bar'. Additionally, already existing case studies can also be loaded from the same Menu.

Chapter 5

Conclusions

In the current study, a mathematical programming formulation has been proposed for networks based on the smart grid generation, in residential scale, scoping in the planning of operation for the energy needed. Two main different networks have been developed, one considering electricity share between the houses of the system and dealing with no electricity share. Significant consequences not only for the operation regarding the electricity or not electricity share between the houses have been noticed, but also for the conventional operation for no use of the micro-CHP unit. It is clear that the micro-generation system overwhelm the use of the conventional units such as the back-up gas burner. Contrary to the approach mentioned above, the total cost of the network seems not to change significantly when the costs of the carbon dioxide emissions are taken into account. However, the result is totally different when the main aspect of the problem is the minimization of the carbon dioxide cost instead of the total cost. In that case, the total cost increases dramatically. Also, the last instance of the first case study demonstrates that the approach of smaller time interval and the use of a wind turbine to the network, can decrease the total cost in a great extend. The framework seems to be flexible and capable of supporting even a new addition like the one of the wind turbine.

Furthermore, a graphical user interface has been created for easier user approach of the problem. The GUI seems to be flexible enough as the user is able of selecting all the input data and compile the problem to every case needed. By that way, different house models, number and types of smart appliances, characteristics of the systems (such as micro-CHP, back-up gas burner, storage tanks, batteries), use or not of the renewable sources can be modified by the user. Moreover, the demand and target temperatures depending on the season can also be properly added to the model. The user can also select the time interval and the time waiting for the solution to be found. As a result of that, it can easily be said that the GUI can be fully adapted to the user's willing and also offer demonstrative and easily understandable results through the various result pages and figures.

It would be important to conclude with potential for future improvement of the research. Some of those improvements could lay on:

- Finding a way for faster solution of big problems for many houses.
- Possible directly on-line corresponding of the input data about the outside temperature, air speed, solar radiation with available forecasting.
- Investigating the role an administrator could play so as to find the best way for GUI usage based on whom can insert the input data and share the final results.
- Indirectly input of electricity demand by possible adding the number of people living in each house.
- Even greater flexibility of the model in case that extra renewable source apart from PV and wind turbine could be used.

Last but not least, that kind of technologies is expected to develop significantly in the near future, especially if the government support and policies are the proper ones. Finally, alternative micro-CHP structures and also different environmental aspects could be an area for future research.

Chapter 6

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Appendices

Appendix A

Nomenclature

Indices / Sets

$i \in I$	households including in the optimization
$I^{OM1} \in I$	households in which the micro-CHP operates in mode 1
$I^{OM2} \in I$	households in which the micro-CHP operates in mode 2
$I^{OM3} \in I$	households in which the micro-CHP operates in mode 3
$j \in J$	flexible power consumption task of the appliances
$k \in K$	start-up (or shut-down) periods
$n \in N$	surfaces of the house
$t \in T$	time intervals
$z \in Z$	intervals for operational mode 2

Superscripts

min	minimum
max	maximum
on	starting-up
off	shutting-down
$+$	start-up period
$-$	shut-down peiod

Parameters

α_i^-	number of start-up periods for the micro-CHP of household i (in time intervals)

α_i^+	number of shut-down periods for the micro-CHP of household i (in time intervals)
β_i^{min}	minimum storage level of the battery for household i
β_i^{max}	maximum energy storage level of the battery for household i
β_i^{DHWmin}	minimum heat buffer tank capacity of the DHW tank for household i
β_i^{DHWmax}	maximum heat buffer tank capacity of the DHW tank for household i
β_i^{HSTmin}	minimum heat buffer tank capacity of the HST tank for household i
β_i^{HSTmax}	maximum heat buffer tank capacity of the HST tank for household i
γ_i^{min}	minimum heat generation capacity for the back-up gas burner of household i
γ_i^{max}	maximum heat generation capacity for the back-up gas burner of household i
δ_i^{air}	air density
δ_i^{water}	water density
δ_i^{on}	minimum running time for the micro-CHP of household i (in time intervals)
δ_i^{off}	minimum shut-down time for the micro-CHP of household i (in time intervals)
ε_t^{min}	minimum total electricity production for the micro-CHP during time interval t
ε_t^{max}	maximum total electricity production for the micro-CHP during time interval t
$\varepsilon_{(i,z)}^{min}$	end-point of the pw-slot for operation mode 2 t
$\varepsilon_{i,z}^{max}$	start-point of the pw-slot for operation mode 2 t

$\zeta^{el}_{(i,t)}$	electrical energy demand for every household i at time interval t; includes electricity and cooling load
$\zeta^{DHW}_{(i,t)}$	domestic hot water demand for every household i at time interval t
η^{panel}	efficiency of the panel
$\eta^{reflection}$	reflection efficiency
η^{system}	system efficiency
$\eta^{temperatures}$	thermal efficiency
θ^{min}_i	minimum heat generation from the micro-CHP of household i
θ^{max}_i	maximum heat generation from the micro-CHP of household i
θ^S_i	start-up cost of the micro-CHP i
θ^F_i	shutting-down cost of the micro-CHP i
$\lambda^-_{(i,k)}$	heat generation loss for the micro-CHP of household i during start-up period k
$\lambda^+_{(i,k)}$	heat generation excess for the micro-CHP of household i during shut-down period k
$\nu^{co2,b}$	tariff for carbon dioxide emission from the micro-CHP opertion
$\nu^{co2,eb}$	tariff for carbon dioxide emission from the back-up gas burner opertion
$\nu^{co2,c}$	tariff for carbon dioxide emission from the purchased electricity
$\xi_{(i,t)}$	fuel cost for operating the micro-CHP of household i at time interval t
$\xi^{GB}_{(i,t)}$	fuel cost for operating the back-up gas burner of household i at time interval t
π_t	selling price of electricity produced by micro-CHP generators at time interval t

π_t^{CHP}	selling price of electricity produced by micro-CHP generators at time interval t
π_t^{PV}	feed in tariff of electricity produced by the PV panels at time interval t
π_t^{wind}	feed in tariff of electricity produced by the wind turbine at time interval t
ρ_i^{min}	minimum heat to elextricity ratio for the micro-CHP of household i for operation mode 2
ρ_i^{max}	maximum heat to electricty ratio for the micro-CHP of household i for operation mode 2
$\rho_{(i,z)}$	electrical energy to heat production ratio for the micro-CHP of household i for operation mode 2
ρOpt_i	different operating mode for the micro-CHP for each household i for operation mode 2
ψ_t	purchase price of electricity from the macrogrid at time interval t
a^{PV}	area of the PV panel
a^{wind}	swept area of the wind turbine
a_i^{DHW}	area of the DHW tank for every house i
a_i^{HS}	area of the HS tank for every house i
a_i^n	area of the house i
cp_i	comfortable penalty for every house i
c_i^{min}	minimun disharged rate of the battery for every house i
c_i^{max}	maximun disharged rate of the battery for every house i
c_p^{air}	specific heat capacity of air
c_p^{water}	specific heat capacity of water
c_p^{wind}	air coefficient of the wind turbine
dp_i	dispend penalty for every house i
$elcon_{(i,t)}$	constant, not scheduable electricity demand for every house i at time interval t

n_i	number of air changes for every house i
$q_{(i,t)}^{fabric_g}$	heat gains from fabric for every house i at time interval t
$q_{(i,t)}^{fabric_l}$	heat losses from fabric for every house i at time interval t
$q_{(i,t)}^{gains}$	heat gains every house i at time interval t
$q_{(i,t)}^{internal_g}$	heat gains from internal factors for every house i at time interval t
$q_{(i,t)}^{solar_g}$	heat gains from solar energy for every house i at time interval t
$q_{(i,t)}^{vent_l}$	heat losses by the air changes for every house i at time interval t
rad_t	radiation for the PV panel
$ramp_i^{down}$	lower ramp limitation for the micro-CHP for every house i
$ramp_i^{up}$	upper ramp limitations for the micro-CHP for every house i
t_i	temperature range of tolerance for every house i
t_i^{DHWmin}	minimum temperature inside the DHW tank for every house i
t_i^{DHWmax}	maximum temperature inside the DHW tank for every house i
t_i^{HSmin}	minimum temperature inside the HS tank for every house i
t_i^{HSmax}	maximum temperature inside the HS tank for every house i
t_t^{target}	target temperature for every house i
u_i^{DHW}	heat transfer coefficient of the DHW tank for every house i
u_i^{HS}	heat transfer coefficient of the HS tank for every house i
u_i^{n}	heat transfer coefficient of the house for every house i

Variables

Δt	time divitation
$B_{(i,t)}^{DHW}$	heat storage level of the DHW tank of household i at time t
$B_{(i,t)}^{HS}$	heat storage level of the HS tank of household i at time t
$DE_{(i,t)}$	electricity demand of household i at time t
$E_{(i,t)}^{DEM}$	electricity required and not stored to the battery of household i at time t
$e_{(i,t)}^{PV}$	maximum temperature inside the DHW tank for every house i
$E_{(i,t)}$	electricity production by the micro-CHP of household i during time interval t
$E_{(i,t)}^{buy}$	purchased electricity from the macro-grid for house i at time interval t
$E_{(i,t)}^{sales}$	sold electricity to the macro-grid from house i at time interval t
E_t^{excess}	extra electricity added to the micro-grid from the wind turbine or the main grid at time interval t
E_t^{sales}	sold electricity to the macro-grid from all houses at time interval t
$EB_{(i,t)}$	energy level of the battery for house i at time interval t
$EB_{(i,t)}^{in}$	electricity charged to the battery for house i at time interval t
$EB_{(i,t)}^{out}$	electricity discharged from the battery for house i at time interval t
$MG_{(i,t)}^{in}$	electricity imported by the micro-grid for house i at time interval t
$MG_{(i,t)}^{out}$	electricity exported from the micro-grid for house i at time interval t
$Q_{(i,t)}$	real heat production by the micro-CHP of household i during time interval t; delivered to heat buffer tank

$Q^{disp}_{(i,t)}$	heat disposed from household i during time interval t; delivered to heat buffer tank
$Q^{DHW_{in}}_{(i,t)}$	heat supplied to the DHW tank for household i during time interval t
$Q^{DHW_{out}}_{(i,t)}$	heat supplied from the DHW tank for household i during time interval t; delivered to heat buffer tank
$Q^{DHW_{loss}}_{(i,t)}$	heat losses from the DHW tank for household i during time interval t
$Q^{disp}_{(i,t)}$	heat disposed from household i during time interval t; delivered to heat buffer tank
$Q^{GB}_{(i,t)}$	heat production by the back-up gas burner of household i during time interval t
$Q^{HOUSE_{loss}}_{(i,t)}$	heat losses for household i during time interval t
$Q^{HS_{in}}_{(i,t)}$	heat supplied to the HS tank for household i during time interval t; delivered to heat buffer tank
$Q^{HS_{out}}_{(i,t)}$	heat supplied from the HS tank for household i during time interval t
$Q^{HS_{loss}}_{(i,t)}$	heat losses from the HS tank for household i during time interval t
$Q^{S}_{(i,t)}$	real heat production of the micro-CHP for household i during time interval t
$Q^{DT}_{(i,t)}$	heat required to moderate the temperature for household i during time interval t
$Q^{max}_{(i,t)}$	maximum eat production from the micro-CHP for household i during time interval t
$T^{dev}_{(i,t)}$	absolute temperature difference between the target temperature and the room temperature for household i during time interval t
$T^{DHW}_{(i,t)}$	temperature of the DHW tank for household i during time interval t

$T_{(i,t)}^{DHW_{room}}$	temperature of the room where the DHW tank is stored for household i during time interval t
$T_{(i,t)}^{HS}$	temperature of the HS tank for household i during time interval t
$T_{(i,t)}^{HS_{room}}$	temperature of the room where the HS tank is stored for household i during time interval t
$T_{(i,t)}^{house}$	temperature of the house for household i during time interval t
$TMG_{(i,t)}^{in}$	total electricity shared within the micro-grid going in the houses i during time interval t
$TMG_{(i,t)}^{out}$	total electricity shared within the micro-grid going out of the houses i during time interval t

Binary Variables

$F_{(i,t)}$	$= 1$, if the micro-CHP of household i stops operating at time point t (i.e., $X_{it-1} = 1$ and $X_{it} = 0$)
$P_{(i,z,t)}$	$= 1$, if the micro-CHP of household i operates at the pw-slot for operation mode 2 at time point t
$S_{(i,t)}$	$= 1$, if the micro-CHP of household i starts operating at time point t (i.e., $X_{it-1} = 0$ and $X_{it} = 1$)
$W_{(i,j,t)}$	$= 1$, if task j has been completes for household i at time point t
$X_{(i,t)}$	$= 1$, if the micro-CHP of household i is operating at the beginning of time interval t
$X_{(i,t)}^{GB}$	$= 1$, if the back-up gas burner of household i is operating at the beginning of time interval t
$Y_{(i,t)}^{OUT}$	$= 1$, if electricity is not being inserted in the house i within the micro-grid at the time interval t

Appendix B

Problem Statement

The problem is being set considering the following items:

(i) A planning horizon that is being divided into a set of time intervals $t \in T$.

(ii) A number of households $i \in I$ that includes the micro-CHP generator and for each of them $(\varepsilon_{(i,z)}^{min})$,$(\varepsilon_{(i,z)}^{max})$, $(\theta_i^{min})$for the start and end point in case of the second mode (variable heat to electricity ratio), also for that case $(\rho_{(i,z)})$ for the heat to electricity ratio of the pw-slot, $(\rho_{(i)}^{min})$, $(\rho_{(i)}^{max})$, for the minimum and maximum heat to electricity ratio for modes 2 and 3 respectively. The sets $I^{OM1} \in I$, $I^{OM2} \in I$,$I^{OM3} \in I$ for the different operational modes of the micro-CHP. The (θ_i^S), (θ_i^F) for the starting and shutting down cost of the micro-CHP.

(iii) A set of start-up and shut-down periods $k \in K$ is defined for every micro-CHP generator i. Also, the parameters (α_i^-) and (α_i^+) for the number of start-up and shut-down periods (in time intervals) for micro-CHP generator i, respectively, (δ_i^{on}), (δ_i^{off}) for the minimum period that the micro-CHP should remain shut down or the minimum time it should operate once started, $(\lambda_{(i,k)}^-)$, $(\lambda_{(i,k)}^+)$ for the surplus heat after the shutting down or the loss when it starts up.

(iv) A set of the flexible power consumption task regarding the operation of the appliances, $j \in J$.

(v) A set of the intervals for operation of the micro-CHP in mode 2, $z \in Z$.

(vi) Minimum and maximum total electricity production of the micro-CHP for every time interval, (ε_t^{min}), (ε_t^{max}).

(vii) Minimum and maximum heat generation of the back-up boiler for every household, (γ_i^{min}),(γ_i^{max}).

(viii) Every household is provided with two tanks, one for the storage of the domestic hot water with $(\zeta_{(i,t)}^{DHW})$ to be the demand for DHW and the second one for the storage of heat (HS). For each of the tanks there is a minimum and maximum storage capacity, (β_i^{DHWmin}), (β_i^{DHWmax}), (β_i^{HSTmin}), (β_i^{HSTmax}) respectively.

(ix) Each household includes a battery for the storage of excess electricity. For the battery: (β_i^{min}), (β_i^{max}) indicates the minimum and the maximum stored energy and (c_i^{min}), (c_i^{max}) the minimum and maximum discharge rate.

(x) The fuel cost for the operation of the micro-CHP $(\xi_{(i,t)})$, the cost of the gas burner $(\xi_{(i,t)}^{GB})$, and the cost of buying electricity from the main grid (ψ_t).

(xi) On the one hand, there are some feed-in tariffs that minimize the total cost such as the tariff for producing electricity from a micro-CHP, a PV panel, for a wind turbine or for the electricity being sold to the main grid, (π^{CHP}), (π^{PV}), (π^{W}), (π_t) respectively. On the other hand there are the tariffs that boost the total cost due to the carbon dioxide emissions, $(\nu^{co2,b})$ for the heat production emissions, $(\nu^{co2,c})$ for the electricity production emissions, $(\nu^{co2,eb})$ for the emissions by the purchased electricity.

The energy that can be produced from the PV panel and the wind turbine can be calculated from the following equations. It should be mentioned that the wind turbine operates only in a range of air speed (m/s), $3.5 \leq v_t^{wind} \leq 63$

Appendix C

Input Data

The main input data are also presented in the input pages of the GUI and the sources of them are the followings:

Coefficients Most of the coefficient constraints and the values for the houses' areas have been conduced based on [49].

Ventilation-Losses-Gains The ventilation rates and the heat gains and losses of the houses have been gathered based on the Government Standard Assessment Procedure depending on the living people, the type of the houses, the number of the appliances etc.

DHW consumption The consumption of the DHW has been deducted by the surveys available at [51], [52].

Micro-CHP All the characteristics regarding the micro-CHP unit have been taken by [17].

Tanks The tanks' characteristics have been taken from [51]. As a result the volume for the DHW and HS tank have been assumed to be $0.12m^3$ and $0.45m^3$ respectively. Finally, the type of them is assumed to be cylinder.

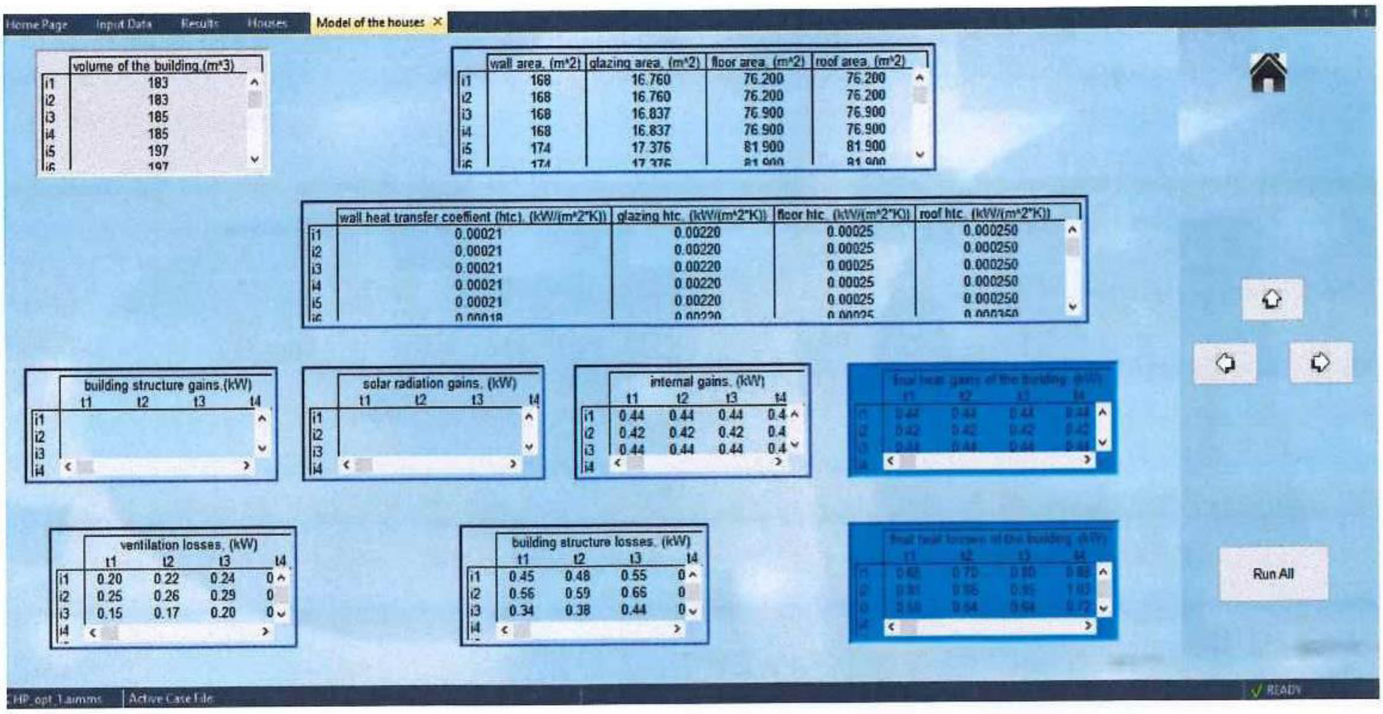
Batteries Regarding the batteries the [53] was the main source used and as an outcome the efficiency of them was chosen to be 95% and the maximum output 4.8kWh. Also, the discharge and charge rate of them is equal to 0.5 and that is about the capacity that it can discharge or charge per hour.

Costs The purchased cost, the selling cost, the FIT tariffs and the gas cost were taken based on [54].

Appendix D

Graphical User Interface

Input, Model of the house



	volume of the building.(m^3)
i1	183
i2	183
i3	185
i4	185
i5	197

	wall area. (m^2)	glazing area. (m^2)	floor area. (m^2)	roof area. (m^2)
i1	168	16.760	76.200	76.200
i2	168	16.760	76.200	76.200
i3	168	16.837	76.900	76.900
i4	168	16.837	76.900	76.900
i5	174	17.376	81.900	81.900

	wall heat transfer coeffient (htc). (kW/(m^2*K))	glazing htc. (kW/(m^2*K))	floor htc. (kW/(m^2*K))	roof htc. (kW/(m^2*K))
i1	0.00021	0.00220	0.00025	0.000250
i2	0.00021	0.00220	0.00025	0.000250
i3	0.00021	0.00220	0.00025	0.000250
i4	0.00021	0.00220	0.00025	0.000250
i5	0.00021	0.00220	0.00025	0.000250

building structure gains.(kW)	t1	t2	t3	t4
i1				
i2				
i3				
i4				

solar radiation gains. (kW)	t1	t2	t3	t4
i1				
i2				
i3				
i4				

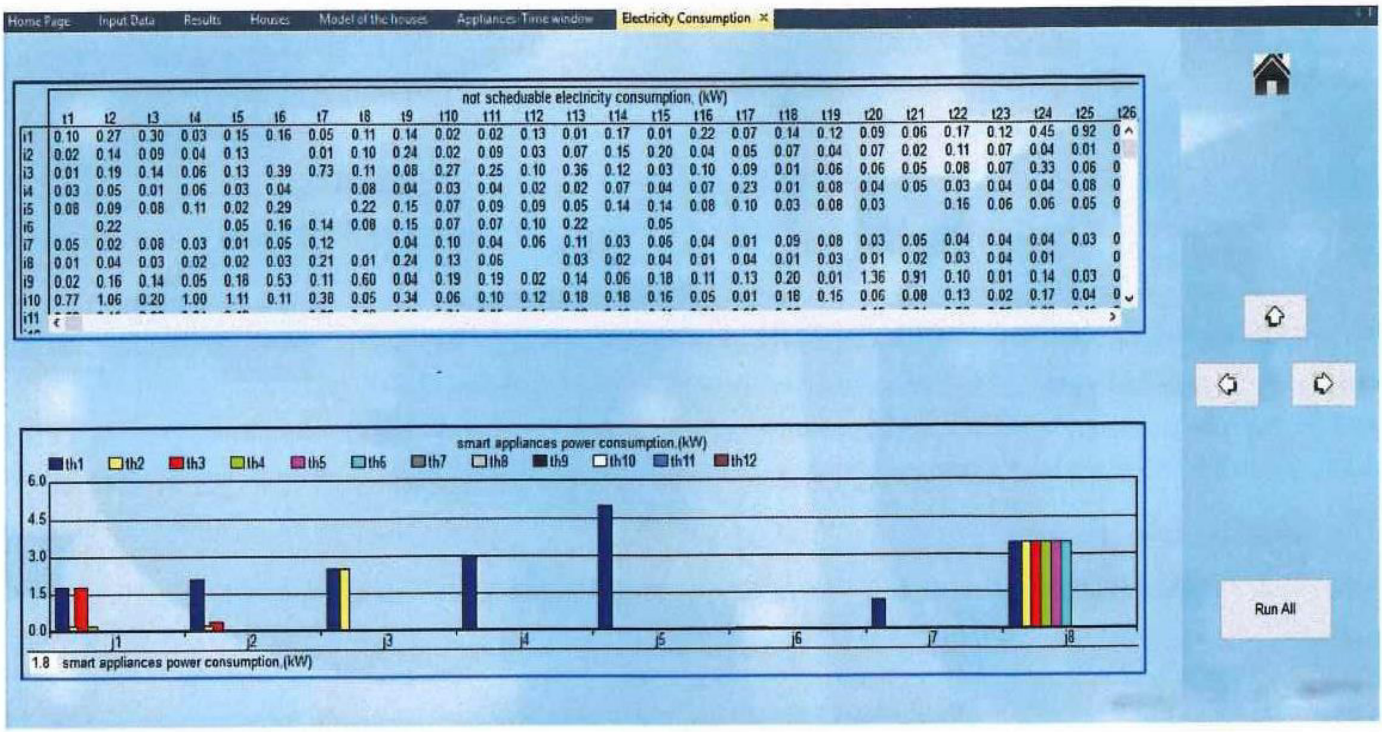
internal gains. (kW)	t1	t2	t3	t4
i1	0.44	0.44	0.44	0.4
i2	0.42	0.42	0.42	0.4
i3	0.44	0.44	0.44	0.4
i4				

ventilation losses. (kW)	t1	t2	t3	t4
i1	0.20	0.22	0.24	0
i2	0.25	0.26	0.29	0
i3	0.15	0.17	0.20	0
i4				

building structure losses. (kW)	t1	t2	t3	t4
i1	0.45	0.48	0.55	0
i2	0.56	0.59	0.66	0
i3	0.34	0.38	0.44	0
i4				

Figure D.1: GUI: Input, Model of the house.

Input, Electricity Consumption.



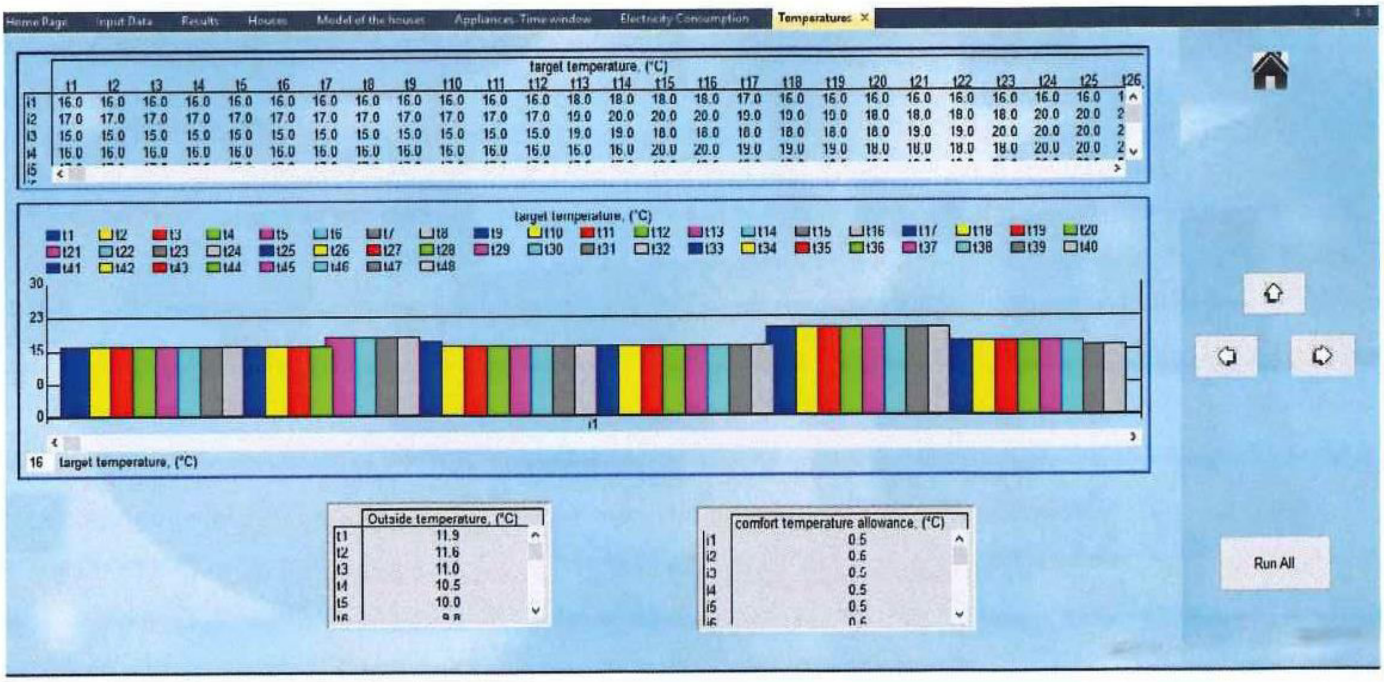
not scheduable electricity consumption, (kW)

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24	t25	t26
i1	0.10	0.27	0.30	0.03	0.15	0.16	0.05	0.11	0.14	0.02	0.02	0.13	0.01	0.17	0.01	0.22	0.07	0.14	0.12	0.09	0.06	0.17	0.12	0.45	0.92	0
i2	0.02	0.14	0.09	0.04	0.13		0.01	0.10	0.24	0.02	0.09	0.03	0.07	0.15	0.20	0.04	0.05	0.07	0.04	0.07	0.02	0.11	0.07	0.04	0.01	0
i3	0.01	0.19	0.14	0.06	0.13	0.39	0.73	0.11	0.08	0.27	0.25	0.10	0.36	0.12	0.03	0.10	0.09	0.01	0.06	0.06	0.05	0.08	0.07	0.33	0.06	0
i4	0.03	0.05	0.01	0.06	0.03	0.04		0.08	0.04	0.03	0.04	0.02	0.02	0.07	0.04	0.07	0.23	0.01	0.08	0.04	0.05	0.03	0.04	0.04	0.08	0
i5	0.08	0.09	0.08	0.11	0.02	0.29		0.22	0.15	0.07	0.09	0.09	0.05	0.14	0.14	0.08	0.10	0.03	0.08	0.03		0.16	0.06	0.06	0.05	0
i6		0.22			0.05	0.16	0.14	0.08	0.15	0.07	0.07	0.10	0.22		0.05											
i7	0.05	0.02	0.08	0.03	0.01	0.05	0.12		0.04	0.10	0.04	0.06	0.11	0.03	0.06	0.04	0.01	0.09	0.08	0.03	0.05	0.04	0.04	0.04	0.03	0
i8	0.01	0.04	0.03	0.02	0.02	0.03	0.21	0.01	0.24	0.13	0.06		0.03	0.02	0.04	0.01	0.04	0.01	0.03	0.01	0.02	0.03	0.04	0.01		0
i9	0.02	0.16	0.14	0.05	0.18	0.53	0.11	0.60	0.04	0.19	0.19	0.02	0.14	0.06	0.18	0.11	0.13	0.20	0.01	1.36	0.91	0.10	0.01	0.14	0.03	0
i10	0.77	1.06	0.20	1.00	1.11	0.11	0.38	0.05	0.34	0.06	0.10	0.12	0.18	0.18	0.16	0.05	0.01	0.18	0.15	0.06	0.08	0.13	0.02	0.17	0.04	0
i11																										

1.8 smart appliances power consumption,(kW)

Figure D.2: GUI: Input, Electricity Consumption.

Temperatures



target temperature, (°C)

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24	t25	t26
i1	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	18.0	18.0	18.0	18.0	17.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	1
i2	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	19.0	20.0	20.0	20.0	19.0	19.0	19.0	18.0	18.0	18.0	18.0	20.0	20.0	2
i3	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	19.0	19.0	18.0	18.0	18.0	18.0	18.0	18.0	19.0	19.0	20.0	20.0	20.0	2
i4	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	16.0	20.0	20.0	19.0	19.0	19.0	18.0	18.0	18.0	18.0	20.0	20.0	2
i5																										

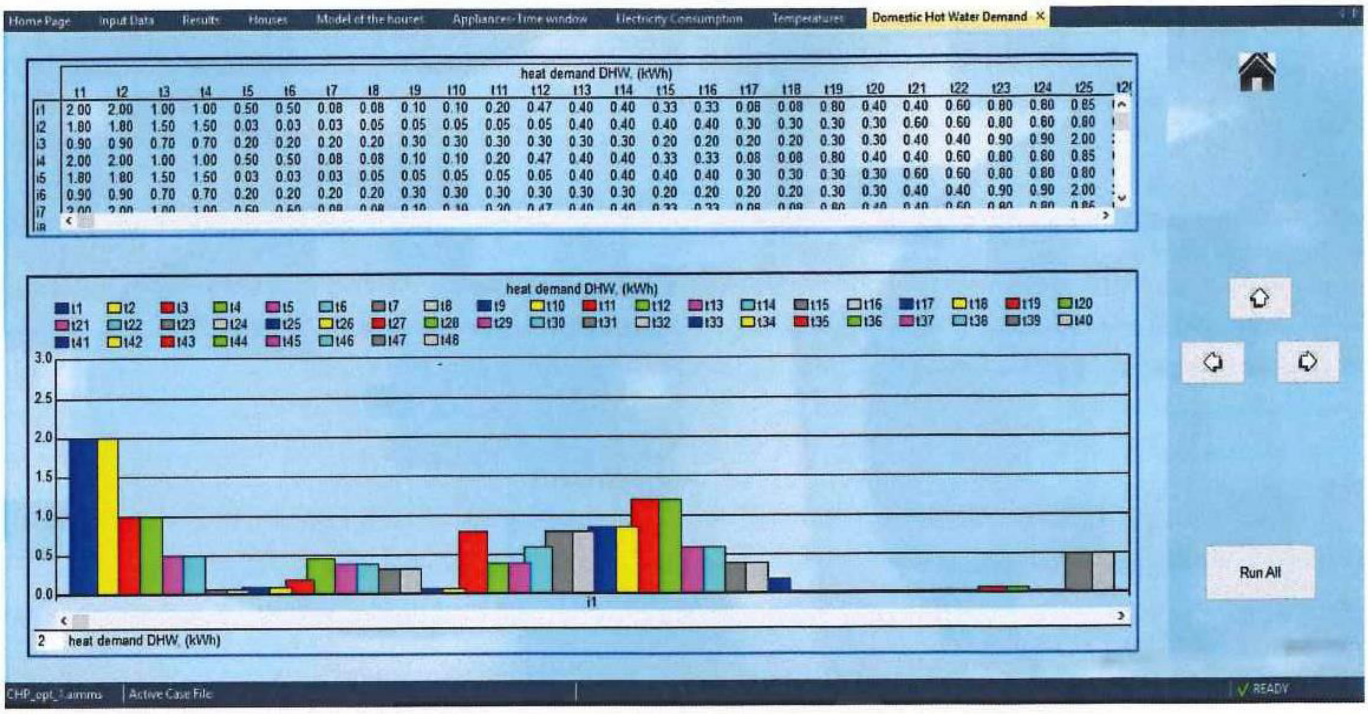
16 target temperature, (°C)

	Outside temperature, (°C)
t1	11.9
t2	11.6
t3	11.0
t4	10.5
t5	10.0

	comfort temperature allowance, (°C)
i1	0.5
i2	0.6
i3	0.5
i4	0.5
i5	0.5

Figure D.3: GUI: Input, Temperatures.

Domestic Hot Water Demand

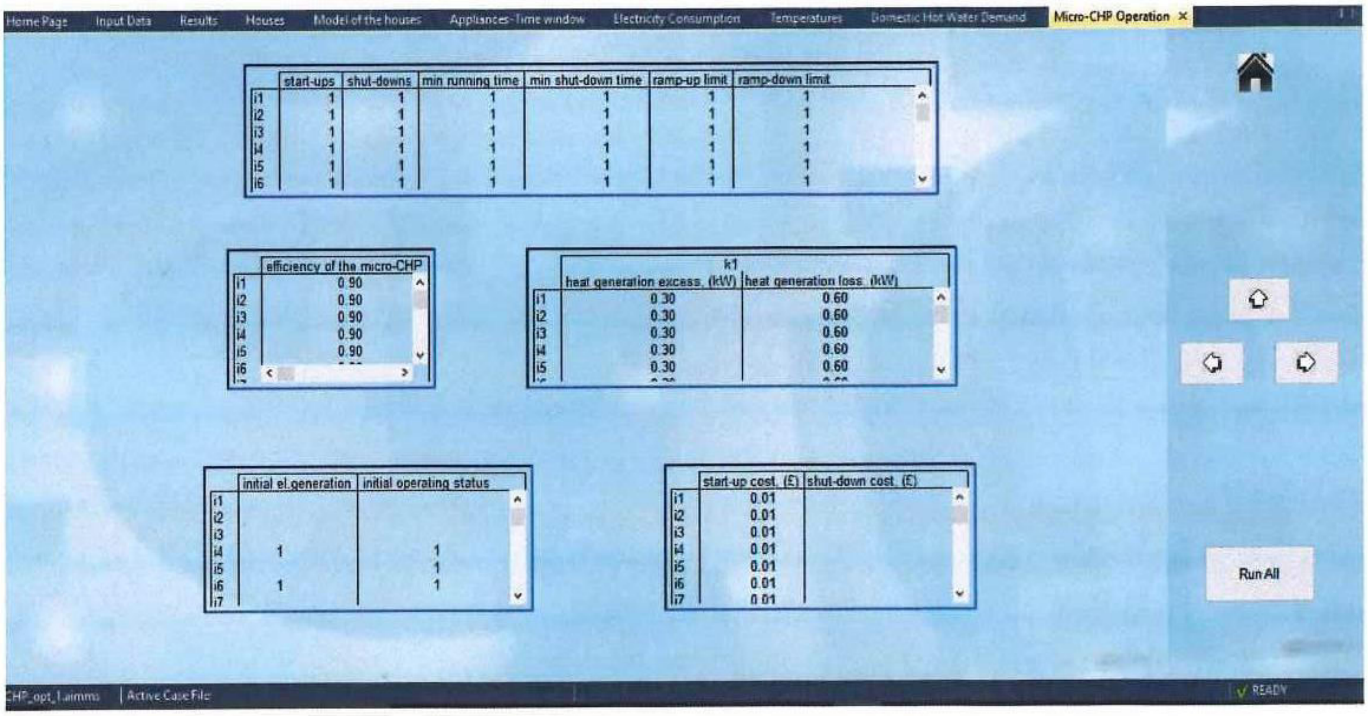


heat demand DHW, (kWh)

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24	t25
i1	2.00	2.00	1.00	1.00	0.50	0.50	0.08	0.08	0.10	0.10	0.20	0.47	0.40	0.40	0.33	0.33	0.08	0.08	0.80	0.40	0.40	0.60	0.80	0.80	0.85
i2	1.80	1.80	1.50	1.50	0.03	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.40	0.40	0.40	0.40	0.30	0.30	0.30	0.30	0.60	0.60	0.80	0.80	0.80
i3	0.90	0.90	0.70	0.70	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20	0.20	0.20	0.30	0.30	0.40	0.40	0.90	0.90	2.00
i4	2.00	2.00	1.00	1.00	0.50	0.50	0.08	0.08	0.10	0.10	0.20	0.47	0.40	0.40	0.33	0.33	0.08	0.08	0.80	0.40	0.40	0.60	0.80	0.80	0.85
i5	1.80	1.80	1.50	1.50	0.03	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.40	0.40	0.40	0.40	0.30	0.30	0.30	0.30	0.60	0.60	0.80	0.80	0.80
i6	0.90	0.90	0.70	0.70	0.20	0.20	0.20	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.20	0.20	0.20	0.20	0.30	0.30	0.40	0.40	0.90	0.90	2.00

Figure D.4: GUI: Input, Domestic Hot Water Demand.

Micro-CHP Operation



	start-ups	shut-downs	min running time	min shut-down time	ramp-up limit	ramp-down limit
i1	1	1	1	1	1	1
i2	1	1	1	1	1	1
i3	1	1	1	1	1	1
i4	1	1	1	1	1	1
i5	1	1	1	1	1	1
i6	1	1	1	1	1	1

	efficiency of the micro-CHP
i1	0.90
i2	0.90
i3	0.90
i4	0.90
i5	0.90

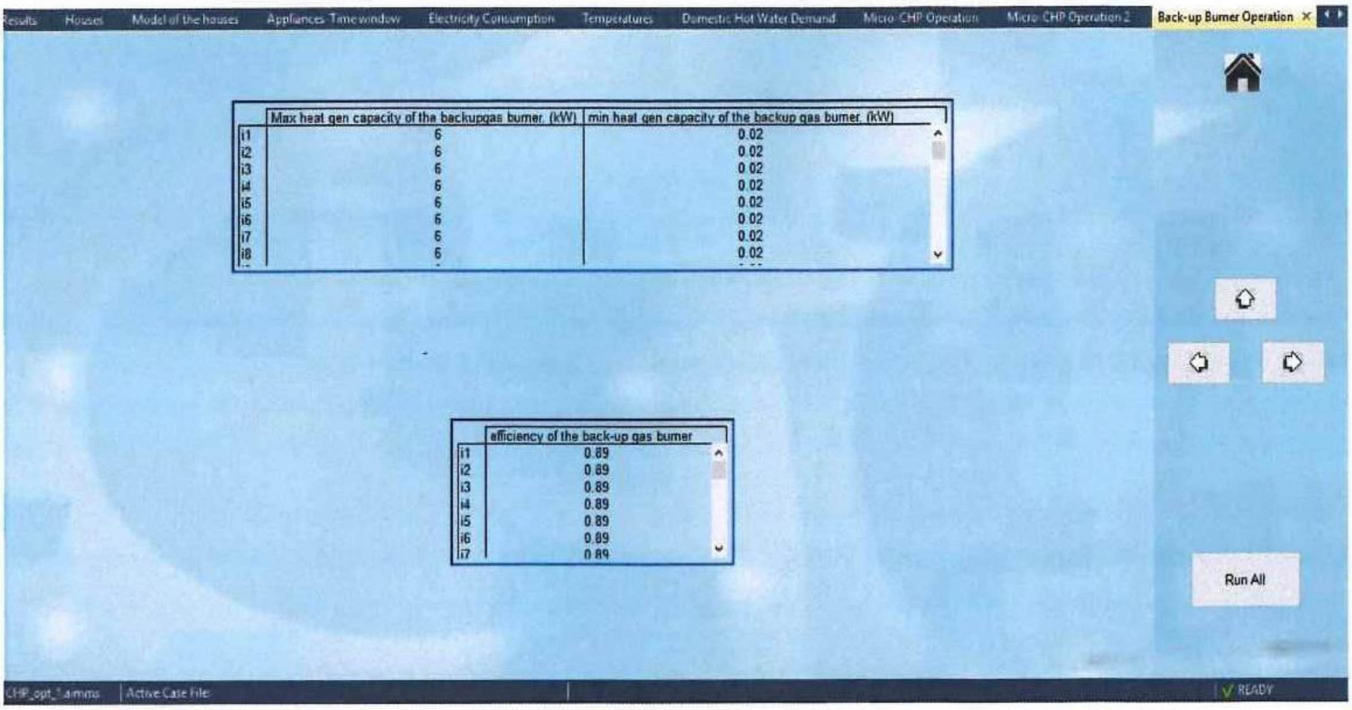
	k1	
	heat generation excess, (kW)	heat generation loss, (kW)
i1	0.30	0.60
i2	0.30	0.60
i3	0.30	0.60
i4	0.30	0.60
i5	0.30	0.60

	initial el.generation	initial operating status
i1		
i2		
i3		
i4	1	1
i5		1
i6	1	1
i7		

	start-up cost, (£)	shut-down cost, (£)
i1	0.01	
i2	0.01	
i3	0.01	
i4	0.01	
i5	0.01	
i6	0.01	
i7	0.01	

Figure D.5: GUI: Input, Micro-CHP Operation.

Back-up Burner Operation

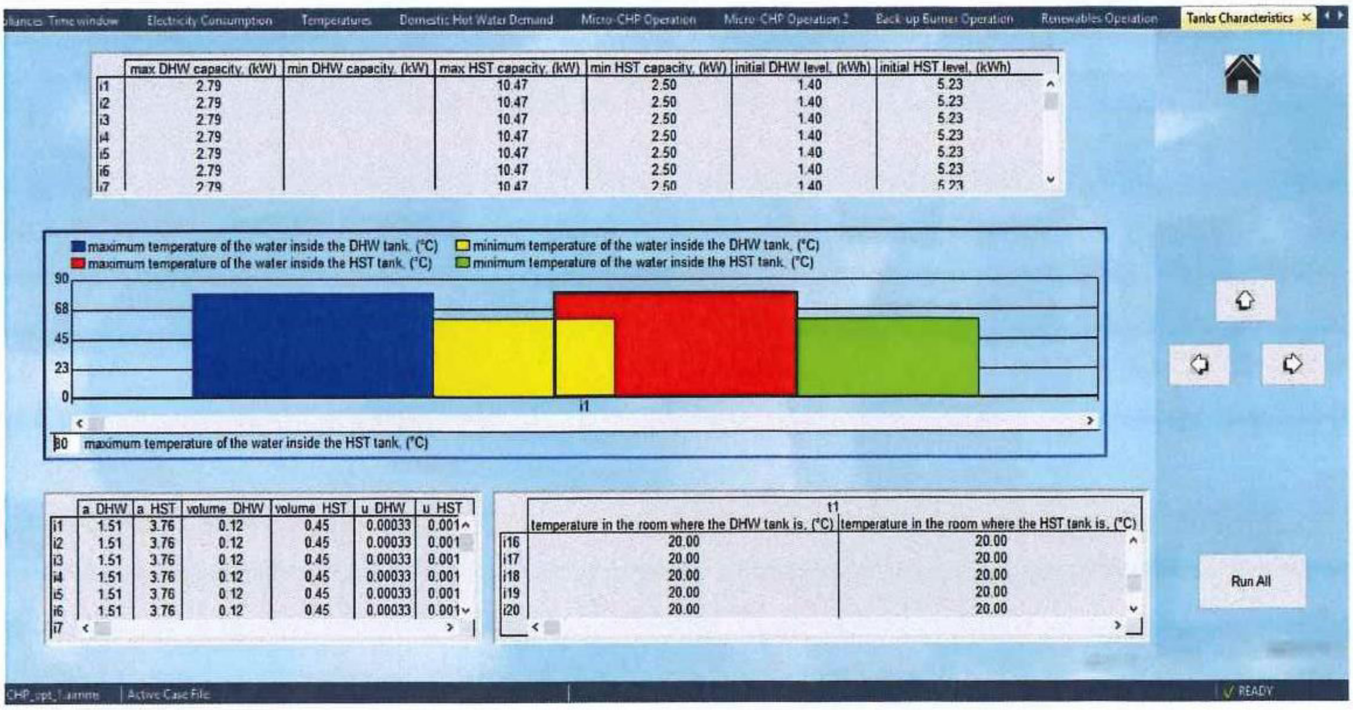


	Max heat gen capacity of tha backupgas burner. (kW)	min heat gen capacity of the backup gas burner. (kW)
i1	6	0.02
i2	6	0.02
i3	6	0.02
i4	6	0.02
i5	6	0.02
i6	6	0.02
i7	6	0.02
i8	6	0.02

	efficiency of the back-up gas burner
i1	0.89
i2	0.89
i3	0.89
i4	0.89
i5	0.89
i6	0.89
i7	0.89

Figure D.6: GUI: Input, Back-up Burner Operation.

Tanks Characteristics



	max DHW capacity, (kW)	min DHW capacity, (kW)	max HST capacity, (kW)	min HST capacity, (kW)	initial DHW level, (kWh)	initial HST level, (kWh)
i1	2.79		10.47	2.50	1.40	5.23
i2	2.79		10.47	2.50	1.40	5.23
i3	2.79		10.47	2.50	1.40	5.23
i4	2.79		10.47	2.50	1.40	5.23
i5	2.79		10.47	2.50	1.40	5.23
i6	2.79		10.47	2.50	1.40	5.23
i7	2.79		10.47	2.50	1.40	5.23

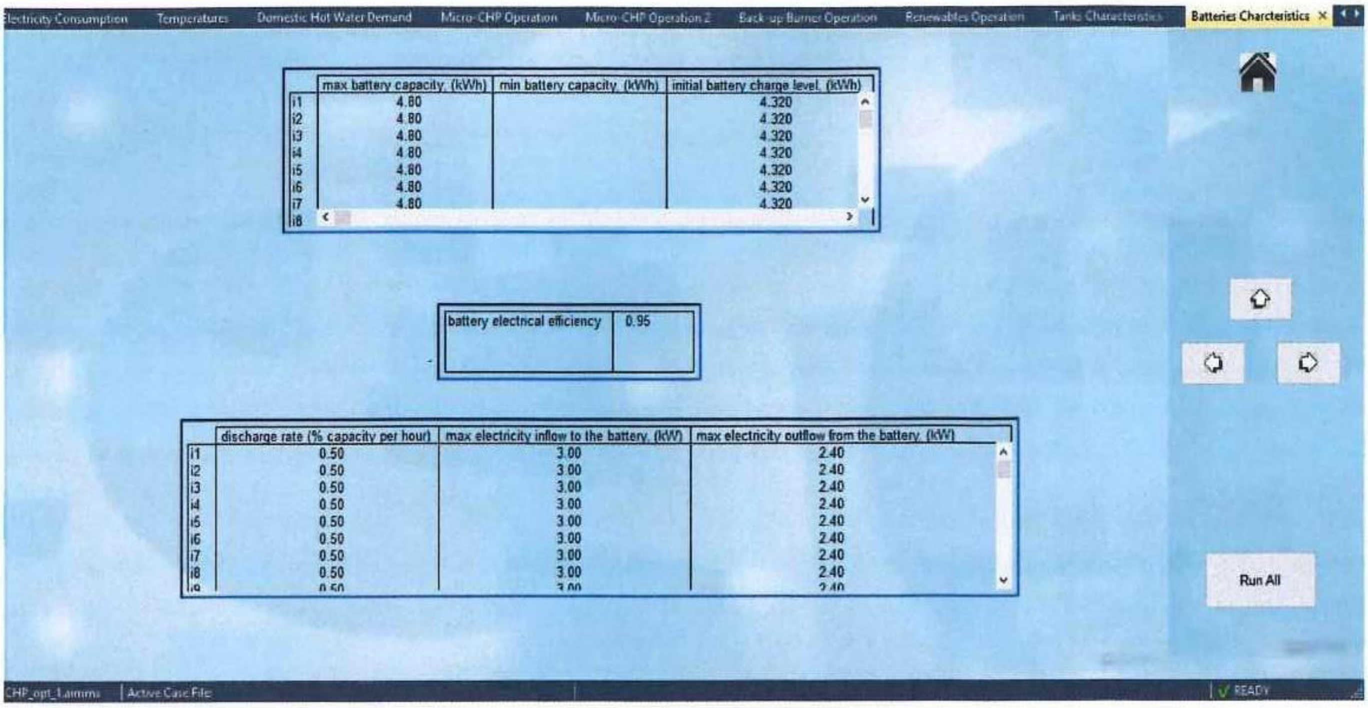
80 maximum temperature of the water inside the HST tank, (°C)

	a DHW	a HST	volume DHW	volume HST	u DHW	u HST
i1	1.51	3.76	0.12	0.45	0.00033	0.001
i2	1.51	3.76	0.12	0.45	0.00033	0.001
i3	1.51	3.76	0.12	0.45	0.00033	0.001
i4	1.51	3.76	0.12	0.45	0.00033	0.001
i5	1.51	3.76	0.12	0.45	0.00033	0.001
i6	1.51	3.76	0.12	0.45	0.00033	0.001
i7						

	t1	
	temperature in the room where the DHW tank is, (°C)	temperature in the room where the HST tank is, (°C)
i16	20.00	20.00
i17	20.00	20.00
i18	20.00	20.00
i19	20.00	20.00
i20	20.00	20.00

Figure D.7: GUI: Input, Tanks Characteristics.

Batteries Characteristics



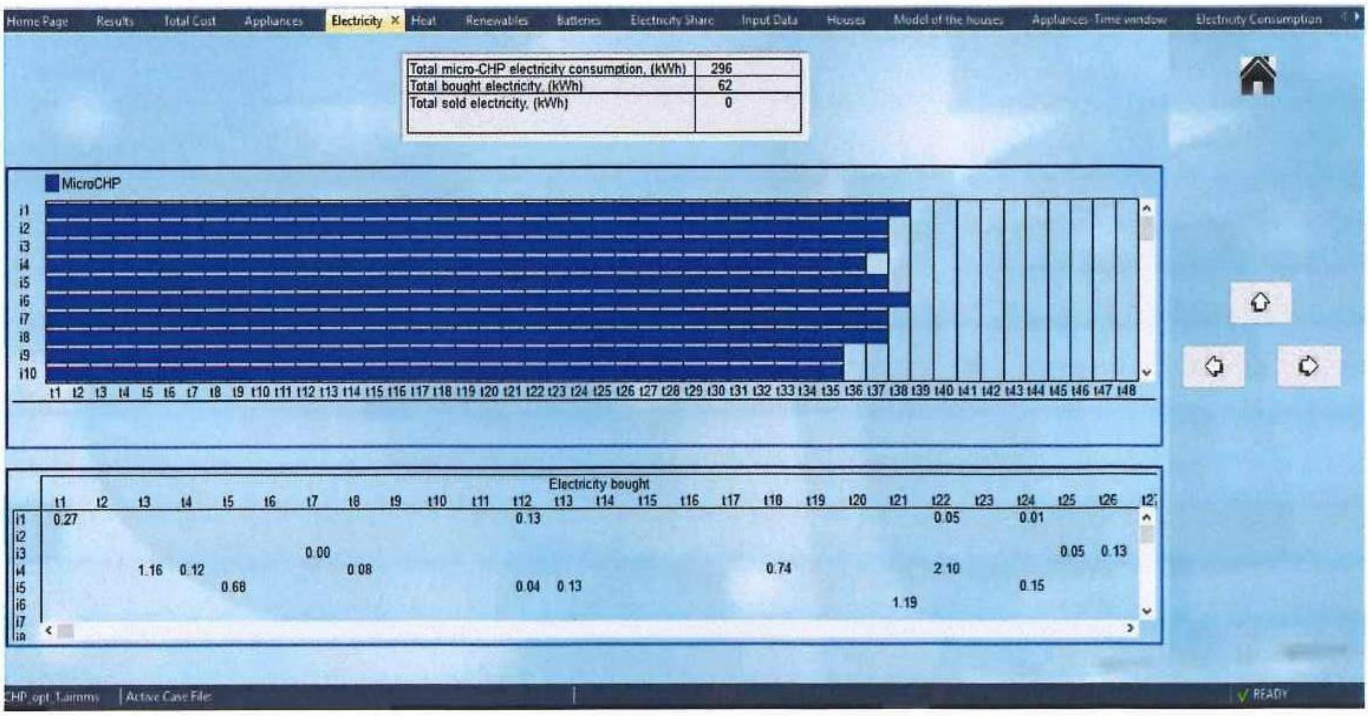
	max battery capacity. (kWh)	min battery capacity. (kWh)	initial battery charge level. (kWh)
i1	4.80		4.320
i2	4.80		4.320
i3	4.80		4.320
i4	4.80		4.320
i5	4.80		4.320
i6	4.80		4.320
i7	4.80		4.320
i8			

battery electrical efficiency	0.95

	discharge rate (% capacity per hour)	max electricity inflow to the battery. (kW)	max electricity outflow from the battery. (kW)
i1	0.50	3.00	2.40
i2	0.50	3.00	2.40
i3	0.50	3.00	2.40
i4	0.50	3.00	2.40
i5	0.50	3.00	2.40
i6	0.50	3.00	2.40
i7	0.50	3.00	2.40
i8	0.50	3.00	2.40

Figure D.8: GUI: Input, Batteries Characteristics.

Results, Electricity



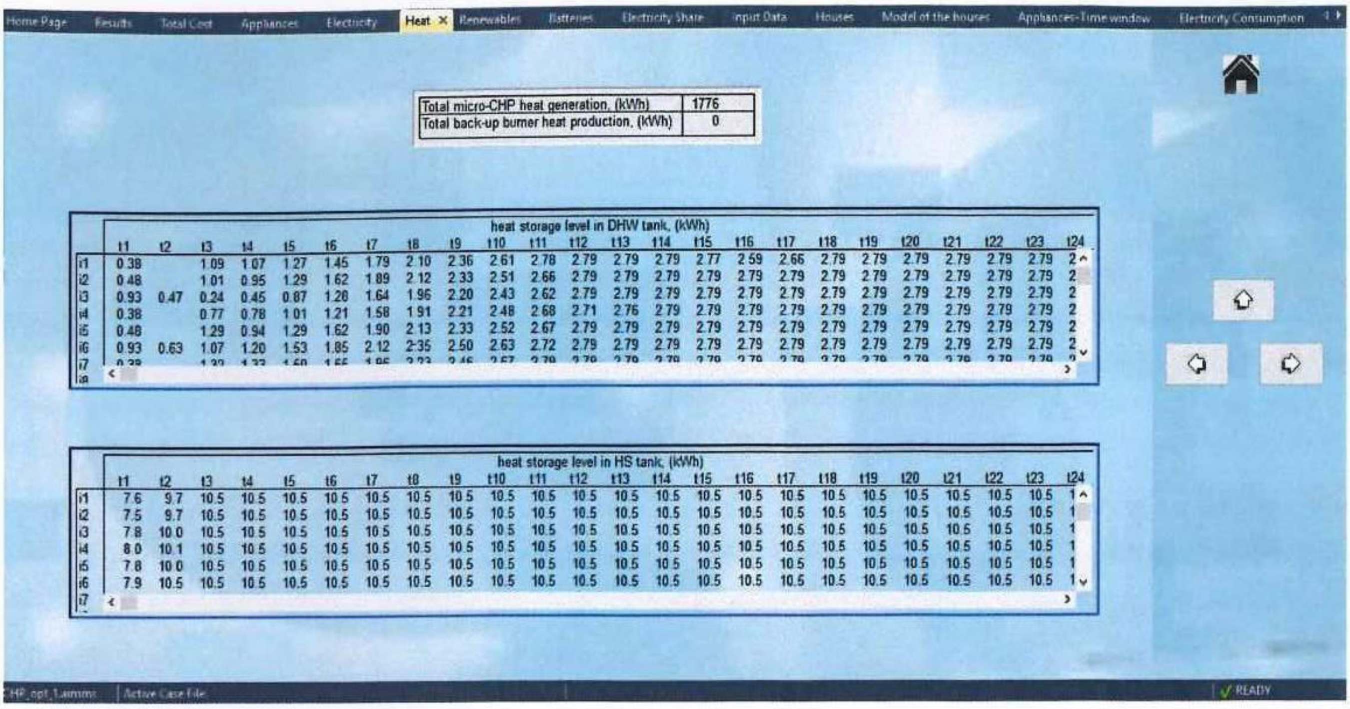
Total micro-CHP electricity consumption. (kWh)	296
Total bought electricity. (kWh)	62
Total sold electricity. (kWh)	0

Electricity bought

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24	t25	t26
i1	0.27											0.13										0.05		0.01		
i2																										
i3							0.00																		0.05	0.13
i4			1.16	0.12				0.08										0.74				2.10				
i5					0.68							0.04	0.13											0.15		
i6																					1.19					
i7																										

Figure D.9: GUI: Input, Electricity.

Results, Heat



Total micro-CHP heat generation, (kWh)	1776
Total back-up burner heat production, (kWh)	0

heat storage level in DHW tank, (kWh)

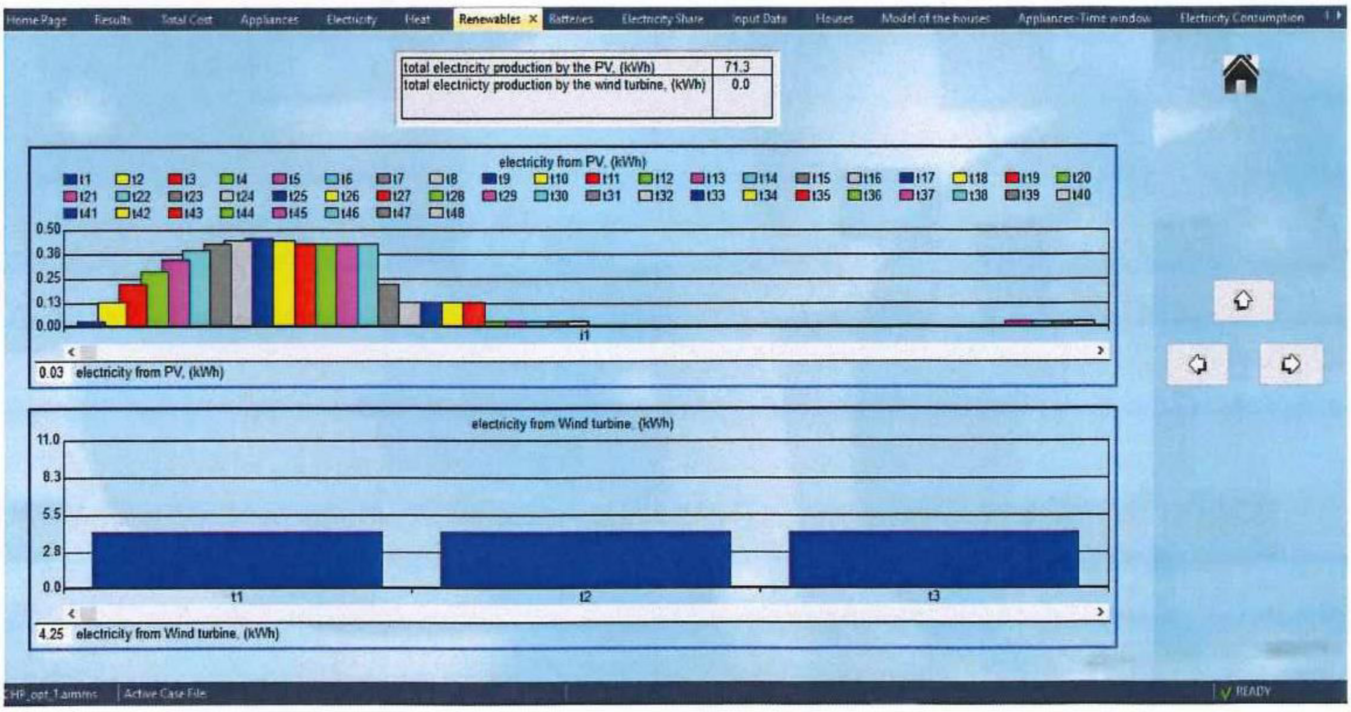
	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
i1	0.38		1.09	1.07	1.27	1.45	1.79	2.10	2.36	2.61	2.78	2.79	2.79	2.79	2.77	2.59	2.66	2.79	2.79	2.79	2.79	2.79	2.79	2
i2	0.48		1.01	0.95	1.29	1.62	1.89	2.12	2.33	2.51	2.66	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2
i3	0.93	0.47	0.24	0.45	0.87	1.28	1.64	1.96	2.20	2.43	2.62	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2
i4	0.38		0.77	0.78	1.01	1.21	1.58	1.91	2.21	2.48	2.68	2.71	2.76	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2
i5	0.48		1.29	0.94	1.29	1.62	1.90	2.13	2.33	2.52	2.67	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2
i6	0.93	0.63	1.07	1.20	1.53	1.85	2.12	2:35	2.50	2.63	2.72	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2.79	2

heat storage level in HS tank, (kWh)

	t1	t2	t3	t4	t5	t6	t7	t8	t9	t10	t11	t12	t13	t14	t15	t16	t17	t18	t19	t20	t21	t22	t23	t24
i1	7.6	9.7	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	1
i2	7.5	9.7	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	1
i3	7.8	10.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	1
i4	8.0	10.1	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	1
i5	7.8	10.0	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	1
i6	7.9	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	1

Figure D.10: GUI: Results, Heat.

Results, Renewables



total electricity production by the PV, (kWh)	71.3
total electricity production by the wind turbine, (kWh)	0.0

0.03 electricity from PV, (kWh)

4.25 electricity from Wind turbine, (kWh)

Figure D.11: GUI: Results, Renewables.