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SIMULATION OF INDUSTRIAL POWER CONSUMPTION WITH ELECTRIC ENERGY STORAGE

Iñaki Suescun Zudaire

Judith Equiza Arbizu

Prof. Dr. Klaus Kuhnke

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Hochschule Osnabrück
University of Applied Sciences

Fakultät Ingenieurwissenschaften und Informatik

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Simulation of industrial power consumption with electric energy storage

Erstprüfer: Herr Prof. Dr. Klaus Kuhnke
Zweitprüfer: Herr Dipl.-Ing. Mike Voss

Bearbeiterin: Judith Equiza Arbizu
Matrikelnummer:

Bearbeiter: Iñaki Suescun Zudaire
Matrikelnummer:

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Nomenclature

CO_2	Carbon dioxide
Cop	Operational annual cost
Ee	Electric energy produced in a year
Eh	Heat energy produced in a year
H_2	Hydrogen
Top	Operation time per year
Tsim	Time of the simulation in hours

Abbreviations

BPS	Bulk power system
CAES	Compressed air energy storage
CHP	Combined heat and power
DLC	Double layer capacitors
EES	Electrical energy storage
FES	Flywheel energy storage
GUI	Graphical user interface
LA	Lead acid
Li-ion	Lithium ion
NaS	Sodium Sulphur
NiCd	Nickel cadmium
NiMH	Nickel metal hydride
PHS	Pumped hydro storage
PV	Photovoltaic
RFB	Redox flow battery
SNG	Synthetic natural gas
SOC	State of charge
UPS	Uninterruptible power supply
i.e	That is

Zusammenfassung

Dieses Projekt besteht in der Entwicklung eines Modells, um den Stromverbrauch eines Industrieunternehmens zu simulieren. Das Modell verfügt über eine Batterie, ein Kraft-Wärme-Kopplungssystem, ein elektrisches Netz und einen Solarstrom-Eingang, um den Stromverbrauch zu decken.

Für diese Simulation wurde das Programm Matlab/Simulink gewählt. Ein besonderer Schwerpunkt wurde auf die Herstellung eines bestimmten Funktionsbausteines gelegt, in welchem die wichtigsten Aspekte der Simulation enthalten sind.
Außerdem wurden einige Skripts entwickelt, mit denen man, durch die Eingabe von Daten, das Modell initialisieren sowie Grafiken und Daten über die Simualtionsergebnisse anzeigen lassen kann.

Das Ziel der Simulation ist es, dem Anwender technische und wirtschaftliche Kriterien für den Einsatz von elektrischen Energiespeichern in einem Industriebetrieb zu geben. Hierzu bewertet das Programm verschiedene Optionen und Möglichkeiten in Bezug auf die Dimensionierung der Batterie und des KWK-Systems, um die kostengünstigste und effizienteste Alternative auszuwählen.

Die Simulationsergebnisse zeigen, dass im industriellen Bereich die Investition in elektrische Batteriespeichersysteme zurzeit nicht wirtschaftlich darstellbar ist. Die Amortisationszeit zur Einsparung der Leistungsskosten durch den Einsatz von Redox-Flow-Batterien in Unternehmen liegt bei 45-60 Jahren.

Resumen

El presente proyecto se basa en el desarrollo de un modelo para la simulación del consumo eléctrico de una empresa de ámbito industrial. Para proveer la carga eléctrica se dispone de la red eléctrica, una batería, un sistema de cogeneración y una entrada para potencia de un sistema solar.

Matlab es el programa elegido para dicha simulación, utilizando mayoritariamente el entorno de programación visual "*Simulink*", que funciona bajo la plataforma de Matlab. Se ha hecho especial hincapié en la elaboración de un bloque de funciones donde, mediante lenguaje de programación, quedan expuestos los aspectos más importantes de la simulación. También se han creado varios *scripts* gracias a los cuales se pueden introducir datos al programa, inicializar el modelo y mostrar los gráficos y datos sobre los resultados de la simulación.

El objetivo de la simulación es facilitar al usuario un balance económico, evaluando diferentes opciones en lo referente al dimensionado de la bateria y del sistema de cogeneración, con el fin de seleccionar la alternativa más rentable y eficiente.

A partir de los resultados de las simulaciones se puede concluir que, para una empresa de ámbito industrial invertir dinero en la compra de una batería para evitar picos de potencia no resultaría una solución económica dado que el tiempo de amortización de la batería estaría en el rango de 45-60 años para una batería de Flujo Redox.

Abstract

The present project is based on developing a model in order to simulate the power consumption of a company in an industrial environment. The grid, a battery, a co-generation system and a solar power input are used to provide the electric load.

Matlab is the program chosen for that purpose, mainly using the visual programming environment "Simulink" which works under Matlab platform. It has particular emphasis on the development of a function block which, through programming language, comprises the most important aspects of the simulation.
Furthermore, several scripts have been created through which the user can enter manually data into the program, initialize the model and display the graphs and data on the results of the simulation.

The simulation aims at giving the user an economic balance, evaluate different options with regard to the size of battery and cogeneration system, in order to select the most profitable and efficient alternative.

On the basis of the simulation results obtained, it can be concluded that, in the industrial sector, the investment of a battery is no an economic solution, because the return of investment time by saving grid power cost is in the range of 45-60 years, for a Redox Flow Battery.

1 Introduction

An important characteristic of electricity is that electrical energy cannot be stored directly unless capacitors are used, but their energy density is much less even if they are supercapacitors, this difference is shown in the Comparison between the different Types of Energy Storage Systems chapter. Thus, the supply of electricity must be balanced continuously with the demand for it. The constant balancing of supply and demand has significant operational and cost implications.

In order to store energy in the form of electricity, there are a wide variety of possible forms in which the energy can be stored. Common examples include chemical energy (batteries), kinetic energy (flywheels or compressed air), gravitational potential energy (pumped hydroelectric), and energy in the form of electrical (capacitors). From the standpoint of the electrical system, these energy storage methods act as loads while energy is being stored (e.g. while charging a battery) and sources of electricity when the energy is returned to the system (e.g. while discharging a battery) [4].

The interest in energy storage has increased due to:

- The increase in peak demand and the need to quickly and efficiently respond to changes in demand given.

- The need to integrate distributed and intermittent renewable energy resources into the electricity supply system.

- Avoiding electrical power failure is a must in some sectors. For example, hospitals need to storage energy to ensure their uninterrupted operation.

- The need to ensure the network stability and not to deliver too much or too little electricity into it. To ensure the continuity of the power supply against voltage dips is a must. Not to surmount the network limit capacity is not less important than the previous point.

Energy storage is necessary to manage, sustainably and effectively, the electricity networks, with the greatest renewable energy penetration and by applying criteria for the smoothing of the demand curve. However, currently, their widespread use is not a reality.

2 Terms and Definitions

- Battery capacity: The energy stored in a battery.

- Battery cycle life: The number of complete charge-discharge cycles that a battery can perform before its nominal capacity falls below 80% of its initial rated capacity.

- Memory effect: A feature of nickel-cadmium rechargeable batteries where the battery capacity to hold charge is reduced if the battery is recharged before it has been fully discharged. For example if a battery still has half its original charge when it is recharged, it appears only to have the capacity to carry the new half-charge rather than a full charge. It seems, in effect, to have a memory of the last level of its charge [6].

- Electric energy time shift: Energy time shift involves storing energy during low price times, and discharging during high price times [26].

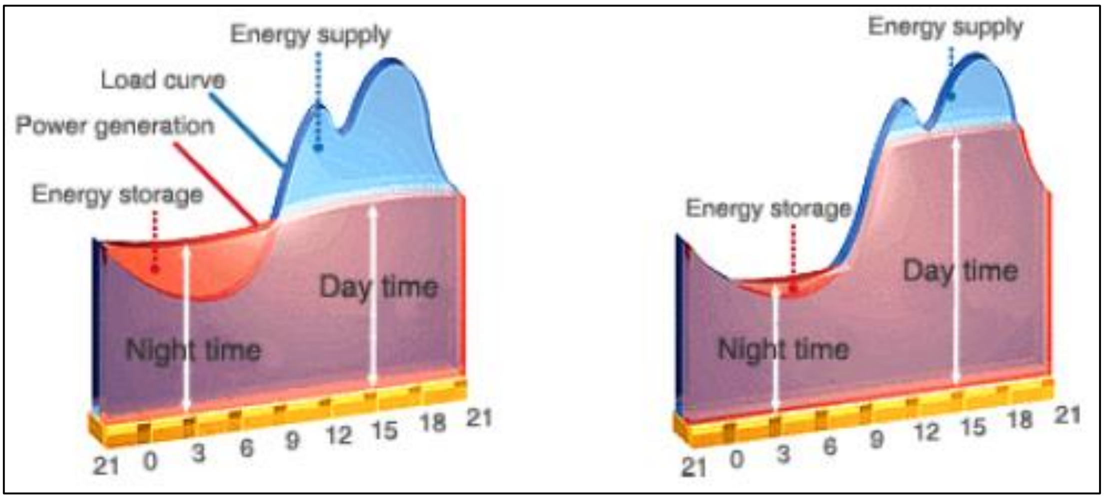

Figure 2.1: Daily load leveling and daily peak shaving [4].

- Electric Supply Reserve Capacity-Non-Spinning: Generation capacity that may be offline, or that comprises a block of interruptible loads, and that can be available within 10 minutes. Unlike spinning reserve capacity, non-spinning reserve capacity is not synchronized with the grid (frequency). Non-spinning reserves are used after all spinning reserves are online [26].

- Electric Supply Reserve Capacity-Spinning: Generation capacity that is online but unloaded and that can respond within 10 minutes to compensate for generation or transmission outages. 'Frequency-responsive' spinning reserve responds within 10 seconds to maintain system frequency. Spinning reserves are the first type used when a shortfall occurs [26].

- Uninterruptible power supply (UPS): It provides nearly instantaneous power when the main utility power source fails, allowing either time for power to return or for the user to shut down the system or equipment normally by closing running computer system applications and using the operating system to shut down the system.

- Reliability and quality: The electric reliability application entails use of energy storage to provide highly reliable electric service. In the event of a complete power breakdown lasting more than a few seconds, the storage system provides enough energy to a) ride through outages of extended duration or b) to complete an orderly shutdown of processes, c) transfer to on-site generation resources. The electric power quality application involves use of energy storage to protect loads downstream against short duration events which affect the quality of power delivered to the load [26].

- Transmission and distribution: Storage can provide transmission and distribution utilities with a means to regulate power quality, reduce congestion on lines or transformers, and defer infrastructure upgrades. Both transmission and distribution lines operate within optimum voltage and frequency ranges.

To maintain steady high quality power, voltage and frequency must be regulated to stay within these ranges. Storage can alternate between absorbing and injecting power to keep voltage and frequency within required ranges [4].

- Bulk power management: A bulk power system (BPS) is a large interconnected electric system made up of different generation and transmission facilities and their control systems. A BPS does not include facilities used in the local distribution of electric energy. If a bulk power system is disrupted, the effects are felt in more than one location [26].

3 Types of Energy Storage Systems

This chapter summarizes the different types and features of energy storage systems adapted from the second section of the White Paper by the IEC MSB (Market Strategy Board) [15].

3.1 Classification of Electrical Energy Storage Systems

A widely-used approach for classifying electrical storage systems is the determination according to the form of energy used. In Figure 3.1 the different kind of storage systems are classified into mechanical, electrochemical, chemical, electrical energy storage systems.

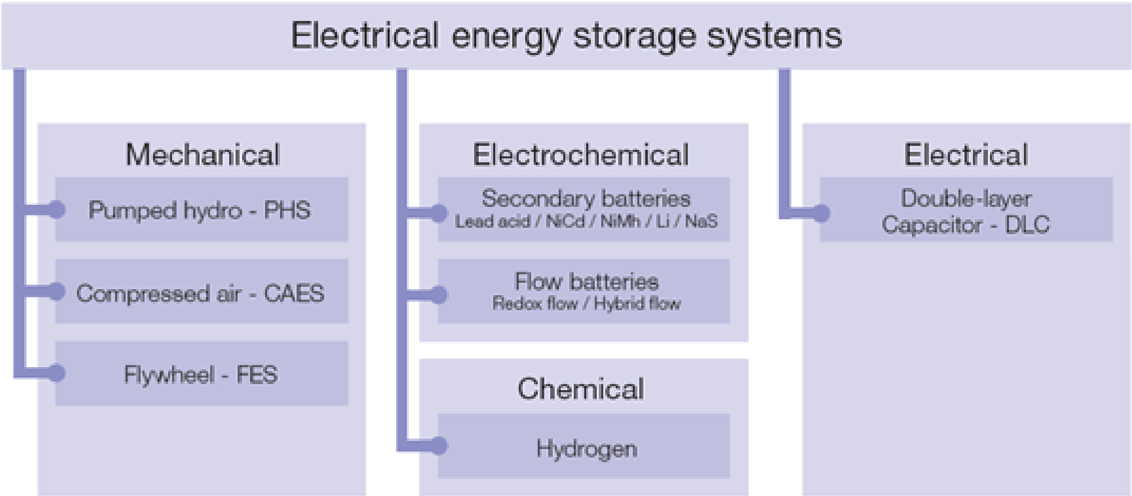

Figure 3.1: Classification of electrical energy storage systems according to energy [15].

3.1.1 Mechanical Storage Systems

The most common mechanical storage systems are pumped hydroelectric power plants (pumped hydro storage, PHS), compressed air energy storage (CAES) and flywheel energy storage (FES).

3.1.1.1 Pumped Hydro Storage (PHS)

With over 120 GW, pumped hydro storage power plants represent nearly 99 % of world-wide installed electrical storage capacity, which is about 3 % of global generation capacity.

Conventional Pumped Hydro Storages use two water reservoirs at different elevations to pump water during off-peak hours from the lower to the upper reservoir (charging). When required, the water flows back from the upper to the lower reservoir, powering a turbine with a generator to produce electricity (discharging).

Typical discharge times range from several hours to a few days.
The efficiency of PHS plants is in the range of 70 % to 85 %. Advantages are the very long lifetime, relatively low cost per unit of stored energy and practically unlimited cycle stability of the installation. Main drawbacks are the dependence on topographical conditions and large land use. The main applications are for energy management via time shift, namely nonspinning reserve and supply reserve.

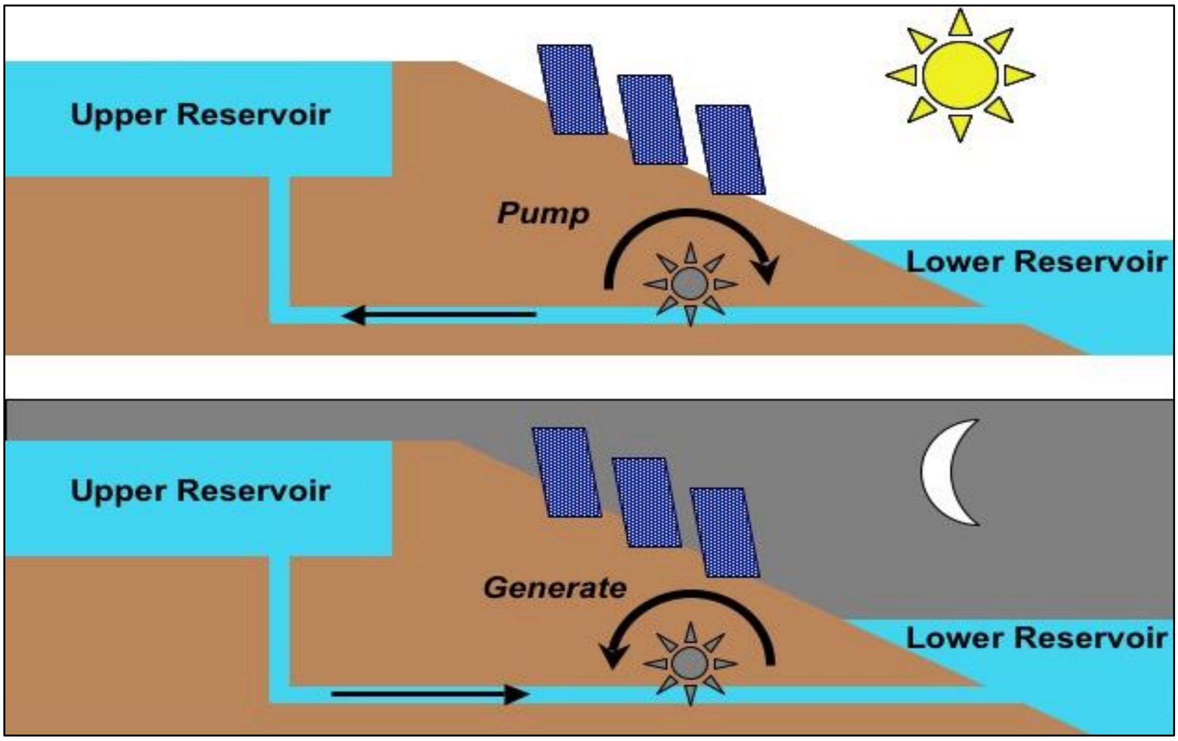

Figure 3.2: Operation scheme of a Hydro Pumped Storage System [5].

3.1.1.2 Compressed Air Energy Storage (CAES)

Electricity is used to compress air and store it in either an underground structure or an aboveground system of vessels or pipes. When needed, the compressed air is mixed with natural gas, burnt and expanded in a modified gas turbine.
If the heat released during compression is dissipated by cooling and not stored, the air must be reheated prior to expansion in the turbine.

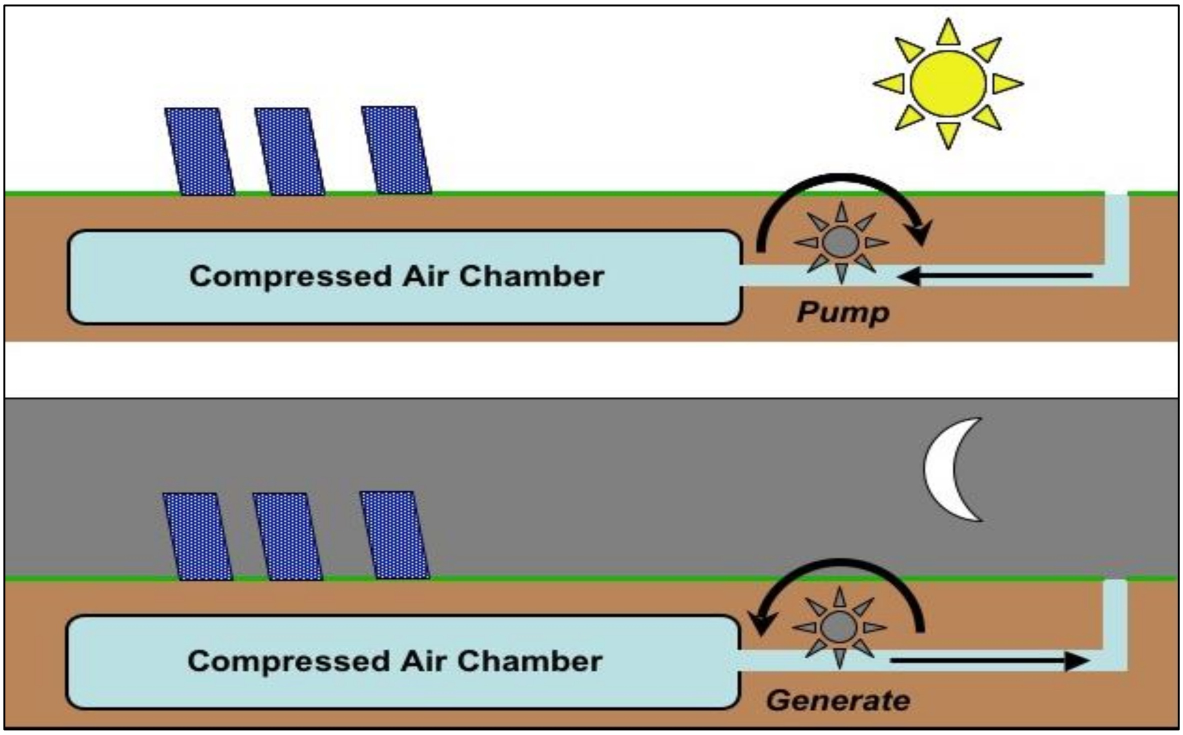

Figure 3.3: Operation scheme of a Compressed Air Energy Storage System [5].

This process is called diabatic CAES and results in low round-trip efficiencies of less than 50 %. Diabatic technology is well proven; the plants have a high reliability and are capable of starting without extraneous power. The advantage of CAES is its large capacity; disadvantages are low round-trip efficiency and geographic limitation of locations.

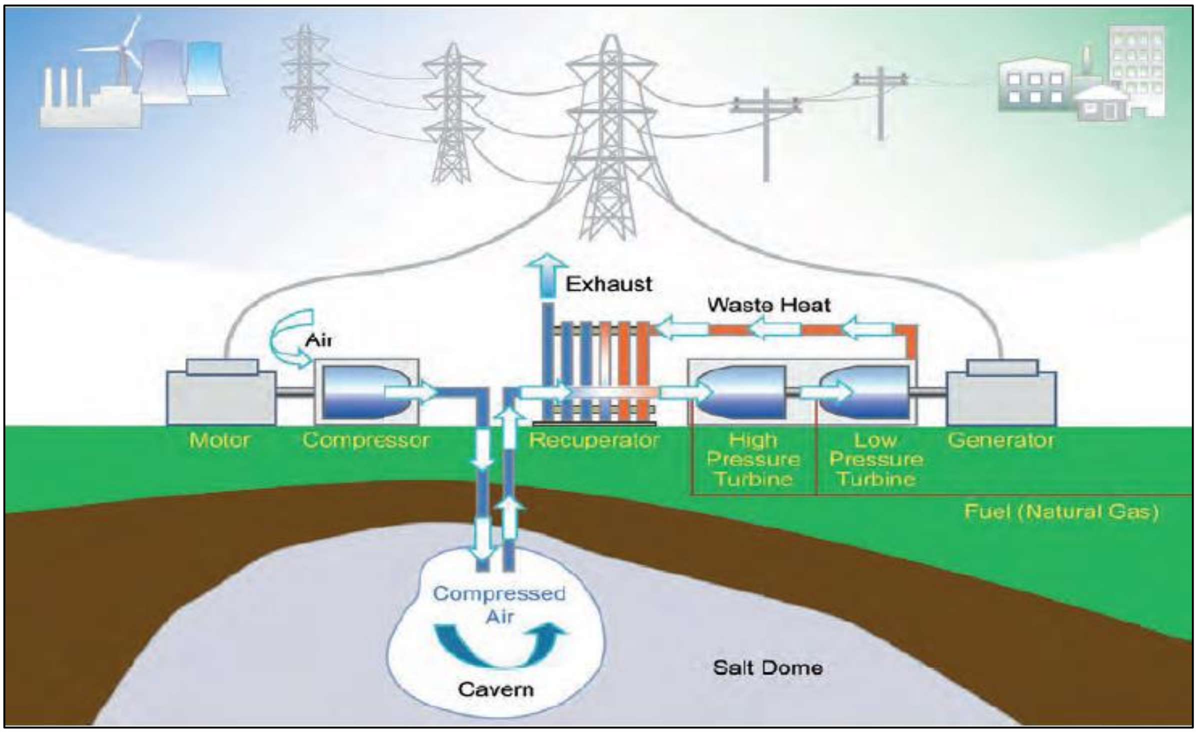

Figure 3.4: Compressed Air Energy Storage System [15].

3.1.1.3 Flywheel Energy Storage (FES)

In a flywheel energy storage, rotational energy is stored in an accelerated rotor. The main components of a flywheel are the rotating body/cylinder (comprised of a rim attached to a shaft) in a compartment, the bearings and the transmission device (motor/generator mounted onto the stator). The energy is maintained in the flywheel by keeping the rotating body at a constant speed. An increase in speed results in a higher amount of energy stored. To accelerate the flywheel, electricity is supplied by an electric motor. If the flywheel's rotational speed is reduced, electricity is extracted from the system by the same motor, acting now as a generator.

Summarizing, a flywheel is a heavy rotating disc that speeds up when electrical energy is applied to it. The flywheel stores energy that is instantly available when needed.

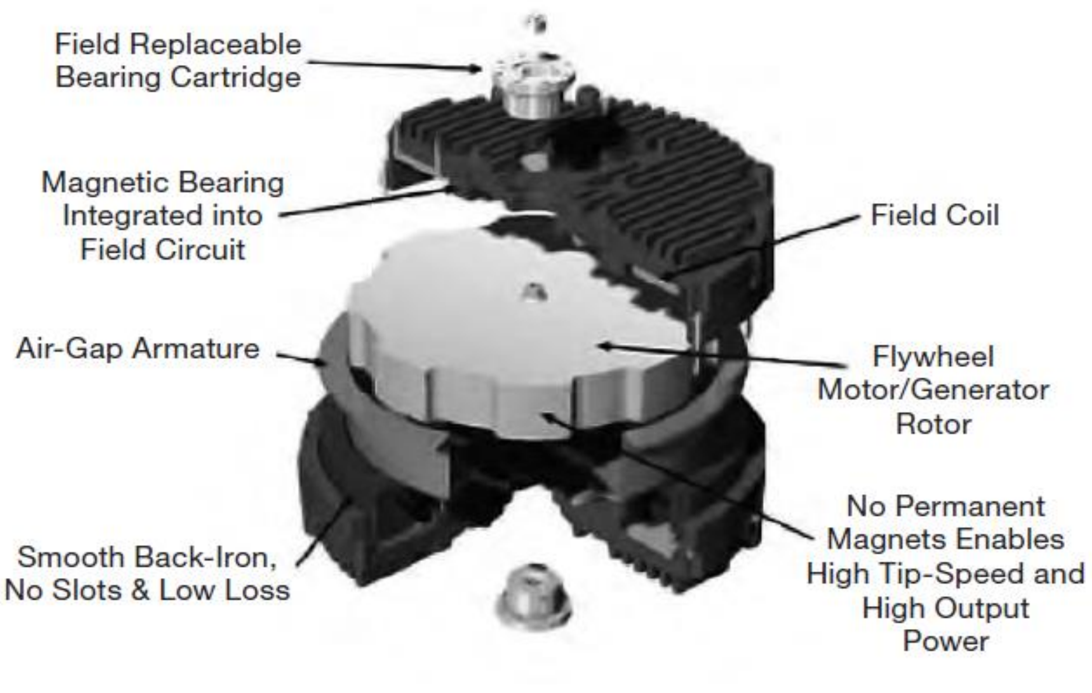

Figure 3.5: Flywheel Storage System [5].

The main features of flywheels are the excellent cycle stability and a long life, little maintenance, high power density and the use of environmentally inert materials.

Today flywheels are commercially deployed for power quality in industrial and UPS applications (uninterruptible power supply). Efforts are being made to optimize flywheels for long-duration operation (up to several hours) as power storage devices for use in vehicles and power plants.

3.1.2 Electrochemical Storage Systems

In this section various types of batteries are described. Most of them are technologically mature for practical use. First, five secondary battery types are listed: lead acid, NiCd/NiMH, Li-ion and sodium sulphur; then follows the redox flow battery.

Secondary batteries are rechargeable electric cells that convert chemical energy into electrical energy by a reversible chemical reaction. The difference with the primary batteries is that these last ones have an irreversible chemical reaction, which means that they cannot be recharged.

3.1.2.1 Lead Acid Battery (LA)

Lead acid batteries are the world's most widely used battery type. Their typical applications are emergency power supply systems, stand-alone systems with PV, battery systems for mitigation of output fluctuations from wind power and as starter batteries in vehicles.

Lead acid batteries offer a mature and well-researched technology at relatively low cost. There are many types of lead acid batteries available.

Figure 3.6: Lead Acid Battery [23].

One disadvantage of lead acid batteries is the usable capacity decrease when high power is discharged. For example, if a battery is discharged in one hour, only about 50 % to 70 % of the rated capacity is available. Other drawbacks are low energy density, high maintenance required, low cycle life, and the use of lead, a hazardous material prohibited or restricted in various situations. Advantages are a favorable cost/performance ratio, easy recyclability, a simple charging technology, relatively low self-discharge rate and a good performance at low and high temperatures.

Table 3.1: Advantages and disadvantages of lead-acid batteries.

Advantages	Disadvantages
• Easy to manufacture • Known technology. • Low self-discharge • Good performance at low and high temperatures.	• Low power. • Low energy density. • High maintenance. • Low cycle life. • Hazardous material.

3.1.2.2 Nickel Cadmium and Nickel Metal Hydride Batteries (NiCd, NiMH)

Figure 3.7: Nickel Cadmium Battery [3].

From a technical point of view, NiCd batteries are a very successful battery product; in particular, these are the only batteries capable of performing well even at low temperatures in the range from -20 °C to -40 °C. However, because of the toxicity of cadmium, these batteries are presently used only for stationary applications in Europe. Since 2006 they have been prohibited for consumer use.

NiMH batteries have all the positive properties of NiCd batteries. Furthermore, NiMH batteries have much higher energy densities. NiMH batteries currently cost about the same as lithium ion batteries.

Table 3.2: Advantages and disadvantages of Nickel Cadmium batteries.

Advantages	Disadvantages
• Good cycle life • Good performance at low temperature with a fair capacity • High discharge rates (discharging in one hour or less).	• Higher price • High self-discharge rates • Memory effect. • Bad for the enviroment.

Table 3.3: Advantages and disadvantages of Nickel Metal Hydride batteries

Advantages	Disadvantages
• No toxicity issue • Double energy density	• More susceptible to overcharging or over-discharging • Faster self-discharge

3.1.2.3 Lithium Ion Battery (Li-ion)

Lithium ion batteries have become the most important storage technology in the areas of portable and mobile applications.

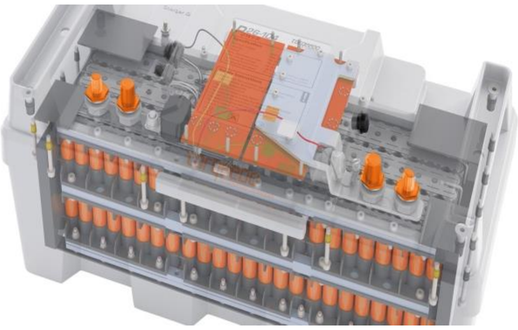

Figure 3.8: Lithium ion battery [3].

High cell voltage levels of up to 3.7 nominal Volts mean that the number of cells in series with the associated connections and electronics can be reduced to obtain the target voltage. For example, one lithium ion cell can replace three NiCd or NiMH cells which have a cell voltage of only 1.2 Volts. Another advantage of Li-ion batteries is their high gravimetric energy density.

They generally have a very high efficiency, in the range of 95 % - 98 %.

Nearly any discharge time from seconds to weeks can be realized, which makes them a very flexible and universal storage technology.
Since lithium ion batteries are currently still expensive, they can only compete with lead acid batteries in those applications which require short discharge times or light weight solutions as in vehicles.
Safety is a serious issue in lithium ion battery technology.

Table 3.4: Advantages and disadvantages of Lithium Ion batteries.

Advantages	Disadvantages
• High energy density and power. • High cycle life. • Low self-discharge. • Low maintenance. • Light weight. • High energy density	• Protection from over charged and discharged required • Aging.

3.1.2.4 Sodium Sulphur Battery (NaS)

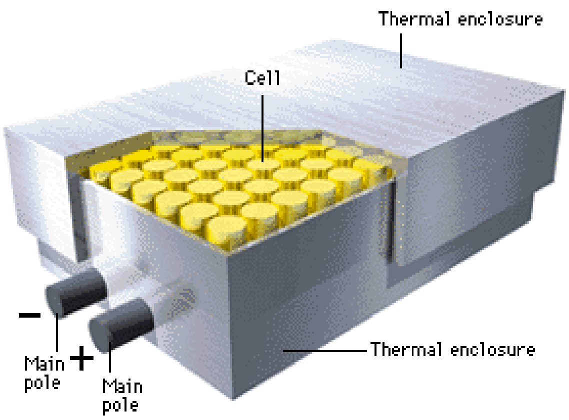

Figure 3.9: Sodium Sulphur Battery [10]

Sodium Sulphur batteries are efficient and have fast response.

They are economically used in combined power quality and time shift applications with high energy density.

The main drawback is that for operations, they require high temperatures and a heat source, which uses the battery's own stored energy, thus reducing the battery performance. In daily use the temperature of the battery can almost be maintained by just its own reaction heat, with appropriately dimensioned insulation.

Table 3.5: Advantages and disadvantages of Sodium Sulphur batteries.

Advantages	Disadvantages
• High energy density. • High efficiency of charge/discharge (82-92%). • Long cycle life. • Fabricated from inexpensive materials.	• Operating temperatures of 300 to 350ºC. • Higly corrosive nature of the sodium polysulfides.

These disadvantages make this kind of batteries suitable for grid energy storage and not for mobile applications.

3.1.2.5 Redox Flow Battery (RFB)

In conventional secondary batteries, the energy is charged and discharged in the active masses of the electrodes. A flow battery is also a rechargeable battery, but the energy is stored in one or more electroactive materials which are dissolved in liquid electrolytes. The electrolytes are stored externally in tanks and pumped through the electrochemical cell that converts chemical energy directly to electricity and vice versa. The power is defined by the size and design of the electrochemical cell whereas the energy depends on the size of the tanks.

In redox flow batteries (RFB) two liquid electrolyte solutions containing dissolved metal ions as active mass are pumped to the opposite sides of the electrochemical cell. The electrolytes at the negative and positive electrodes are called anolyte and catholyte respectively. During charging and discharging the metal ions stay dissolved in the fluid electrolyte as liquid; no phase change of these active masses takes place. Anolyte and catholyte flow through porous electrodes, separated by a membrane which allows protons to pass through for the electron transfer process.

Table 3.6: Advantages and disadvantages of Redox Flow batteries.

Advantages	Disadvantages
• Long cycle service life. • High-output power. • The storage capacity can be increased easily by increasing the capacity of the electrolyte tanks. • No harmful emissions. • Tolerance to overcharge/overdischarge.	• Low energy density. • Expensive ion-exchange membranes required.

The Vanadium Redox Flow Battery (VRFB) uses a V^{2+}/ V^{3+} redox couple as oxidizing agent and a V^{5+}/ V^{4+} redox couple in mild sulphuric acid solution as reducing agent.

The main advantage of this battery is the use of ions of the same metal on both sides. Although crossing of metal ions over the membrane cannot be prevented completely (as is the case for every redox flow battery), in VRFBs the only result is a loss in energy. In other RFBs, which use ions of different metals, the crossover causes an irreversible degradation of the electrolytes and a loss in capacity.

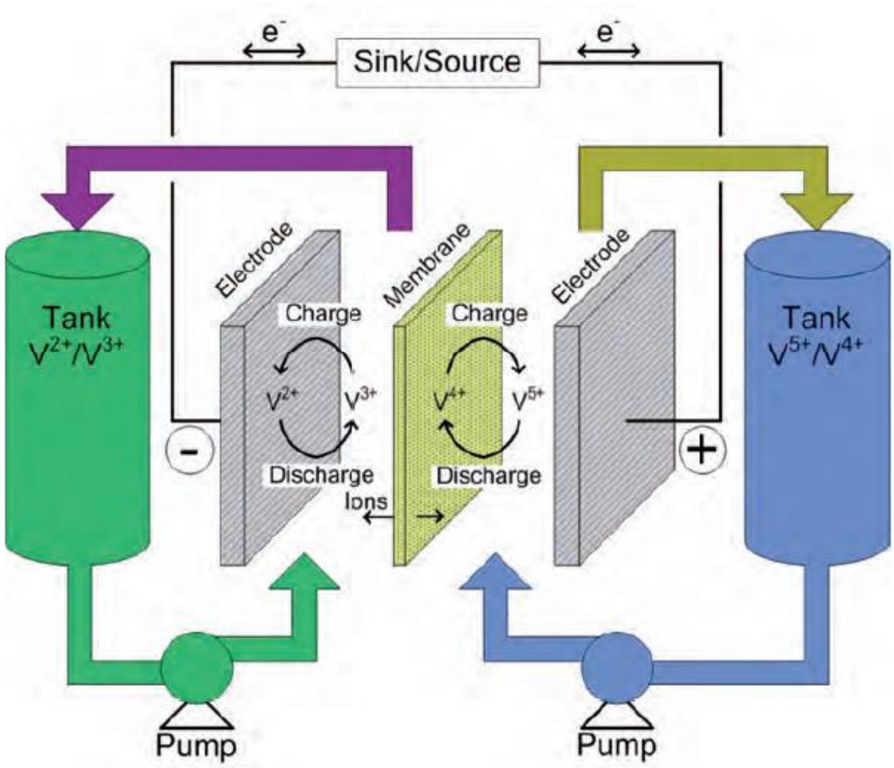

Figure 3.10: Schematic of a Vanadium Redox Flow Battery [11].

3.1.3 Chemical Energy Storage

The main difference with the electrochemical energy storage is that this last ones allow storage of large amounts of energy, up to the TWh range, and for greater periods of time – even as seasonal storage.
Another advantage of hydrogen is that these universal energy carriers can be used in different sectors, such as transport, mobility, heating and the chemical industry.

3.1.3.1 Hydrogen (H_2)

A typical hydrogen storage system consists of an electrolyzer, a hydrogen storage tank and a fuel cell. An electrolyzer is an electrochemical converter which splits water with the help of electricity into hydrogen and oxygen. This is an endothermal process, i.e. energy is required during the reaction. Hydrogen is stored under pressure in gas bottles or tanks, and this can be done practically for an unlimited time.

To generate electricity, both gases flow into the fuel cell where an electrochemical reaction which is the reverse of water splitting takes place: hydrogen and oxygen react and produce water, heat is released and electricity is generated. For economic and practical reasons oxygen is not stored but vented to the atmosphere on electrolysis, and oxygen from the air is taken for the power generation.

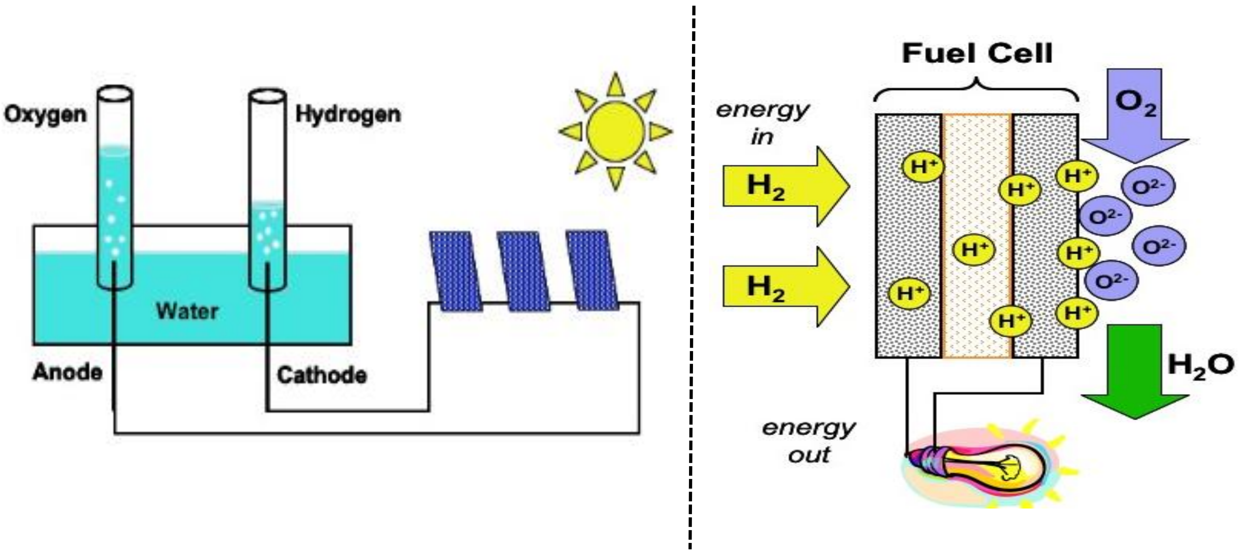

Figure 3.11: Schematic of a hydrogen fuel cell [5].

Up to now there have not been any commercial hydrogen storage systems used for renewable energies.

3.1.3.2 Synthetic Natural Gas (SNG)

Synthesis of methane (also called synthetic natural gas, SNG) is the second option to store electricity as chemical energy. Here a second step is required beyond the water splitting process in an electrolyzer, a step in which hydrogen and carbon dioxide react to methane in a methanation reactor. As is the case for hydrogen, the SNG produced can be stored in pressure tanks, underground, or fed directly into the gas grid, which has a high storage volume, too. Several CO_2 sources are conceivable for the methanation process, such as fossil-fuelled power stations, industrial installations or biogas plants.

To minimize losses in energy, transport of the gases CO_2 (from the CO_2 source) and H_2 (from the electrolysis plant) to the methanation plant should be avoided. The production of SNG is preferable at locations where CO_2 and excess electricity are both available. In particular, the use of CO_2 from biogas production processes is promising as it is a widely-used technology. Nevertheless, intermediate on-site storage of the gases is required, as the methanation is a constantly running process.

The main advantage of this approach is the use of an already existing gas grid infrastructure (e.g. in Europe). Pure hydrogen can be fed into the gas grid only up to a certain concentration, in order to keep the gas mixture within specifications (e.g. heating value). Moreover, methane has a higher volumetric energy density, and transport in pipelines requires less energy (higher density of the gas). The main disadvantage of SNG is the relatively low efficiency due to the conversion losses in electrolysis, methanation, storage, transport and the subsequent power generation. A comprehensive overview of the combined use of hydrogen and SNG as chemical energy storage is shown in Figure 3.12.

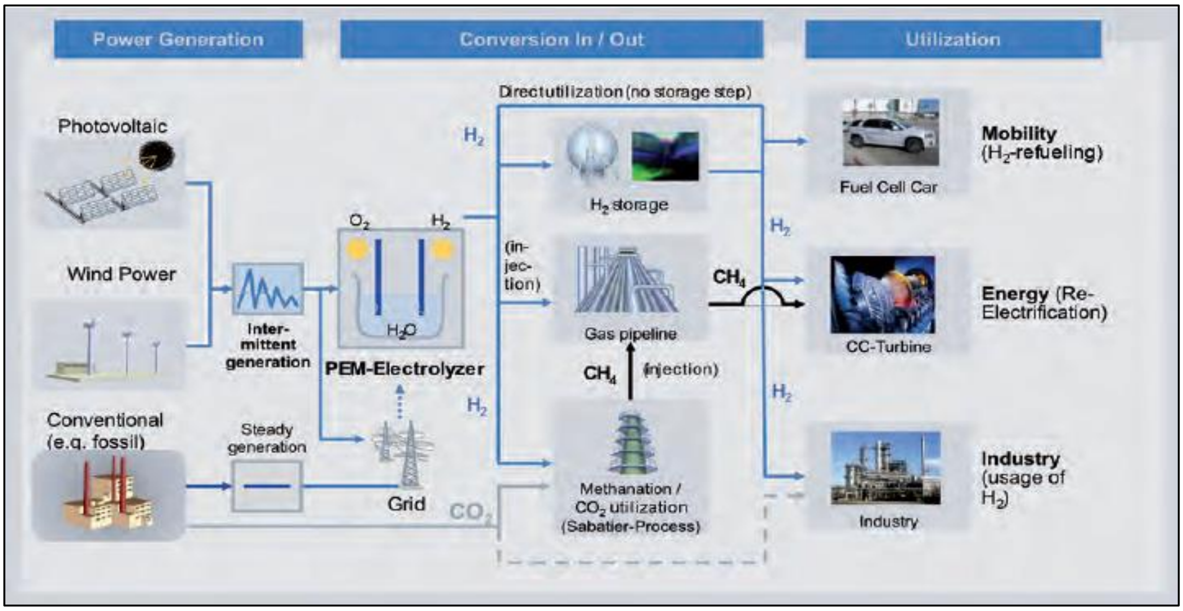

Figure 3.12: Overall concept for the use of hydrogen and SNG as energy carriers [15].

Table 3.7: Advantages and disadvantages of Synthetic natural gas.

Advantages	Disadvantages
• Use of an already existing gas grid infrastructure. • Methane has a higher energy density. • Transport in pipelines requires less energy (higher density of the gas).	• Relatively low efficiency.

3.1.4 Electrical Energy Storage

3.1.4.1 Double Layer Capacitors (DLC)

Electrochemical double-layer capacitors (DLC) are also known as supercapacitors. They have nearly an unlimited cycle stability as well as extremely high power capacity and a many orders of magnitude higher energy storage capacity when compared to traditional capacitors. This technology still exhibits a large development potential that could lead to even greater capacitance and energy density than today capacitors, thus enabling more compact designs.

The two main features are the extremely high capacitance values, of the order of many thousand farads, and the possibility of very fast charges and discharges. Still other advantages are durability, high reliability, no maintenance, long lifetime and operation over a wide temperature range and in diverse environments (hot, cold and moist). The lifetime reaches one million cycles (or ten years of operation) without any degradation, except for the solvent used in the capacitors whose disadvantage is that it deteriorates in 5 or 6 years irrespective of the number of cycles. That means that if the solvent has a lower lifetime than the capacitor, then the lifetime of this last one will be lifetime of the solvent. The efficiency is typically around 90 % and discharge times are in the range of seconds to hours.
They can reach a specific power density which is about ten times higher than that of conventional batteries (only very-high-power lithium batteries can reach nearly the same specific power density), but their specific energy density is about ten times lower.
Because of their properties, DLCs are suited especially to applications with a large number of short charge/discharge cycles, where their high performance characteristics can be used. DLCs are not suitable for the storage of energy over longer periods of time, because of their high self-discharge rate, their low energy density and high investment costs.

Table 3.8: Advantages and disadvantages of Double Layer capacitors.

Advantages	Disadvantages
• Virtually unlimited cycle life. • High specific power. • Good performance at low temperatures. • No memory effect.	• Low specific energy. • High self-discharge. • High cost per Wh.

3.2 Comparison between the different Types of Energy Storage Systems

In this section, the features of the different types of energy storage systems will be compared to each other as well as their costs and uses. This is intended to show their differences easily to have a good overview in order to have a better understanding of all of them.

First, in the Figure 3.13, the rated power (W) is plotted against the energy (Wh). The time of discharge of the different types of energy storage are also shown.

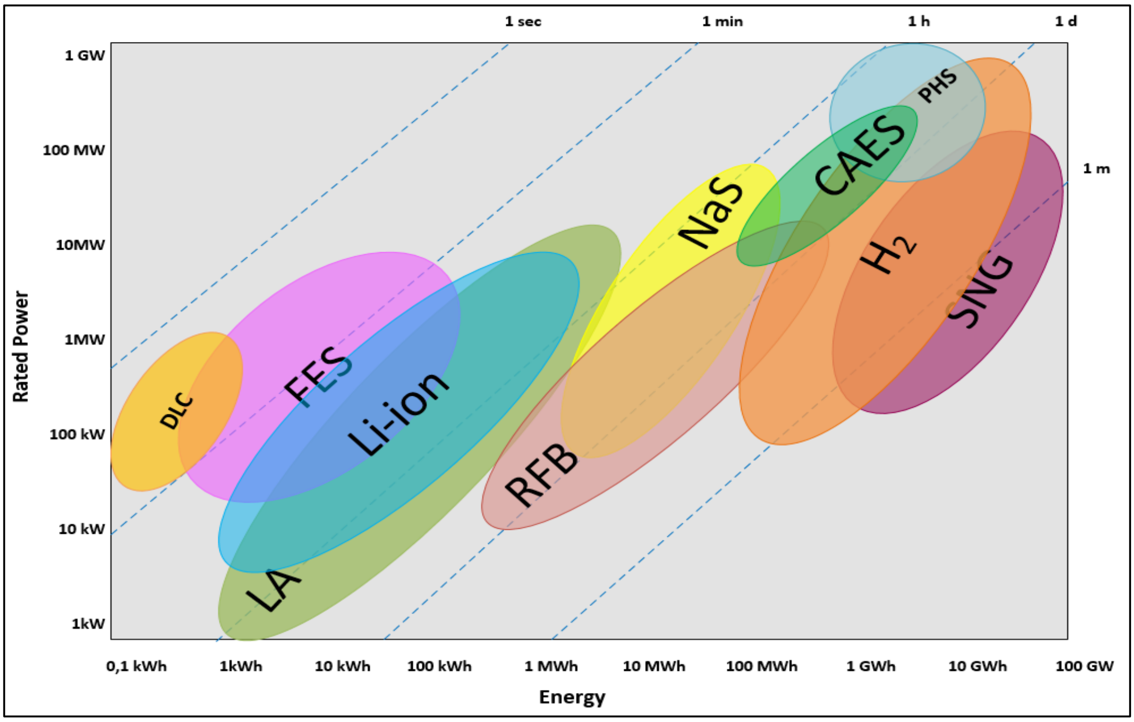

Figure 3.13: Comparison of rated power, energy content and discharge time of different EES technologies [15], modified.

The technologies with short discharge time, which have already been mentioned, are the double-layer capacitor (DLC) and flywheels (FES). Their energy-to-power ratio is less than 1 h (e.g. a capacity of less than 1 kWh for a system with a power of 1 kW). These technologies are mainly used for power applications. As we move towards the upper right corner, the technologies are more suitable for energy applications.

Flywheel energy storage, Lead-acid (LA), Lithium ion (Li-ion) and Sodium sulphur (NaS) batteries have a discharge time from minutes to hours with an energy-to-power ratio of between 1 and 10 h (e.g. between 1 kWh and 10 kWh for a 1 kW system).

Hydrogen (H_2) and synthetic natural gas (SNG) have a long discharge time (days to months). For these EES systems, the energy-to-power ratio is considerably greater than 10 h.

Pumped hydro storage (PHS), compressed air energy storage (CAES) and redox flow batteries are situated between storage systems for medium and long discharge times. These EES technologies have external storage tanks. But the energy densities are rather low, which limits the energy-to-power ratio to values between approximately 5 and 30.

The second comparison will be based on the power output and how quickly they can discharge it. This comparison is useful when considering which technologies are best for providing a particular benefit. Figure 3.14 has three benefit categories, UPS and power quality, transmission-distribution and load shifting, and bulk power management.
Flywheels and some of the electrochemical batteries are appropriate for UPS and power quality. Flow batteries, NaS batteries, Lead-acid batteries and NiMH batteries are appropriate for load shifting, transmission and distribution of the grid support. On the other hand, pumped hydro is used for bulk power management.

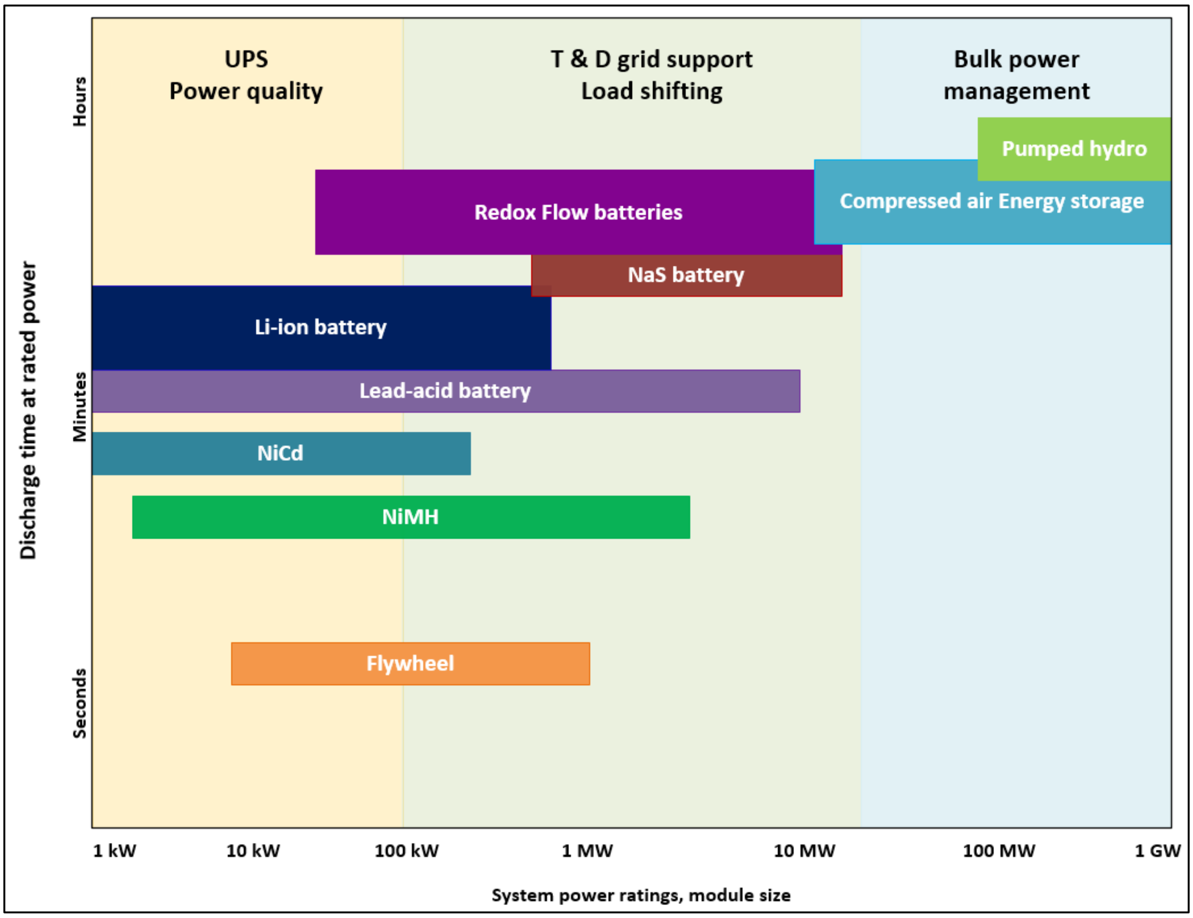

Figure 3.14: Power rating and discharge duration at rated power [4], modified.

In Figure 3.15 the power density (per unit volume, not weight) of different EES technologies is plotted versus the energy density. The higher the power and energy density, the lower the required volume for the storage system. Highly compact EES technologies suitable for mobile applications can be found at the top right. Large area and volume-consuming storage systems are located at the bottom left. Here it is again clear that PHS and flow batteries have a low energy density compared to other storage technologies. DLC and FES have high power densities but low energy densities. Li-ion has both a high energy density and high power density, which explains the broad range of applications where Li-ion is currently deployed. NaS has higher energy densities in comparison to the mature battery types such as LA and NiCd, but their power density is lower in comparison to NiMH and Li-ion. Flow batteries have a high potential for larger battery systems (MW/MWh) but have only moderate energy densities. The main advantage of H_2 and SNG is the high energy density, superior to all other storage systems.

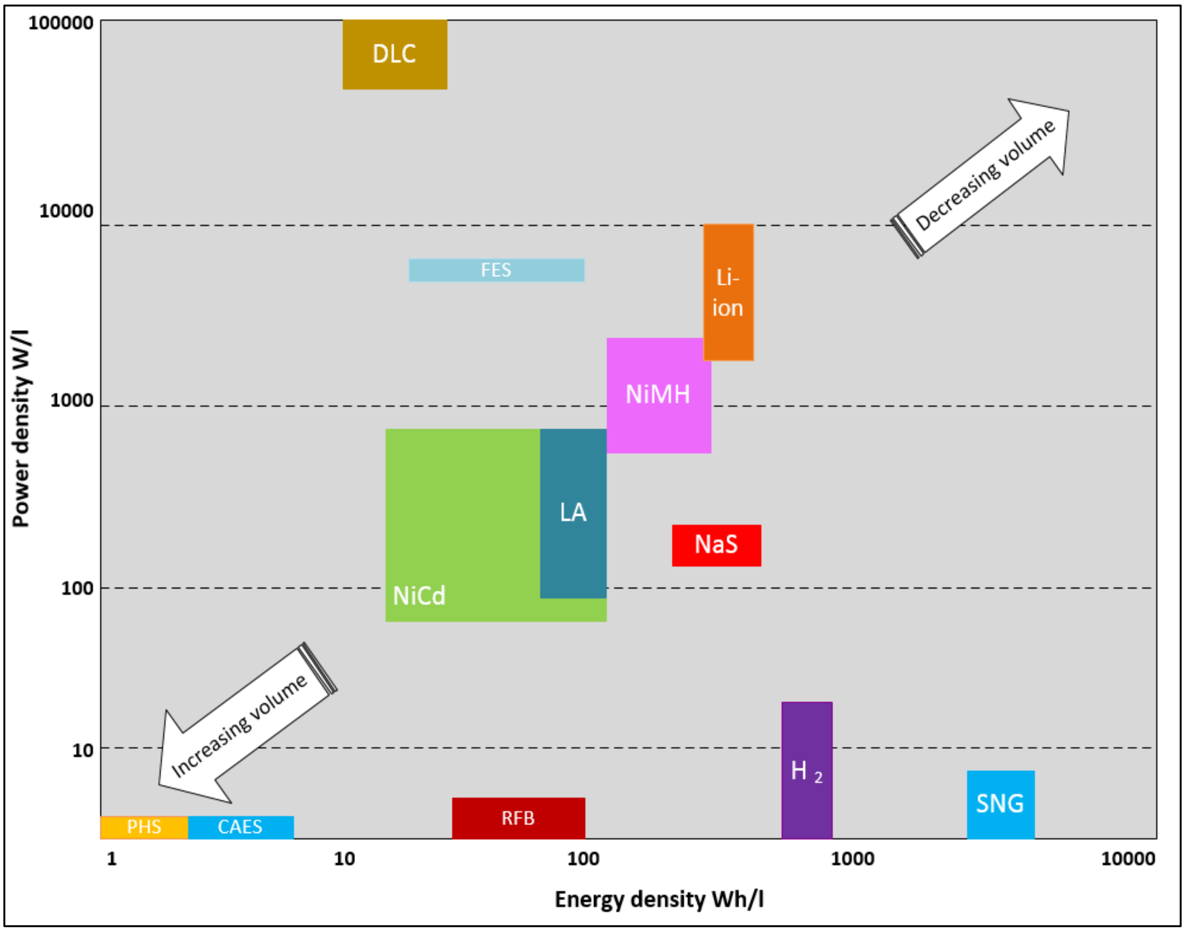

Figure 3.15: Comparison of power density and energy density [15], modified.

4 Simulation Software Simulink/Matlab

The program selected for the simulation is Matlab. This program has been chosen after a full inquiry carried out by Silvia Donazar [8] and Matthias Kuhr. The main reason for this choice is that this software is widely used in academic and research institutions as well as industrial enterprises, but besides, the Matlab user can extend the capabilities of Matlab with additional products.
Furthermore, the software was known beforehand by the authors of this project because this program has been used before during their career.

MATLAB is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include:

- Math and computation
- Algorithm development
- Modeling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics

Simulink is a block diagram environment for multidomain simulation and Model-Based Design. It supports simulation, automatic code generation and continuous test and verification of embedded systems.
Simulink provides a graphical editor, customizable block libraries and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB and enables to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis.
Simulink provides a set of predefined blocks that you can combine to create a detailed block diagram of a system [16].

5 Simulation

5.1 Basic Principles of the Program

The purpose of this program is the simulation of industrial power consumption in order to avoid its power peaks. It is carried out using cogeneration and storage systems, such as redox flow battery or lead acid. Moreover, the grid provides an amount of energy to ensure the supply of energy to the load of the company. If the industry possesses solar panels, they are taken into account during the simulation.

This project intends to save money avoiding power peaks, in particular, concerning with the electricity. This work does not touch the question of heat consumption.

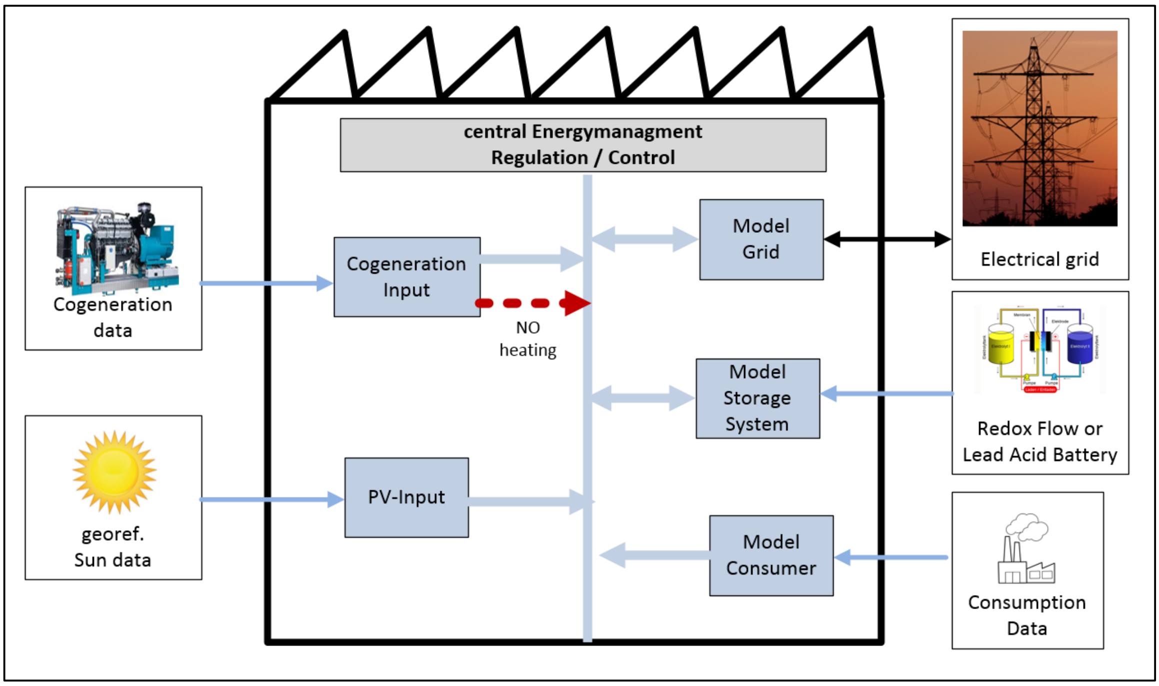

Figure 5.1: Synoptic model of the system.

Once the simulation is finalized, the user obtains several graphs in which the power balance with different cogeneration and battery sizes can be seen. Furthermore, the user gets an Excel worksheet with an economic balance.

5.2 Program Implementation

This section presents all the scripts through which the program has been implemented. They are described in detail, one by one, in the following paragraphs.

5.2.1 Main Program Script

The main Program script is the script which contains all the scripts.

Its main function is to carry out the simulation of all the scripts, six times.
The first three simulations will be carried out with the power of the CHP as the average of the power consumption divided by 2, but changing the maximum discharge power of the battery and consequently the other parameters of the battery. The maximum discharge power of the battery will be first 10 % of the maximum power peak, then 15 % and finally 20 %. Then, the other three simulations will be carried out with the CHP power being the average of the power consumption divided by 3 and following the same criterion as before to select the maximum power discharge of the battery.

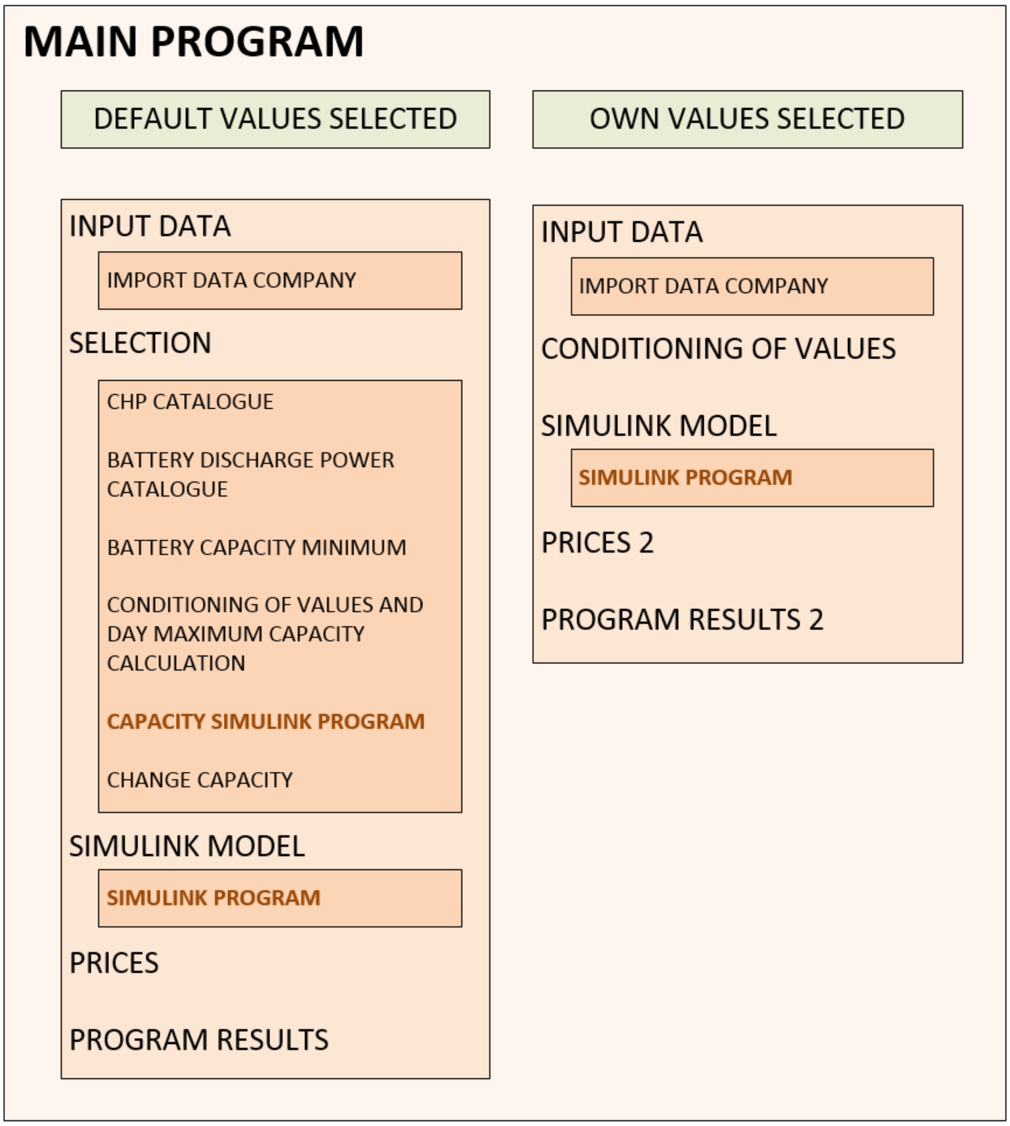

Figure 5.2: Schematic of the scripts contained in the main program.

5.2.2 Input Data Script

The Input data script has been developed in order to input the data with which the user wants to make the simulation. In this script, also the default values are defined, that will be taken to make the simulation if the user do not want to put in different parameters by itself.

Through this script, the data from the company are read from the Excel sheet that the user has to feed into the main folder of this program. These data will be the load of the company and if the company has solar panels, their power as well.

Furthermore, in this script the different windows are programmed that have to show up during the simulation. If the user has entered the data by itself to run the simulation, they will be kept in a variable.

5.2.3 Selection Script

This script is one of the most complete scripts in the whole program because it contains most of the other scripts. And as mentioned above, in this script will be selected the majority of the parameters that will be taken into account during the simulation.

First of all, the power of the CHP is selected and standardized following the range of electrical capacity and efficiency as well as thermal capacity and efficiency shown in the catalogue of the company 2G Energy AG [1].

Secondly, the maximum consumption power of the battery is selected. As noted, it will be first 10 % of the maximum power peak. Then, 15 %, and finally 20 %.
As with the CHP power, the discharge power of the battery has to be standardized. In order to make it possible, the company Gildemeister provided some information about the range of discharge power of a redox flow battery and its appropriate capacities.
From there, a bigger range of power and capacities of the battery was made, as shown in the Table 5.1.

Table 5.1: Discharge Power and Capacity of Redox Flow Batteries [20]

		Discharge Power /kW									
Capacity /kWh		**10**	**20**	**30**	**60**	**90**	**120**	**160**	**200**	**260**	**320**
	40	10/40	20/40	30/40							
	70	10/70	20/70	30/70							
	100	10/100	20/100	30/100	60/100						
	130	10/130	20/130	30/130	60/130	90/130					
	400				60/400	90/400	120/400	160/400	200/400	260/400	
	800					90/800	120/800	160/800	200/800	260/800	320/800
	1600							160/1600	200/1600	260/1600	320/1600

Once the maximum discharge power of the battery has been selected, the program selects for that power its minimum storage capacity and calculates the other parameters needed to run the simulation.

One of the most important parameters that the program has to calculate is the max desired power grid, this values is independent of the power from the solar panels. The program calculates it as:

$$\text{Max desired power grid} = \text{Maximum} - \text{CHP max} - \text{Max discharge power}$$

where:
Maximum = the highest power peak of the load.
CHP_max = the maximum power that the cogeneration system can supply.
Max_desired_power_grid = the upper limit power from the grid.

After that, the day of maximum energy is sought and selected in order to ensure that the battery can supply that amount of energy without being fully discharged. Instead of simulating all the days introduced in the load in order to know the day of maximum energy, that day is selected through instructions and only that day is simulated, making the simulation faster.
The day calculated does not take into account just the day of maximum energy, it also takes into account the time from the end of that day until the time when the battery starts to provide energy the following day. This means that the day calculated includes the time in which the battery is being charged in the following day.

Then, that day is stimulated to check if the battery selected is suitable. If the state of charge (SOC) is lower than the minimum SOC allowed, the program selects the next capacity of the capacity range. Doing this, the supply of energy with the battery is assured.

When the program selects another capacity, all the parameters which depend on it are recalculated. This process is carried out as long as one of these conditions is satisfied.

- If the minimum SOC is less than or equal to the 40 % for a lead acid battery, or 0 % for a redox flow battery.

- If the last data of the SOC is less than the first one.

These two conditions have to be considered because at the end of the maximum energy day, although the first condition is not satisfied, the SOC could have a very low level and the battery could not support another day with high energy demand with such a low capacity remaining. When both conditions are not met any longer, the simulation program stops, and the results can be seen.

5.2.4 CHP Catalogue Script

The function of this script is to standardize all the parameters selected for the co-generation system. This means that, for the CHP power calculated (the average of the power consumption divided by 3 or 4), this script will select the immediate higher value of the catalogue and its corresponding values of electric and heat efficiency and heat power.

5.2.5 Battery Discharge Power Catalogue Script

As the previous script, this script has been developed in order to standardize the discharge power of the battery. Through this script, for the discharge power of the battery, the immediate higher value of the catalogue will be selected.

5.2.6 Battery Capacity Minimum Script

This script has been written in order to choose the minimum battery capacity in accordance with the range of battery discharge power which has been shown above in Table 5.1.
Thus, a 130 kWh of RFB capacity corresponds to a discharge power of 90 kW.

5.2.7 Conditioning of Values and Day of Maximum Energy Script

This script has been developed mainly in order to seek and select the day with the highest energy demanded. The load of this day will be simulated to choose the most suitable battery capacity. But, besides, the program selects the load of the highest energy demand and the load of the following day before the battery starts to provide energy. As already mentioned, the program makes this in order to guarantee the supply of energy from the battery.

The script is the responsible to adequacy the load and PV variables. This means, if the user has not entered the data of the company properly, this script will adjust them to run the program successfully.
When more data than necessary are given, the program will not take it into account. But, on the other hand, if less data are given, the program will complete these data with the last values of that day, this means that the last values will be repeated.

Moreover, the script calculates how many days the battery will be used in order to choose the battery type. If the battery is used more than two days per week in a year, a redox flow battery will be selected as well as a minimum SOC of 0 %, otherwise, a lead acid battery with a minimum state of charge of 40 %.

5.2.8 Change Capacity Script

In this section, a code has been implemented in order to choose the immediate higher value of capacity within the range of values.
As pointed out, this range depends on the discharge power of the battery.

5.2.9 Conditioning of Values Script

This script is employed when the user does not select the default values. Instead of that, the user enters the required data by its own.

As a consequence, it is not necessary to calculate the battery parameters. Thus, the only difference between the Conditioning of Values and Day of Maximum Energy Script is that, in this case, determining the day of maximum energy is not required, as well as the part of the code in which is selected the minimum SOC.

5.2.10 Simulink Model Script

5.2.10.1 General

This script has been created to make the model run, which was built with the Matlab tool, Simulink. With this script, the simulation will show how the consumption of an industry is provided with the power from the cogeneration, from the grid, from the battery and just in case the industry has solar panels, also from them. All these sources will supply power to charge the battery as well.

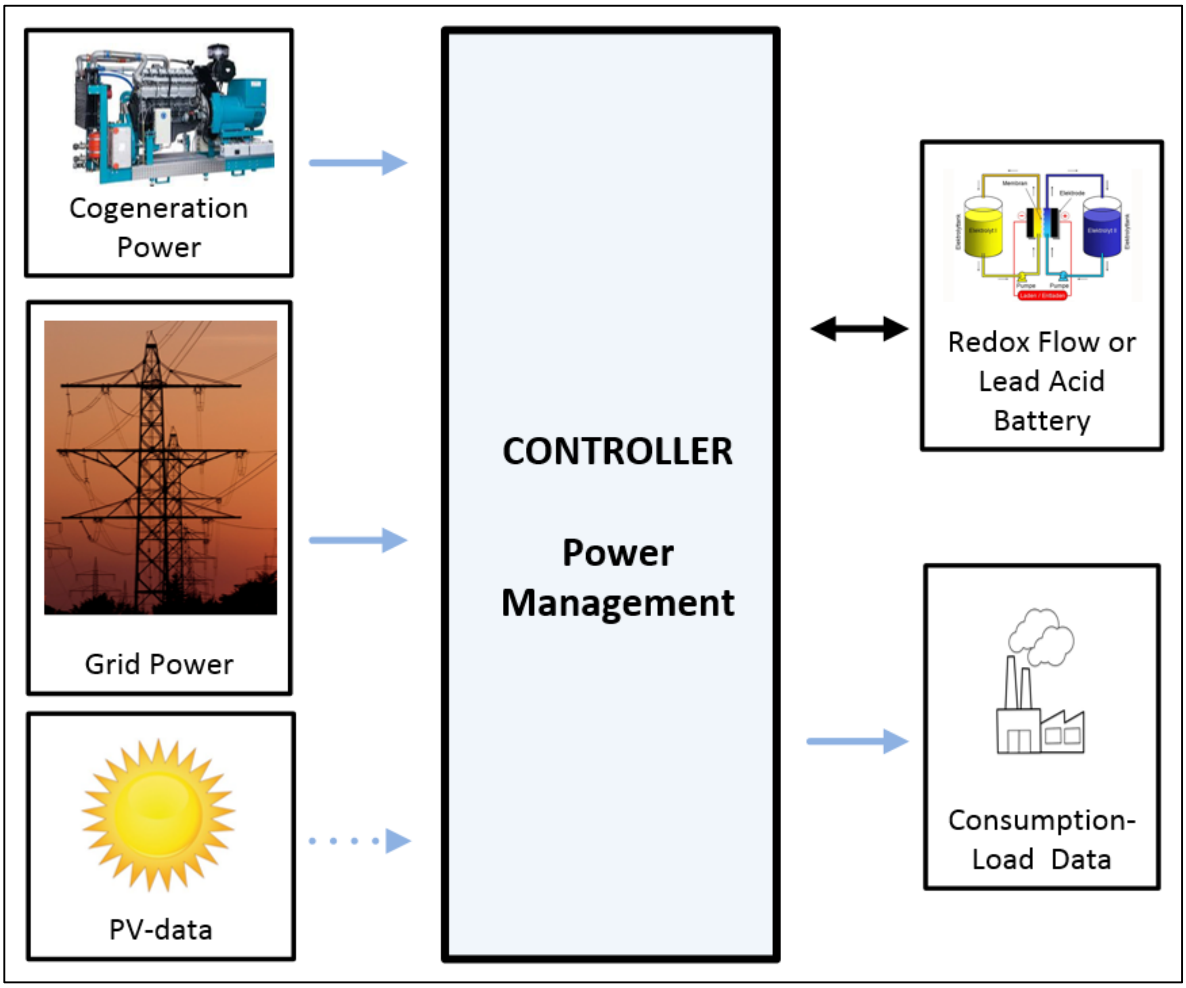

Figure 5.3: Block Diagram of the Simulink Model

The following is a more detailed explanation of the blocks contained in the Simulink model.

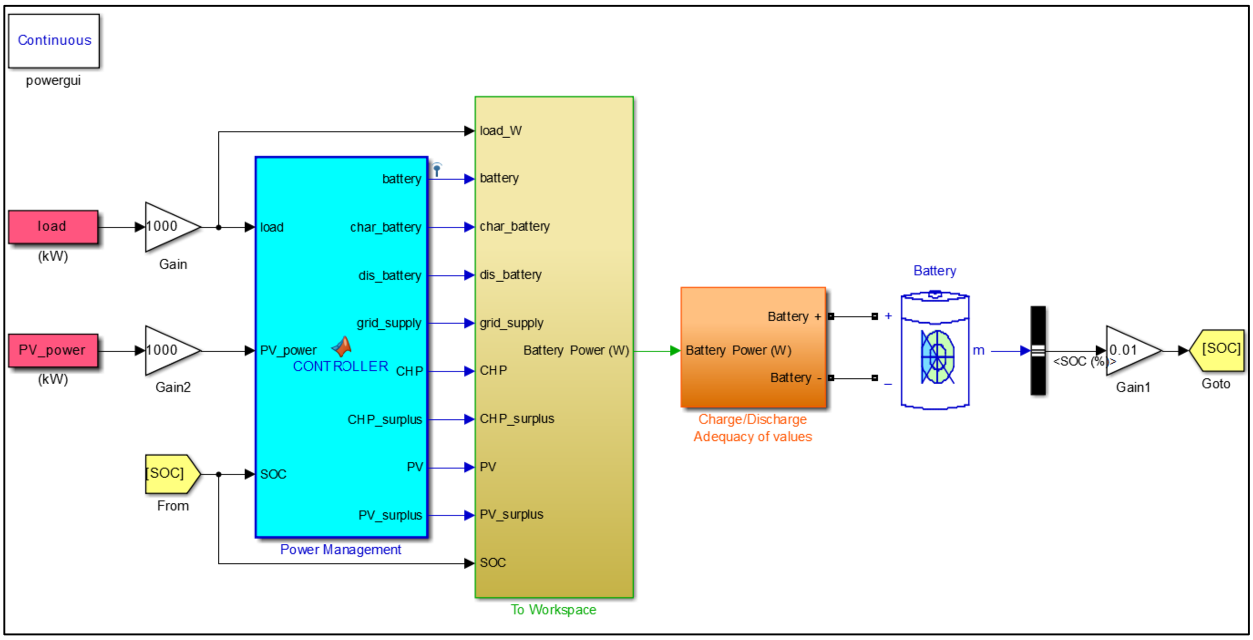

Figure 5.4: Simulink Model

All the blocks of the simulation model are possible to see in the Figure 5.4. The blocks are described in the following lines.

5.2.10.2 Simulation Block Elements

Load block

This block takes the load required by the company in kW as an input. The load will be multiplied by 1000 in order to get Watts.

PV_power block

This block takes the power supplied from the solar panels as an input, just in case that the user selects that option, if not, this input has the value zero. This input is in kilowatts but with the next block it will be multiplied by 1000 in order to get Watts.

Power management block

This block is a function which will be explained in the next section called Power Management Function.

To workspace block

This block sends the value of these variables to the Matlab workspace in order to be able to work with them in the scripts which do not form part of the Simulink tool.

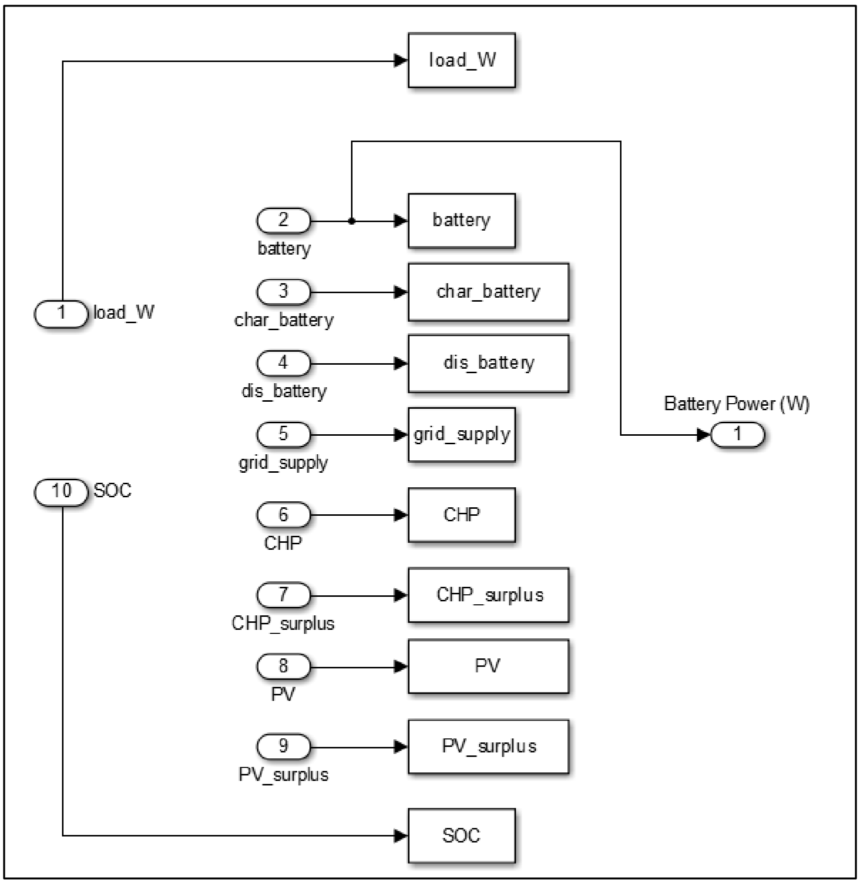

Figure 5.5: "To workspace" block

The first and the last label come from the entry of the Power Management Function block, the others come from the exit of the function.

Charge/discharge and adequacy of values block

The purpose of this block is charge and discharge the battery depending on the value of the Battery Power output. If this variable takes a positive value, the battery will be charged, and if it is negative, the battery will be discharged.

Inside of this block, the battery power is converted into current, because the battery block of simulink works with current.

Furthermore, some changes have been introduced in order to make the simulation faster.

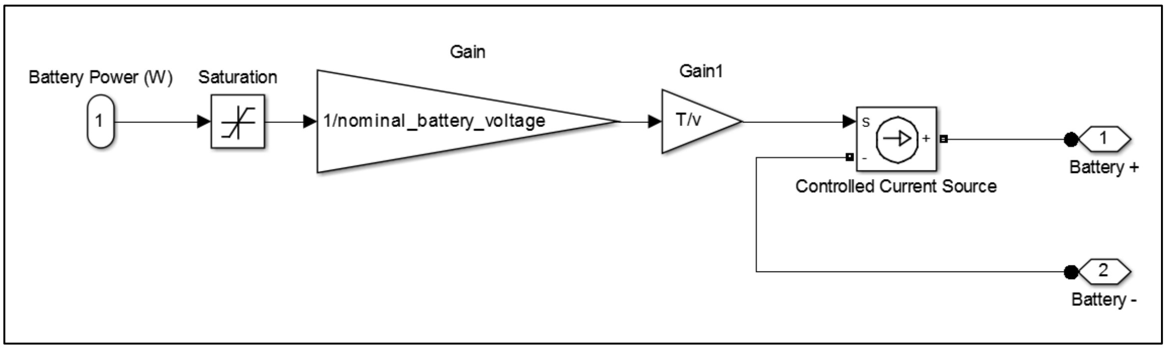

Figure 5.6: "Charge/discharge and adequacy of values" block

First of all, as can be seen from Figure 5.6, there is a sub-block called "Saturation", which limits the charge and discharge power of the battery to its maximum values calculated in the Selection Script.

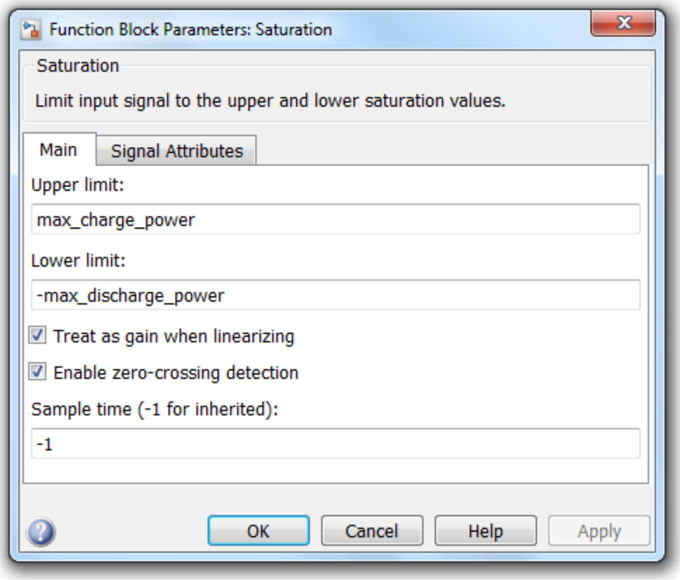

Figure 5.7: "Saturation" block

The following sub-block divides the power provided from the battery by the nominal voltage of the battery in order to get its equivalent current value.
The last and most important sub-block is the speed block. It works as follows:

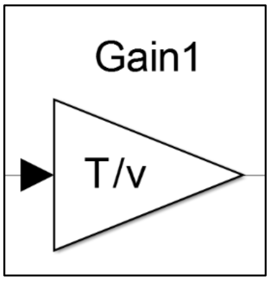

Figure 5.8: Sub-block to speed up the simulation time

The purpose of this sub-block is speed up the simulation time in order to be able to simulate more than one day in a reasonable time. For that, it uses two variables "T" and "v" which have been defined previously in the "input_data" script. With these variables the simulation time is changed by one shorter time.
The "T" variable is the time, in seconds, between two respective data of the company load, i.e. the step time. The "v" variable represents the period time between each step of the simulation. For example, when to "v" variable is assigned a value of 1 means that each step is one by one. If the value assigned is 2, each step is two by two. The default value of this variable in the program is one.
Normally, the electric load of a company is given every 15 minutes, this means that T is equal to 900 seconds.

- If the"v" value is the same as "T", 900 seconds, the gain of the block will be 1, as if there was not any block. Each data load of the company will be simulated during 900 seconds, and the simulation will be slow.

- If "v" value is 1 second, its default value, the gain of the block will be 900. Each load data of the company will be simulated during 1 second, but the charge or discharge battery current will be, at the same time, multiplied by the gain of the block (900 in this case), making the simulation realistic and faster. All this means that, to simulate a day, instead of simulating 86400 s, 96 s are simulated.

These changes are being made in the load variable and also in the power provided by the solar panels.

To verify that these changes make sense, just a few equations are necessary. To do the proof easier, the load is constant with a value of 1000 kW, which causes the battery to discharge with its maximum power. The initial SOC is 100 %, and after the simulation,
Figure 5.9 is obtained.

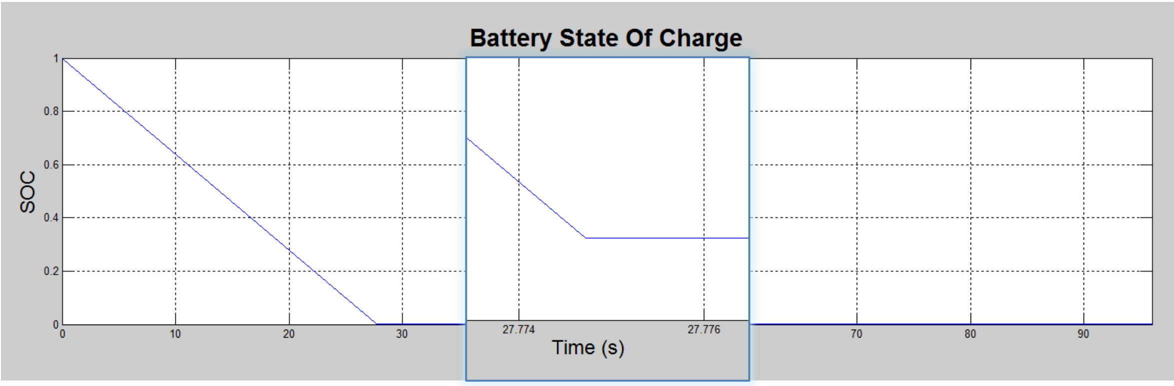

Figure 5.9: Battery State of Charge.

It can be seen Figure 5.9 that the discharge time of the simulation is 27,77 s.

Now, the theoretical discharge time is going to be calculated. The simulation has been done for one day, 86400 s. Then, knowing that:

$$\mathrm{DR} = \frac{\text{Max discharge power}}{\text{Battery capacity}}, \qquad [\mathrm{DR}] = \frac{\mathrm{kW}}{\mathrm{kWh}} = \mathrm{h}^{-1}$$

where:
DR = Discharge Rate.
Max discharge power = maximum discharge power of the battery, 120 kW in this simulation.
Battery capacity = nominal battery capacity, 800 kWh in this simulation.

the following discharge time is obtained:

$$t_{\text{discharge}} = \frac{1}{\text{DR}}, \qquad t_{\text{discharge}} = \frac{1}{\frac{120\ \text{kW}}{800\ \text{kWh}}} = 6{,}67\ \text{h} = 24000\ \text{s}$$

So, if one day is 86 400 s and it takes 24 000 s to discharge the battery, and it is known that one day of simulation takes 96 s, the discharge time of the battery should be:

$$t_{\text{discharge(simulation)}} = \text{Real value} = \frac{96\ \text{s} \cdot 24000\ \text{s}}{86400\ \text{s}} = 26{,}67\ \text{s}$$

With this result and the one obtained in the Figure 5.9, the following errors are calculated:

$$\text{Absolute error} = \text{Simulation value} - \text{Real value} = 26{,}67\ \text{s} - 27{,}77\ \text{s} = -1{,}12\ \text{s}$$

$$\text{Relative error} = \left|\frac{\text{Absolute error}}{\text{Real value}}\right| = \left|\frac{-1{,}12}{26{,}67}\right| = 4{,}19\ \%$$

It could be said that this error is a small error. Due to the battery discharge time obtained is almost the same that the one that the features of the battery indicate, this demonstrates that the simulation works properly.

An explanation about what is the c discharge and c charge rate is at the end of this chapter.

5.2.10.3 Battery Block

The battery block is a block in which several data of the battery can be calculated. They are shown in the Figure 5.10.

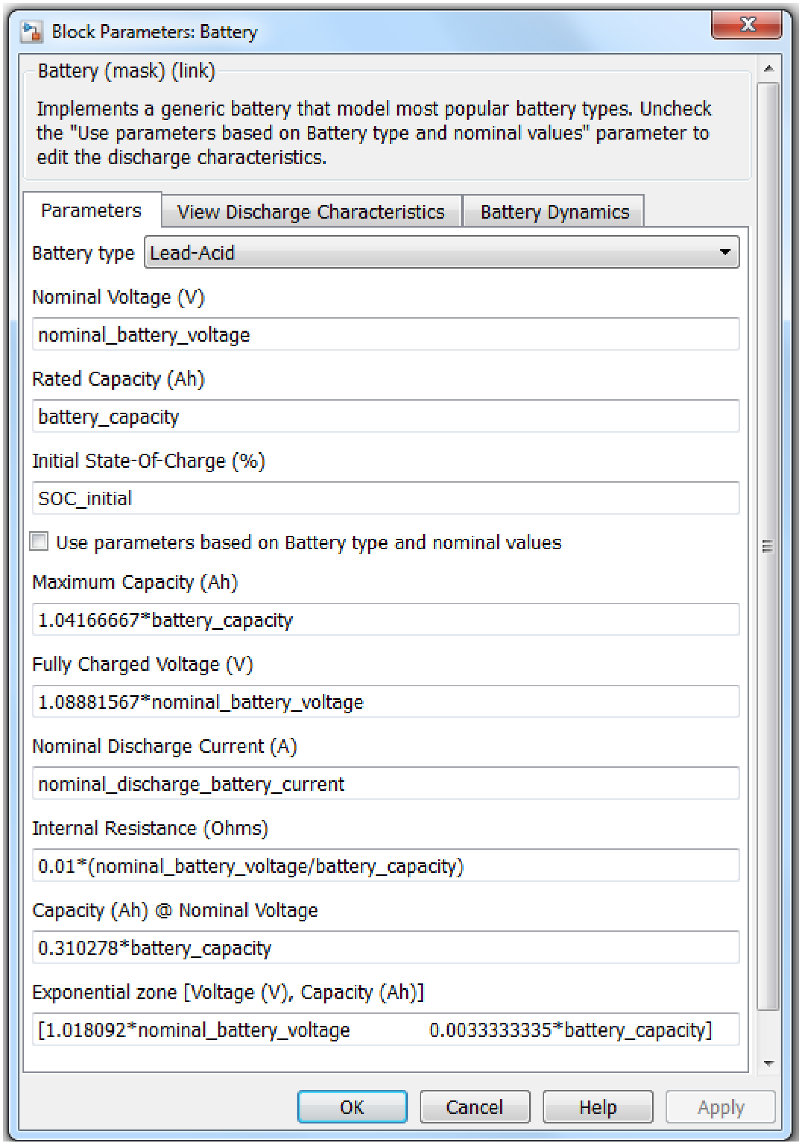

Figure 5.10: Battery block

The battery type selected to make this simulation is the Lead-Acid battery, this means that the Redox Flow battery will be simulated with the features of the Redox Flow Battery (battery capacity, minimum SOC, etc.), but the behavior will be much similar as a Lead-Acid battery.

The values entered in this block such as the Nominal Voltage or the Rated Capacity are defined before in the script called Input Data.

All these parameters are defined in the help of Mathworks.

Mathworks help offers a Battery block in order to implement a generic battery model. The Battery block implements a generic dynamic model parameterized to represent most popular types of rechargeable batteries.

The equivalent circuit of the battery is shown in Figure 5.12.

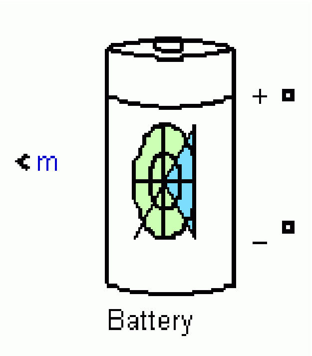

Figure 5.11: Battery block of Simulink

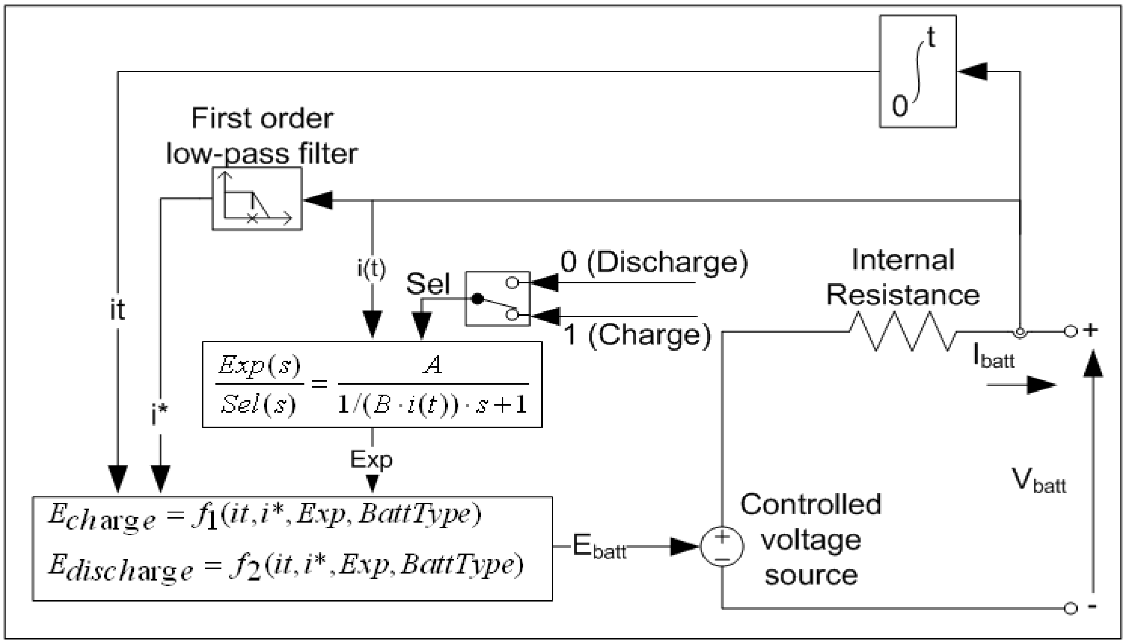

Figure 5.12: Equivalent circuit of the battery model from Simulink

The respective menu points of the Battery block in Figure 5.10 are explained as follows.

a) Battery type

Provides a set of predetermined charge behavior for four types of battery:

Lead-Acid
Lithium-Ion
Nickel-Cadmium
Nickel-Metal-Hydride

b) Nominal Voltage (V)

The nominal voltage (Vnom) of the battery (volts). The nominal voltage represents the end of the linear zone of the discharge characteristics.

c) Rated Capacity (Ah)

The rated capacity (Qrated) of the battery in ampere-hour. The rated capacity is the minimum effective capacity of the battery.

d) Initial State-Of-Charge (%)

The initial State-Of-Charge (SOC) of the battery. 100% indicates a fully charged battery and 0% indicates an empty battery. This parameter is used as an initial condition for the simulation and does not affect the discharge curve (when the option Plot Discharge Characteristics is used).

e) Use parameters based on Battery type and nominal values

Load the corresponding parameters into the entries of the dialog box, depending on the selected Battery type, the Nominal Voltage and the Rated Capacity.

When a preset model is used, the detailed parameters cannot be modified. If you want to modify the discharge curve, select the desired battery type to load the default parameters, and then uncheck the Use parameters based on Battery type and nominal values checkbox to access the detailed parameters.

f) Maximum Capacity (Ah)

The maximum theoretical capacity (Q), when a discontinuity occurs in the battery voltage. This value is generally equal to 105% of the rated capacity.

g) Fully charged Voltage (V)

The fully charged voltage (Vfull), for a given discharge current. Note that the fully charged voltage is not the no-load voltage.

h) Nominal Discharge Current (A)

The nominal discharge current, for which the discharge curve has been measured. For example, a typical discharge current for a 1.5 Ah NiMH battery is numerically 20 % of the rated capacity: 0,2·1,5 Ah / 1h = 0,3 A.

i) Internal Resistance

The internal resistance of the battery (ohms). When a preset model is used, a generic value is loaded, corresponding numerically to 1% of the nominal power (nominal voltage · rated capacity of the battery). The resistance is supposed to be constant during the charge and the discharge cycles and does not vary with the amplitude of the current.

j) Capacity (Ah) @ Nominal Voltage

The capacity (Qnom) extracted from the battery until the voltage drops under the nominal voltage. This value should be between Qexp and Qmax.

k) Exponential zone [Voltage (V), Capacity (Ah)]

The voltage (Vexp) and the capacity (Qexp) corresponding to the end of the exponential zone, see Figure 5.13. The voltage should be between Vnom and Vfull. The capacity should be between 0 and Qnom.

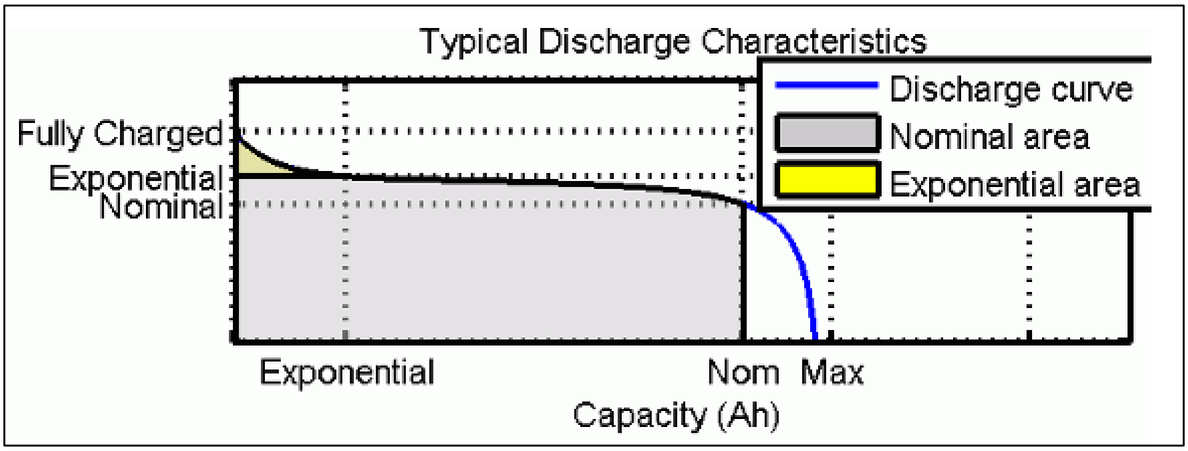

Figure 5.13: Typical Discharge Characteristics.

5.2.11 C Rate

The C rate is a measure of the rate at which a battery is discharged relative to is maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Ah, this equates to a discharge current of 100 A. A 5 C rate for this battery would be 500 A, which means a discharge in the time of 1/5 h, and a C/2 rate would be 50 A [18].

In order to describe the concept of the C rate more exactly, it is in the following replaced by the:

- Charge rate, *CR*.
- Discharge rate, *DR*.

<u>Discharge Rate:</u>

$$DR = \frac{I_{discharge}}{C}, \qquad [DR] = \frac{A}{A \cdot h} = h^{-1}$$

with:

$I_{discharge}$: discharge current of the battery.

C: Battery capacity.

Charge Rate:

$$CR = \frac{I_{charge}}{C}, \qquad [CR] = \frac{A}{A \cdot h} = h^{-1}$$

with:

I_{charge}: charge current of the battery

C: Battery capacity.

5.2.12 Power Management Function

5.2.12.1 Calculation of the Charge and Discharge Power of a Redox Flow Battery

Charge of a Redox Flow battery

In order to calculate the charge power line of the battery, the Gildemeister datasheet offers two different graphs, one as a function of the SOC, and the other one as a function of the charge time.

In this project, the charge power line has been calculated following the graphs as a function of the SOC because it is a variable known during all the simulation time. The following graphs have been used to calculate this function, see Figure 5.14.

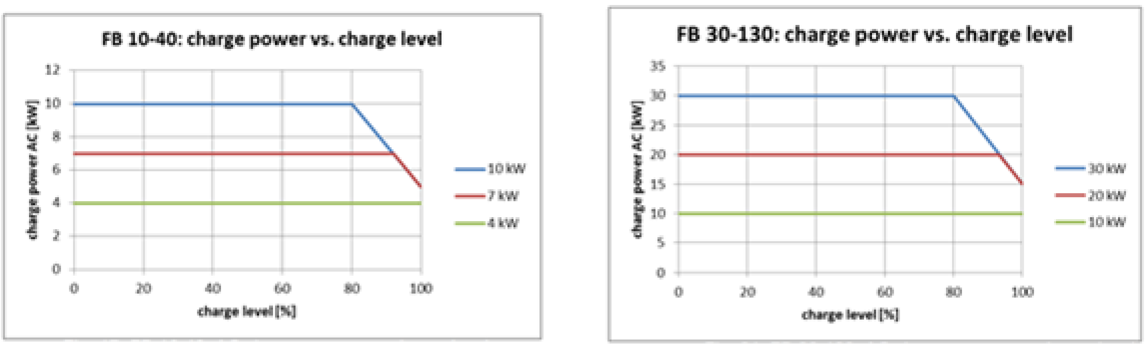

Figure 5.14: AC charge power vs. charge level [13]

In Figure 5.14, the maximum charge powers of these batteries are 10 and 30 kW respectively. The maximum charge power is represented with the blue line, and the red and green one represent different rates of charge power. The highest one has been selected in order to charge the battery as fast as possible.

In these graphs, one can appreciate that, for the blue lines, above 80 % of state of charge of the battery, the charge power decreases down to half of the maximum charge power i.e for a battery with 10 kW of maximum charge power, this value is reduced from 10 kW, with 80 % of SOC to 5 kW with 100 % of SOC and for a battery with a maximum discharge power of 30 kW, it goes down from 30 kW to 15 kW.

The blue line between the 80 % and 100 % of SOC, for each maximum charge power, has been plotted in order to get its equation. Note that, between 0 % and 80 % of SOC, the battery can supply the maximum charge power, which does not represent any problem during the simulation.

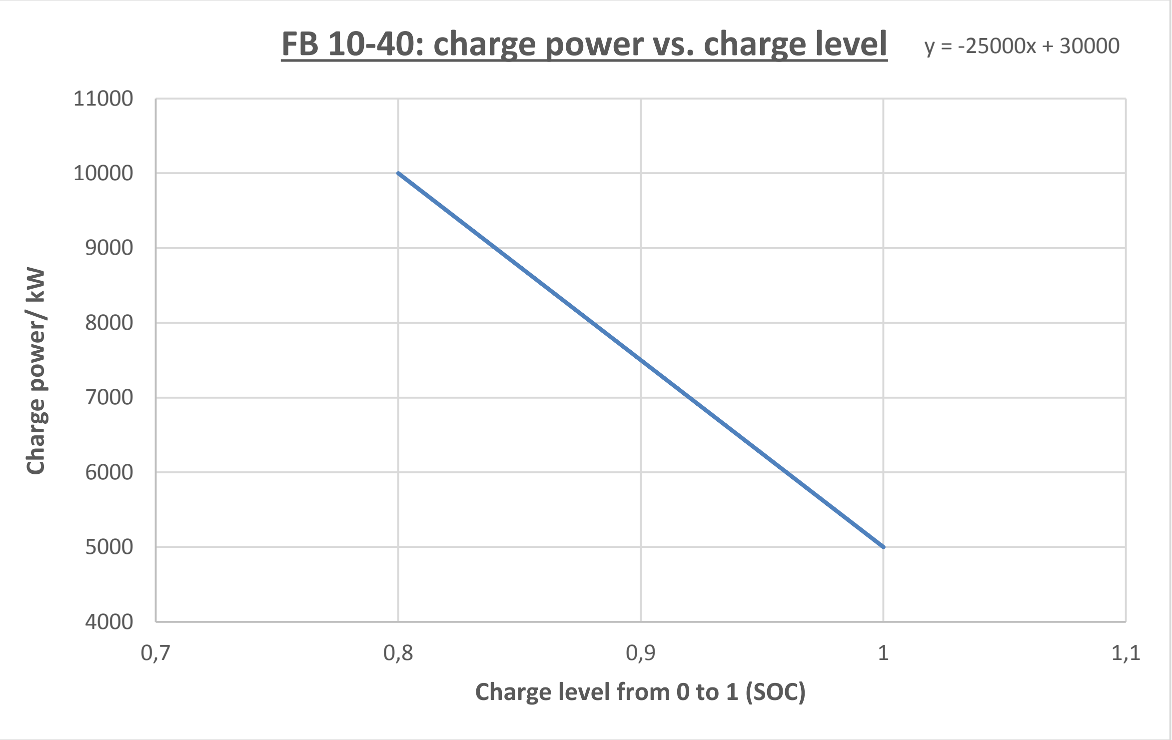

Figure 5.15: FB10-40 Charge power vs. charge level (SOC).

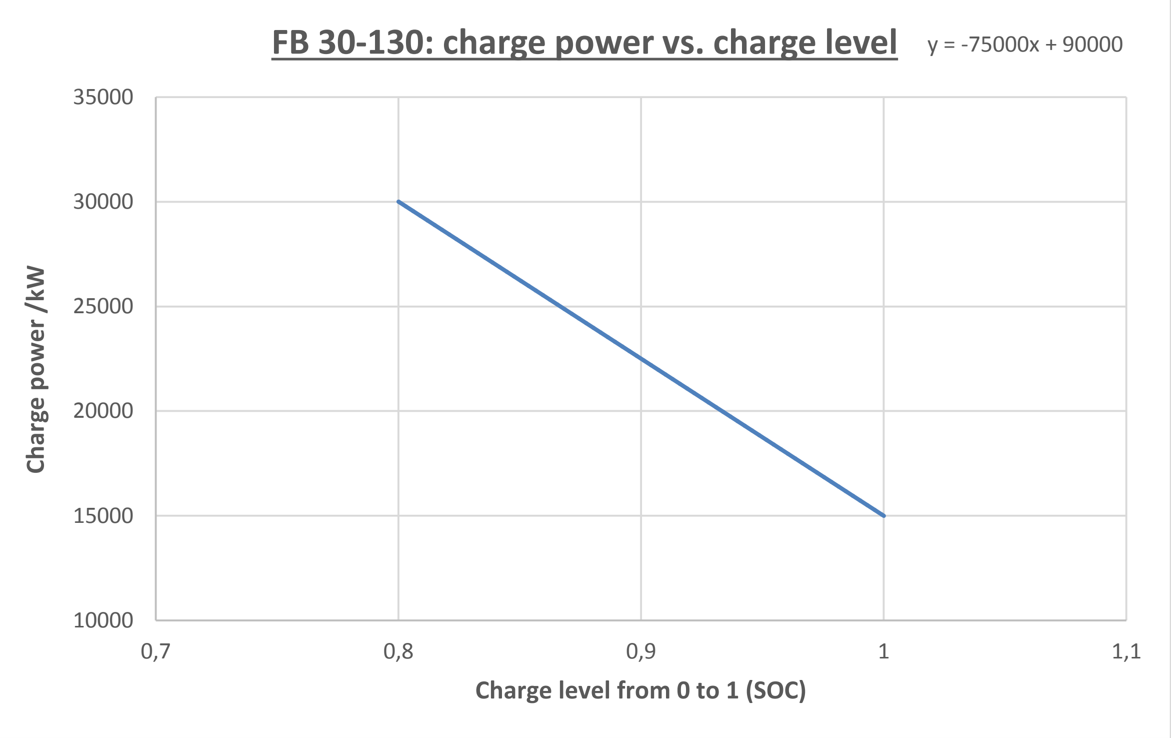

Figure 5.16: FB30-130 Charge power vs. charge level (SOC).

The linear equations of the graphs Figure 5.15 and Figure 5.16 are:

$$\boldsymbol{y = m \cdot x + n}$$

FB 10-40: $y = -25000 \cdot x + 30000$

FB 30-130: $y = -75000 \cdot x + 90000$

where:

m = slope of the line.

n = *y*-intercept.

y = charge power of the battery in Watts.

x = state of charge of the battery (from 0 to 1) = SOC.

Dividing the first parameter of each linear equation and the absolute term by their maximum charge power, a constant value is achieved. With this constant values, it is possible to calculate another linear equation to model each charge line.

Table 5.2: Calculation of the charge linear equation.

Maximum charge power / W	***m***	***n***	$\frac{m}{\text{maximum charge power}}$	$\frac{n}{\text{maximum charge power}}$
10000	-25000	30000	-2,5	3
30000	-75000	90000	-2,5	3

With the results of Table 5.2 it is easy to build the new linear equation.

Charge linear equation:

$$\mathrm{y} = -2{,}5 \cdot \mathrm{max\_charge\_power} \cdot \mathrm{x} + 3 \cdot \mathrm{max\_charge\_power}$$

Verification, example:

max_charge_power = 10000 W

$$y = -2{,}5 \cdot 10000\ \mathrm{W} \cdot 0.8 + 3 \cdot 10000\ \mathrm{W} = 10000\ \mathrm{W}$$

$$y = -2{,}5 \cdot 10000\ \mathrm{W} \cdot 1 + 3 \cdot 10000\ \mathrm{W} = 5000\ \mathrm{W}$$

max_charge_power = 30000 W

$$y = -2{,}5 \cdot 30000\ \mathrm{W} \cdot 0.8 + 3 \cdot 10000\ \mathrm{W} = 30000\ \mathrm{W}$$

$$y = -2{,}5 \cdot 30000\ \mathrm{W} \cdot 1 + 3 \cdot 10000\ \mathrm{W} = 15000\ \mathrm{W}$$

With this verification is demonstrated that the charge linear equation calculated corresponds with the blue line given by the company Gildemeister.

<u>Discharge of a Redox Flow battery</u>

The process to calculate the linear equation of the discharge power is the same as the process to calculate it for the charge power.

In this case, these are the graphs as a function of the SOC offered by the company Gildemeister in its datasheet of Redox Flow Batteries, see Figure 5.17.

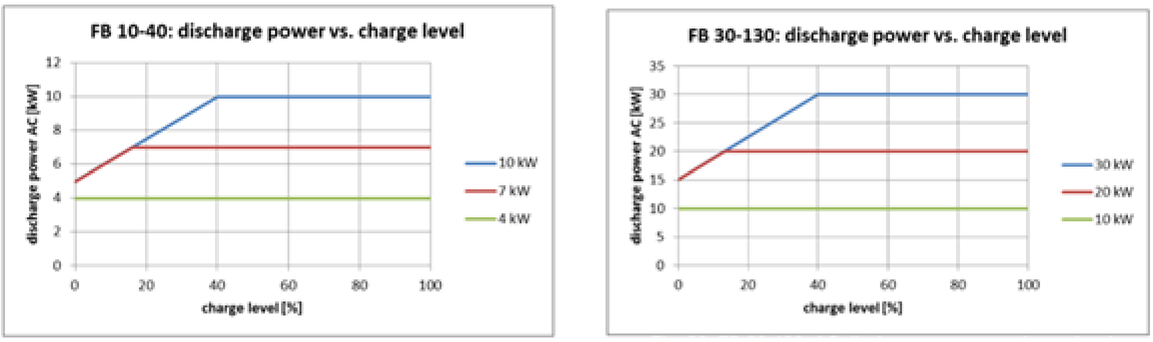

Figure 5.17: AC discharge power vs. charge level [13]

In these graphs, one can appreciate that, for the blue lines, under 40 % of state of charge of the battery, the discharge line decrees down to half of the maximum discharge power i.e for a battery with 10 kW of maximum discharge power, this value is reduced from 10 kW, with 40 % of SOC to 5 kW with 0 % of SOC and for a battery with a maximum discharge power of 30 kW, it goes down from 30 kW to 15 kW.

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In the following graphs, the ends of the discharge lines of the two redox flow batteries provided by Gildemeister have been represented.

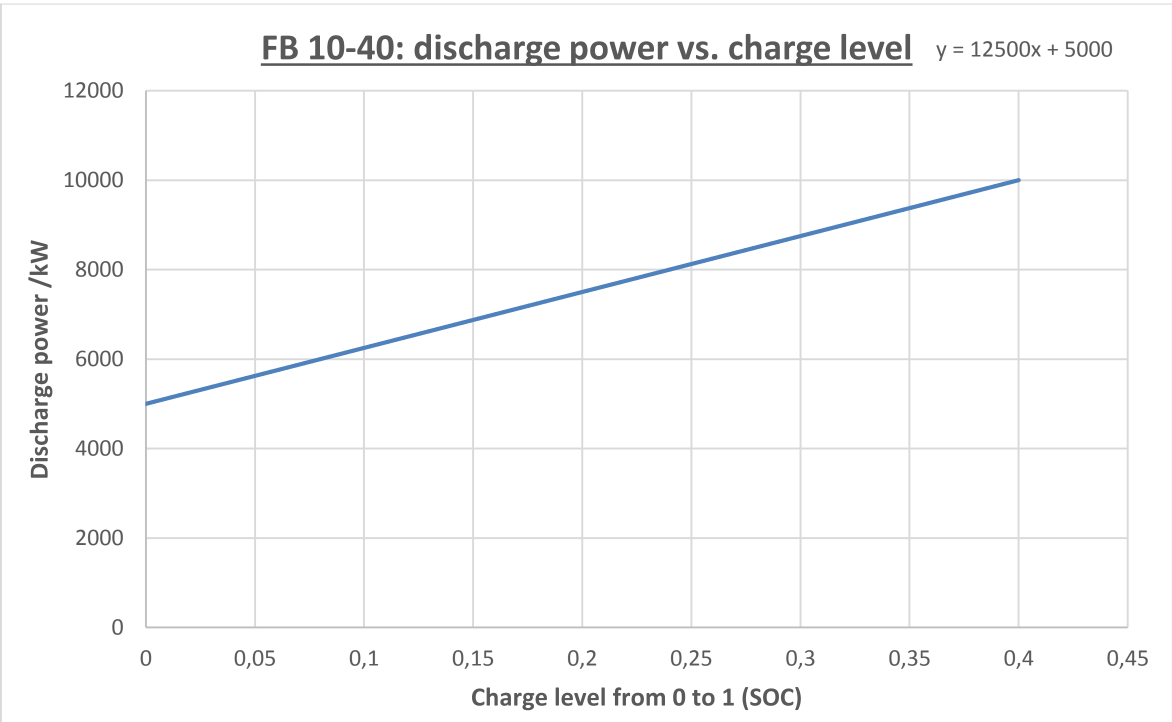

Figure 5.18: FB10-40 Discharge power vs. charge level (SOC).

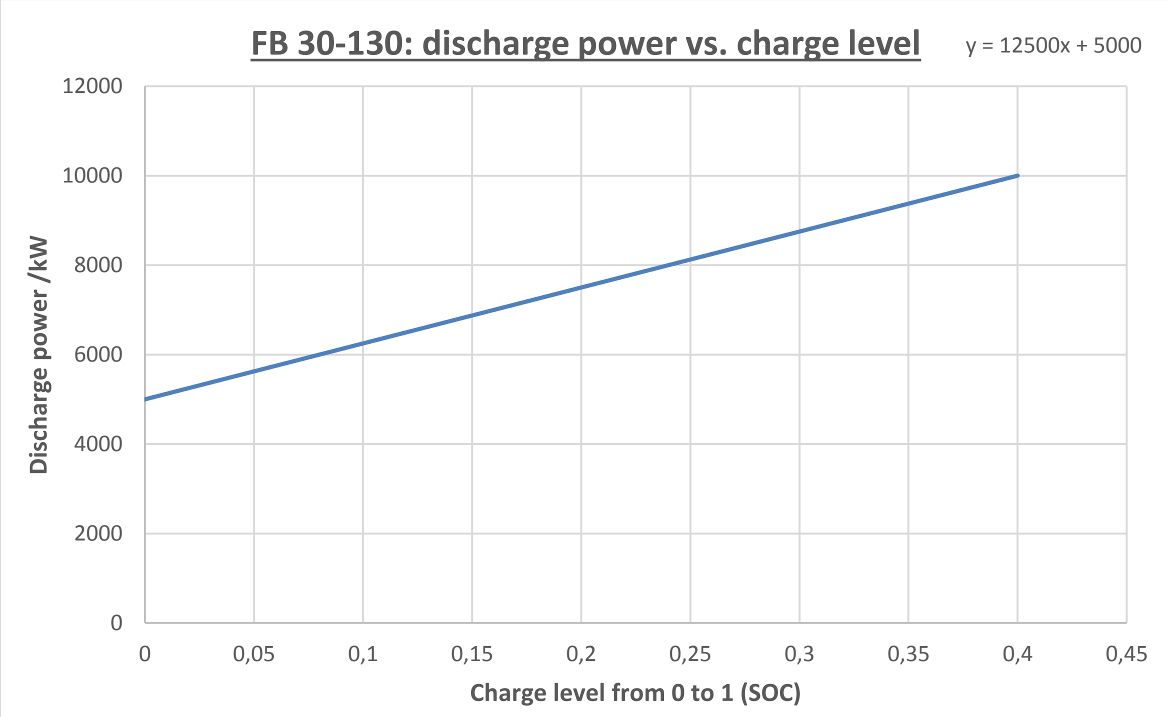

Figure 5.19: FB30-130 Discharge power vs. charge level (SOC).

The linear equations of these graphs are:

$$\boldsymbol{y = m \cdot x + n}$$

FB 10-40: $y = 125000 \cdot x + 5000$

FB 30-130: $y = 375000 \cdot x + 15000$

where:

m = slope of the line

n = y-intercept

y = discharge power of the battery in Watts

x = state of charge of the battery (from 0 to 1) = SOC

Dividing the first parameter of each linear equation and the independent term by the maximum discharge power, a constant value is achieved. With this constant values, it is possible to calculate another linear equation to model each charge line.

Table 5.3: Calculation of the discharge linear equation.

Maximum discharge power / W	*m*	*n*	$\frac{m}{\text{max discharge power}}$	$\frac{n}{\text{max discharge power}}$
10000	12500	5000	1,25	0,5
30000	37500	15000	1,25	0,5

With the results of Table 5.3 it is easy to build the new linear equation.

Discharge linear equation:

$$\text{y} = 1{,}25 \cdot \text{max\_discharge\_power} \cdot \text{x} + 0{,}5 \cdot \text{max\_discharge\_power}$$

Verification, example:

max_discharge_power = 10000 W

$$y = 1{,}25 \cdot 10000\ \text{W} \cdot 0{,}4 + 0{,}5 \cdot 10000\ \text{W} = 10000\ \text{W}$$

$$y = 1{,}25 \cdot 10000\ \text{W} \cdot 0 + 0{,}5 \cdot 10000\ \text{W} = 5000\ \text{W}$$

max_discharge_power = 30000 W

$$y = 1{,}25 \cdot 30000\ \text{W} \cdot 0.4 + 0{,}5 \cdot 30000\ \text{W} = 30000\ \text{W}$$

$$y = 1{,}25 \cdot 30000\ \text{W} \cdot 0 + 0{,}5 \cdot 30000\ \text{W} = 15000\ \text{W}$$

With this verification is demonstrated that the discharge linear equation calculated corresponds with the blue line given by the company Gildemeister.

5.2.12.2 Power Management Function

The power management function has been designed to manage the power in the industry. For its programming, several elements must be taken into account, such as the operation of the battery with its main parameters as the state of charge (SOC), the maximum discharge power, the capacity, etc. Besides, the grid, its limit and the limit of the CHP must be taken into account as well.

The main function of the “power management” controller is the simulation of the charge and discharge of the battery. With this block, the suitable amount of power is selected to charge or discharge the battery depending on other factors which affect the parameters of it. This means that the battery cannot be charged with more than its maximum charge power, or discharged with more than its maximum discharge power. If these values are exceeded in the simulation, the battery would not suffer anything, but on a real one, for example, the cycle life of it would decrease. For that, it must be ensured that these limits are not exceeded. For the simulation, the charge and discharge graphs of a redox flow battery have been taken from the datasheet of the company Gildemeister shown in the Appendix. The equation of the charge and discharge power of the battery have been included in the script in order to make the simulation more realistic.

Furthermore, this program has been developed to charge the battery with the power from the grid, CHP or from solar panels if they are included in the system. This would happen just when the power load required by the company is lower than the sum of the power from the CHP, from the solar panels and from the grid. Otherwise, the battery has to provide power to the load.

The power supply from the battery is one of the most important and complicated facts because it depends on the SOC of the battery and on the load requested by the company. All of this has to be combined minutely to get the desired results.

The elements of the function will be described in the following lines.

The load is the amount of power that the company needs in order to have its machinery operating. It must be provided first of all with the CHP, in order to get the most out of it.

If the load cannot be provided just with the CHP, the grid should supply power, unless there are solar panels in the system which can provide power. This is possible because there is a solar power input enabled. To use it, the user will have to introduce the data from the solar generator in the program. If not, the program will take this input as a zero.

The grid has an upper power limit (threshold) that cannot be surpassed unless the user introduces its own data. For that, when the power load is higher than the upper power limit from the grid, the battery must supply the rest of the needed power. In another script, the discharge power and the capacity of the battery have been calculated in order to provide all the power peaks without discharging the battery completely.

The operation of the function is shown in the following flow chart, Figure 5.20. The script of this function is in the Appendix 11.

The green words are variables and the blue squares are states which describe an operating mode of a system. States can be active or inactive. The activity or inactivity of a state can change depending on events and conditions. The occurrence of an event drives the execution of the state transition diagram by making states become active or inactive. At any point during execution, active and inactive states exist [17].

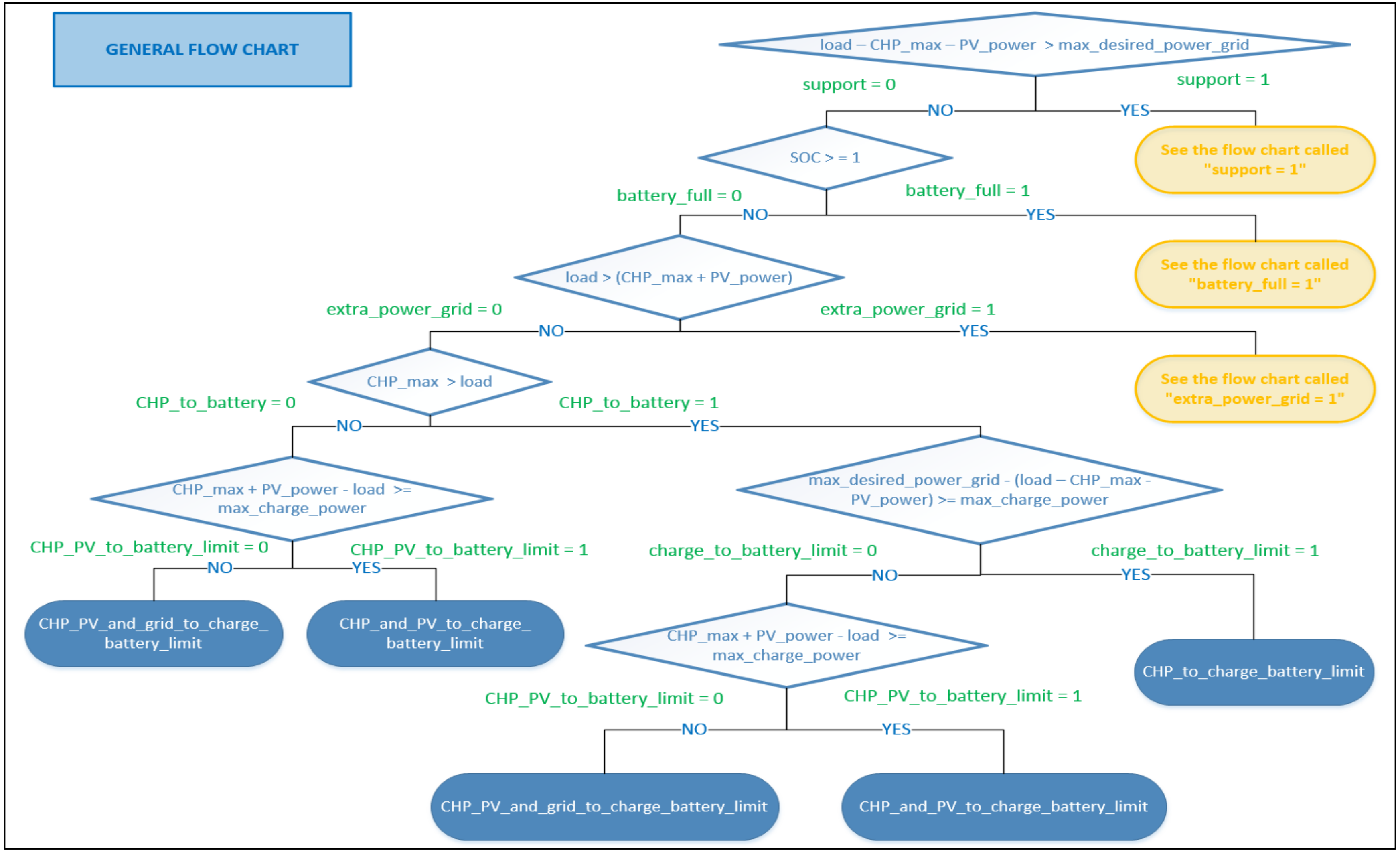

Figure 5.20: General Flow Chart of the Power Management Function

If the variable support takes the value 1, then the states of the flow chat continues as follows, see Figure 5.21:

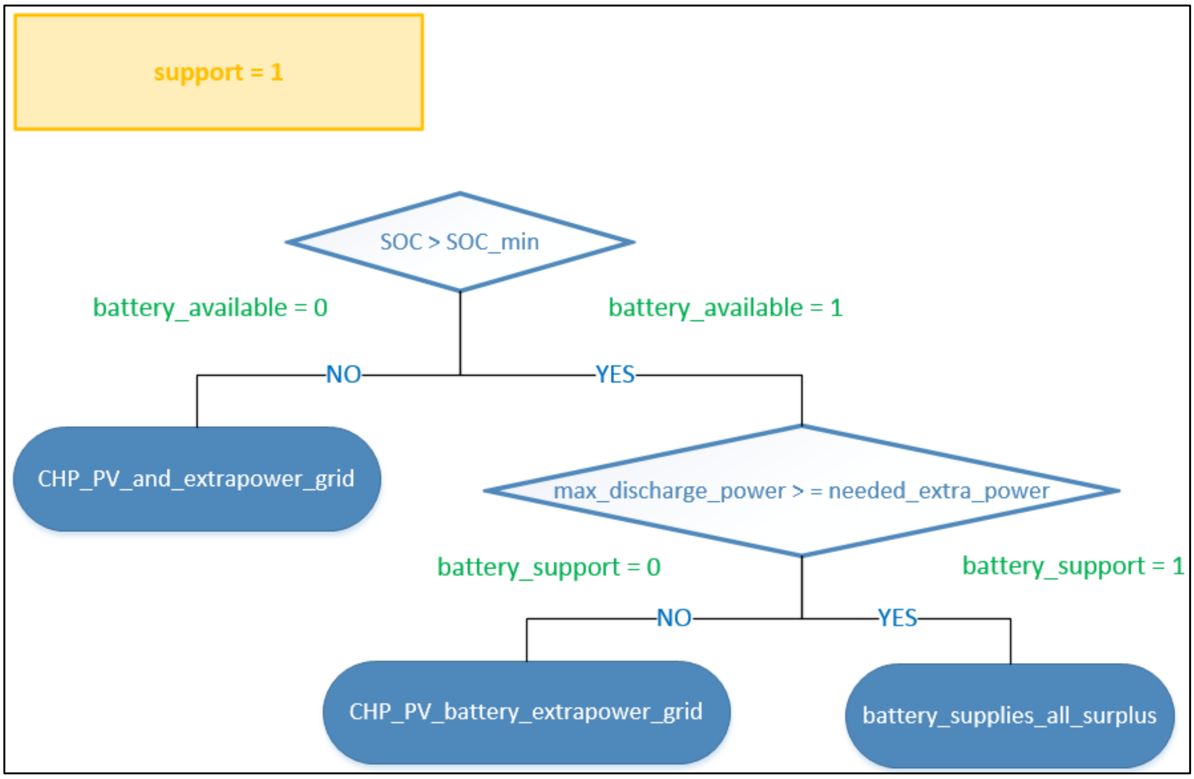

Figure 5.21: Flow Chart, support = 1 selected

If the variable battery_full takes the value 1, then the flow chart continues as follows, see Figure 5.22:

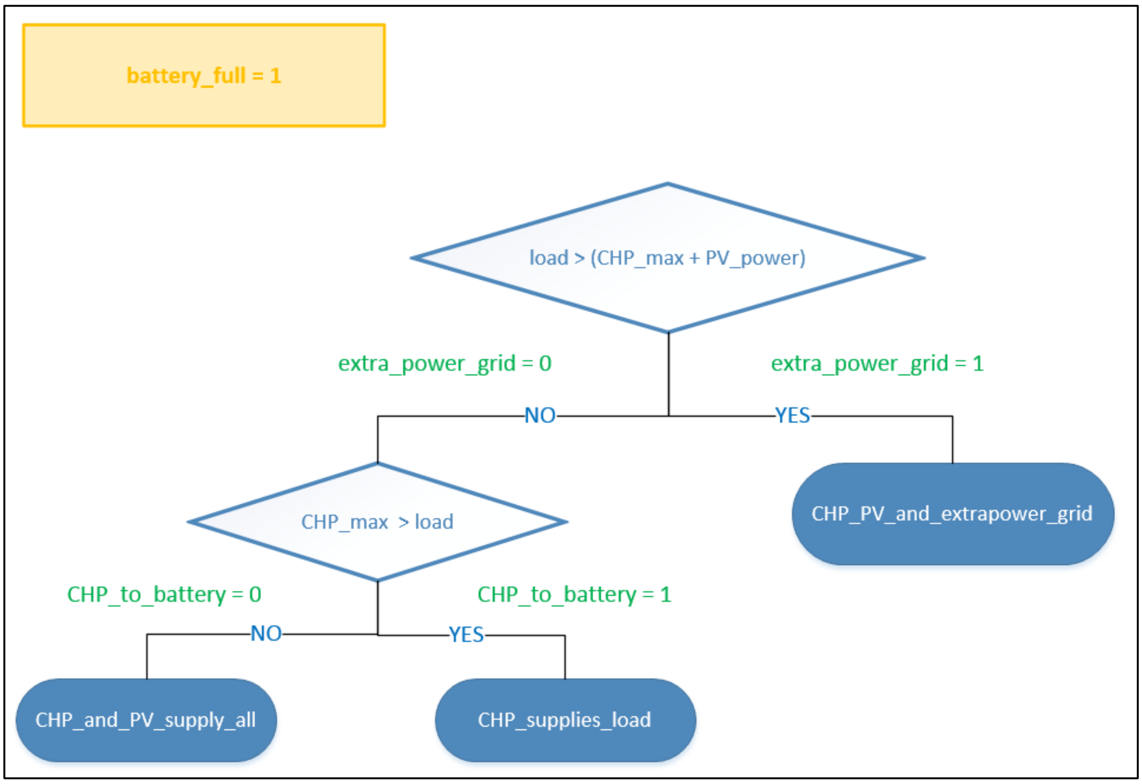

Figure 5.22: Flow Chart, battery_full = 1 selected

If the variable extra_power_grid takes the value 1, then the flow chart continues as follows, see Figure 5.23:

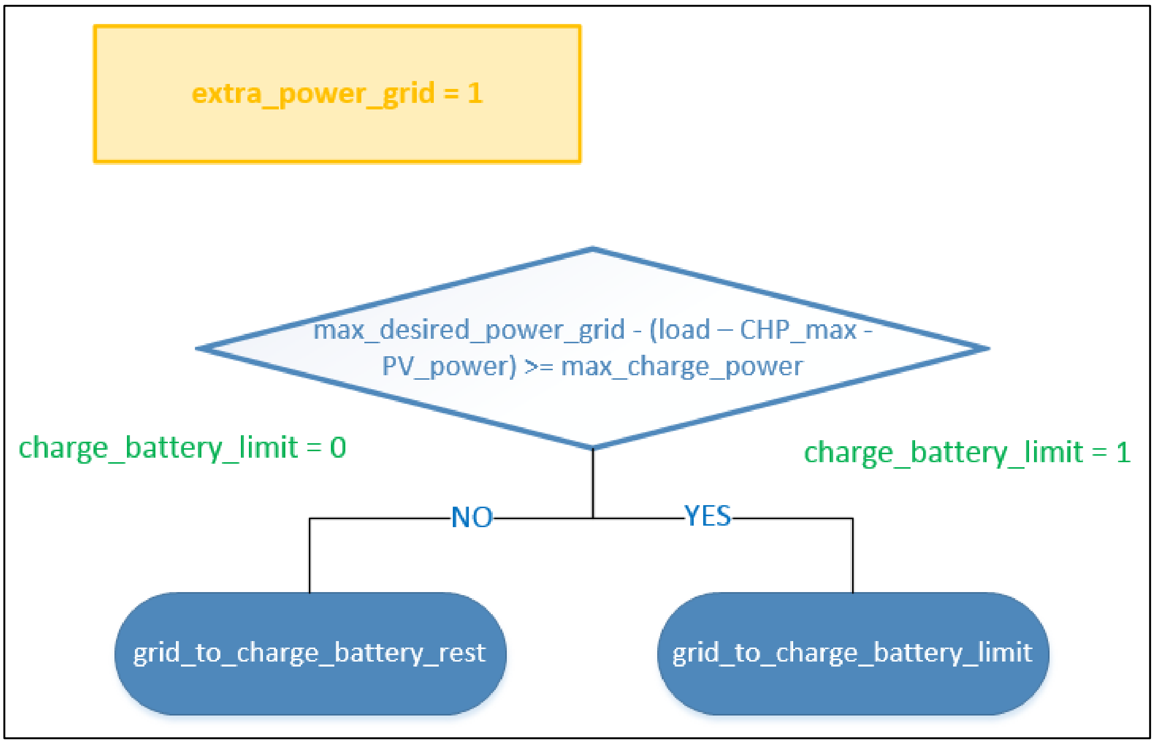

Figure 5.23: Flow Chart, extra_power_grid = 1 selected

5.2.12.3 Explanation of the Different Variables Used in the Power Management Function

<u>Variables taken from the workspace</u>

- max_desired_power_grid: the upper limit power from the grid.
- CHP_max: is the maximum power that the CHP can supply. The CHP will supply all its power all time in order to do the system more economic.
- max_charge_power: is the product of the nominal voltage of the battery and the nominal charge current of the battery. It is the power with which the battery is charged.

- max_discharge_power: is the product of the nominal voltage of the battery and the nominal discharge current of the battery. It is the power with which the battery is discharged.

- load: the power consumption from the company in Watts.

- SOC: the state of charge of the battery.

- SOC_min: the minimum state of charge of the battery, which means that the battery cannot have a lower state of charge during the simulation.

- PV_power: the power that the solar panels can provide, in Watts.

Specific variables of the function

- needed_extra_power: is the result of subtract the values kept in “CHP_max”, “PV_power” and "max_desired_power_grid" variables from the "load" variable. It is the power that should be provided by the battery.

- battery: is the power of the battery, it could be the power as much as to charge the battery or as to discharge it.

- grid_supply: is the power provided from the grid to the load. It cannot be higher than the “max_desired_power_grid”.

- CHP: is the power that the CHP provides to cover the power demand, it cannot be higher than the “CHP_max”.

- CHP_surplus: is the surplus power from the CHP once the power consumption has been supplied.

- PV: is the power that the solar panels provide to cover the power demand, it cannot be higher than the “PV_power”. Only in cases where the user has solar panels in its system.

- PV_surplus: is the surplus power from the solar panels once the power consumption has been supplied.

Table 7.1: Binary variables

Condition	Variable name and value	Explanation
load - CHP_max – PV_power > max_desired_power_grid	support = 1	The grid cannot provide all the surplus power to the load
load - CHP_max – PV_power <= max_desired_power_grid	support = 0	The grid can provide all the surplus power to the load
SOC > SOC_min	battery_available = 1	The battery can supply power
SOC < = SOC_min	battery_available = 0	The battery cannot supply power
SOC > = 1	battery_full = 1	The battery is full
SOC < 1	battery_full = 0	The battery is not full
max_discharge_power >= needed_extra_power	battery_support = 1	The battery can supply all surplus power
max_discharge_power < needed_extra_power	battery_support = 0	The battery cannot supply all surplus power. This option can occur just when the user introduces its own data. It means that its max_desired_power_grid and/or the battery data have been poorly selected.
max_desired_power_grid – (load – CHP_max – PV_power) >= max_charge_power	charge_battery_limit = 1	The battery will be charged with the maximum charge power provided by the grid

max_desired_power_grid – (load – CHP_max – PV_power) < max_charge_power	charge_battery_limit = 0	The battery will be charged with the remaining power from subtract the amount of load from the upper limit grid
CHP_max >= load	CHP_to_battery = 1	The load can be supplied only with the CHP
CHP_max < load	CHP_to_battery = 0	The CHP cannot supply all the power to the load
CHP_max – load >= max_charge_power	CHP_to_battery_limit = 1	The CHP will supply the load and the battery will be charged with the maximum charge power provided by the CHP
CHP_max – load < max_charge_power	CHP_to_battery_limit = 0	The CHP will supply the load and the battery will be charged with the maximum charge power provided by the grid, solar panels or both
load > CHP_max + PV_power	extra_power_grid = 1	The network is necessary to provide the load power
load <= CHP_max + PV_power	extra_power_grid = 0	The network is not necessary to provide the load power
CHP_max + PV_power – load >= max_charge_power	CHP_PV_to_battery_limit = 1	The CHP and the solar panels will supply the load and the battery will be charged with the maximum charge power provided by them
CHP_max + PV_power – load < max_charge_power	CHP_PV_to_battery_limit = 0	The CHP and the solar panels will supply the load and the battery will be charged with power from the CHP, solar panels and from the grid

5.2.12.4 Explanation of the Different States during the Simulation

The three first **states** are used to avoid the power peaks, if the load cannot be provided with the CHP, the solar panels, and the maximum desired power from the grid. As a consequence thereof, the battery will be used to provide the power surplus.

- battery_supplies_all_surplus: the grid will supply its upper power limit as the CHP and the solar panels, if these last ones have been enabled. Then, the battery will provide all surplus power.

- CHP_PV_battery_extrapower_grid: the CHP, the solar panels and the battery will provide their maximum power, but the grid will take a value higher than the maximum power of the grid, max_desired_power_grid. This option can occur just when the user introduces its own data and it means that the max_desired_power_grid has been poorly selected.

- CHP_PV_and_extrapower_grid: in this case, the load is higher than the threshold (max_desired_power_grid + CHP_max + PV_power) so, as in the previous state, the grid will take a value higher than the maximum power of the grid, max_desired_power_grid. This option can occur just when the user introduces its own data. It means that the max_desired_power_grid has been poorly selected.

The following states have been developed in order to supply the load required by the company. It is important to take into account that the CHP will be operating all time in order to get the most out of it, so, if it is not necessary to use all its power, that amount of energy will be sold. The same will happen with the power from the solar panels. Another important aspect is that the surplus energy from the CHP and from the solar panels, first of all, will be used to charge the battery and only then, if there is surplus, it will be sold.

- CHP_supplies_load: the load is supplied just by the CHP. If there is any surplus power, from the CHP or from the solar panels, this amount of energy will be sold.

- CHP_and_PV_supply_all: the load is supplied by the CHP and by the solar panels. If there is any surplus power, from the solar panels, this amount of energy will be sold.

- grid_to_charge_battery_limit: once the load has been supplied by the CHP, with the solar panels and also with the grid, this last one will provide the maximum power to charge the battery, without overtake the maximum power desired to the grid.

- grid_to_charge_battery_rest: this state is similar than the previous one, but in this case, the grid cannot supply the maximum charge power to charge the battery because if that happened, it would exceed its limit.

- CHP_to_charge_battery_limit: in this case, the CHP is able to provide the enough power to cover the demand of the company and to charge the battery.If there is more power than necessary, it will be sold as in the other cases.

- CHP_and_PV_to_charge_battery_limit: the CHP and the solar panels will provide the power that the company needs and with their power, the battery will be charged. If there is more power than necessary, it will be sold as in the other cases.

- CHP_PV_and_grid_to_charge_battery_limit: with this three energy sources will be enough to supply the required demand and to charge the battery with its maximum power of charge.

5.2.13 Prices Script

Everyone who would like to reduce electricity cost has to know what this cost consists of and how it arises. For that reason, a research has been carried out in order to get the information needed.

The demand rate – or power grid charges – is so to say a commitment fee of the grid operator for the all-day provision of the highest required electric power quantity (peak load) that the company, or the consumer used formerly.

This rate arises from the highest call-off electric power in kilowatts of the last measuring period, multiplied by the contractually agreed power price.

Depending on contract and utility company, this price is between 7 and 8 Euros per kilowatt for monthly tariffs and 60 to 95 Euros per kilowatt for annual tariffs. The performance is measured every 15 minutes.

In the contract both parties may agree on measuring periods based on monthly or annual maximum outputs. In case of a monthly agreement, the peak load is paid in the month it appeared. Therewith a one-time peak does not influence the following months. In case of an annual agreement, usually the highest peak load of the rolling last 12 months is being considered [22].

According to that information, in this script, the prices of the grid, battery, CHP and PV electricity are calculated. The differences in prices will be shown, depending on whether the grid supplies the entire load, or if the battery, CHP and PV system help to provide that load.

The names of the variables in this section are shown with the same name that they have in the scripts instructions, to make the program more understandable.

5.2.13.1 Grid to Provide All the Load

At the beginning, the prices are calculated when the grid provides all the power to the load. The grid power price, 63 €/kW [24], multiplied by the maximum value of the load, is the total power cost, but also depends on the number of simulation days:

$$\text{Grid to load total power cost} = \text{Grid power price} \cdot \text{Maximum value load} \cdot \frac{\text{Number days}}{365}$$

$$[\text{Grid to load total power cost}] = \frac{€}{\text{kW}} \cdot \text{kW} = €$$

The grid energy price, 0,15 €/kW [24], multiplied by the energy consumed, is the total energy cost:

$$\text{Grid to load total energy cost} = \text{Grid energy price} \cdot \text{Grid to load energy consumed}$$

$$[\text{Grid to load total energy cost}] = \frac{€}{\text{kWh}} \cdot \text{kWh} = €$$

The sum of both is the price (€) to pay, in the simulation days, when the grid provides all the power to the load:

$$\text{Pay grid povide all} = \text{Grid to load total power cost} + \text{Grid to load total energy cost}$$

5.2.13.2 Grid with Battery, CHP and PV

Afterwards, the prices are calculated when the battery, CHP, solar panels and the grid itself provide the power to the load.

<u>GRID</u>

For the grid, the same calculation applies as seen before.
The grid power price, 63 €/kW, multiplied by the maximum value of the grid, is the total power cost, but also depends on the number of simulation days:

$$\text{Grid total power cost} = \text{Grid power price} \cdot \text{Maximum value grid} \cdot \frac{\text{Number days}}{365}$$

$$[\text{Grid total power cost}] = \frac{€}{\text{kW}} \cdot \text{kW} = €$$

The grid energy price, 0,15 €/kW, multiplied by the energy consumed, is the total energy cost:

$$\text{Grid total energy cost} = \text{Grid energy price} \cdot \text{Grid energy consumed}$$

$$[\text{Grid total energy cost}] = \frac{€}{\text{kWh}} \cdot \text{kWh} = €$$

<u>BATTERY</u>

The battery investment is calculated depending on its capacity and on its maximum discharge power. The company Gildemeister provided some information about the prices of the redox flow battery, see Table 5.4.

Table 5.4: Prices of different sizes of Redox flow Batteries [14].

		Discharge Power /kW			
		10	**20**	**30**	**200**
Energy capacity /kWh	**40**	100000		180000	
	70		150000		
	100	133000	165000		
	130			200000	
	400				870000
	1600				1800000

With these prices, an estimation of the investment in the form of a linear equation has been made, depending on the battery capacity and on the discharge power. These equations are calculated as follows:

Battery investment (€).

Maximum discharge power (W).

For a capacity of 40 kWh:

$$\text{Battery investment} = 4000 \cdot \frac{\text{Maximum discharge power}}{1000} + 60000$$

For a capacity of 70 kWh:

$$\text{Battery investment} = 3700 \cdot \frac{\text{Maximum discharge power}}{1000} + 78000$$

For a capacity of 100 kWh:

$$\text{Battery investment} = 2600 \cdot \frac{\text{Maximum discharge power}}{1000} + 111500$$

For a capacity of 130 kWh:

$$\text{Battery investment} = 3094{,}4 \cdot \frac{\text{Maximum discharge power}}{1000} + 111636$$

For a capacity of 400 kWh:

$$\text{Battery investment} = 2834 \cdot \frac{\text{Maximum discharge power}}{1000} + 284786$$

For a capacity of 800 kWh:

$$\text{Battery investment} = 4096{,}6 \cdot \frac{\text{Maximum discharge power}}{1000} + 372311$$

For a capacity of 1600 kWh:

$$\text{Battery investment} = 5850{,}3 \cdot \frac{\text{Maximum discharge power}}{1000} + 575170$$

If the battery type is lead acid, its price is the same but divided by seven [14].

CHP SYSTEM

For the CHP system, some aspects must be considered. First of all, the initial investment must be calculated.

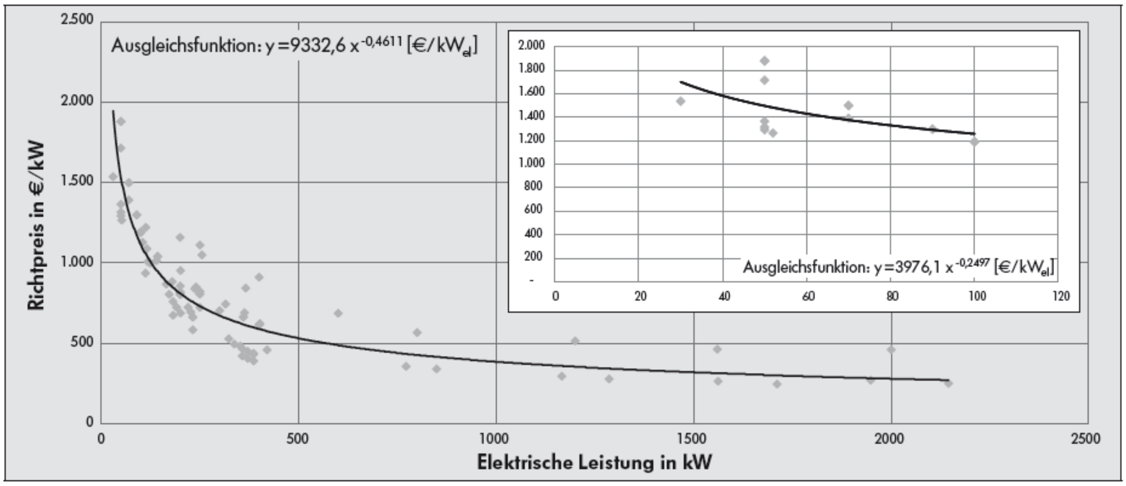

Figure 5.24: Cogeneration investment. Natural gas [2].

$$\text{CHP investment} = \text{CHP max} \cdot 9332{,}6 \cdot \text{CHP max}^{-0{,}4611}$$

where:

CHP investment (€).

CHP max = maximum electric power of the CHP (kW). This is the abscissa in Figure 5.24.

Then, it is necessary to calculate the CHP surplus benefit. The feed-in price of the CHP, 0,105 €/kWh [14], multiplied by the energy surplus, brings a total surplus benefit of:

$$\text{CHP total surplus benefit} = \text{CHP feed in price} \cdot \text{CHP surplus energy}$$

$$[\text{CHP total surplus benefit}] = \frac{€}{\text{kWh}} \cdot \text{kWh} = €$$

Subsequently, the CHP electricity and heat prices, have to be taken into account.

To do this, these parameters must be considered:

Eh = heat energy produced in a year (kWh_{th} /a). It is:

$$\text{Eh} = \text{CHP heat power} \cdot \text{Top} \cdot \text{CHP heat efficiency}$$

where:

CHP heat power (kW).

Top = operation time per year (8000 h/a).

CHP heat power and CHP heat efficiency have already been calculated on the CHP catalogue script.

Heat price (€/kWh_{th}).

$$\text{Heat price} = \frac{\text{Gas price}}{\text{Gas boiler efficiency}}$$

where:

Gas price = 0,045 €/kWh.

Gas boiler efficiency = 90 %.

Ee = electric energy produced in a year (kWh_{e} /a). It is:

$$\text{Ee} = \text{CHP max} \cdot \text{Top} \cdot \text{CHP electric efficiency}$$

where:

CHP max = maximum electric power of the CHP (kW).

Top = operation time per year (8000 h/a).

CHP electric efficiency has already been calculated on the CHP catalogue script.

Cop: operational annual cost (€/kWhe). This is the ordinate in Figure 5.25.

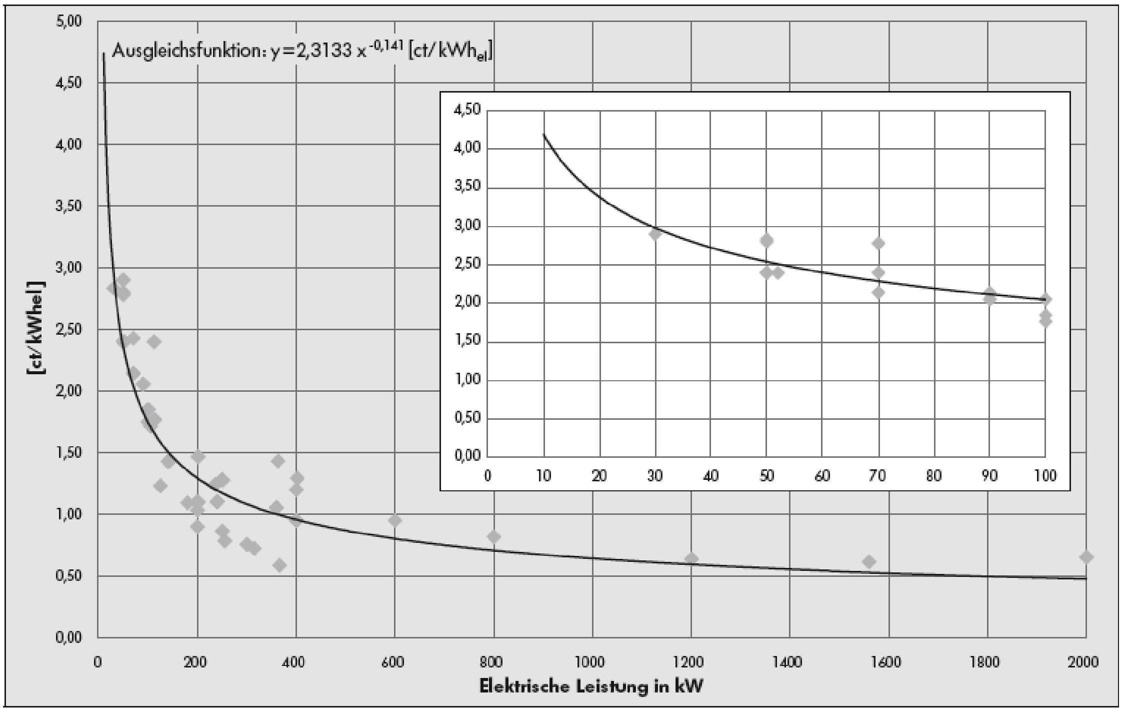

Figure 5.25: Cogeneration electricity cost. Natural gas [2].

$$\text{Cop} = \frac{2{,}3133}{100} \cdot \text{CHP max}^{-0{,}141}$$

CHP electricity price (€/kWhe), is the calculated as follows:

$$\text{CHP electricity price} = \left(\frac{\text{CHP investment}}{\text{Ta}} + \text{Cop} \cdot \text{Ee} - \text{Eh} \cdot \text{Heat price}\right) \cdot \frac{1}{\text{Ee}}$$

where:

Ta = amortization time, payback time of the investment (one years).

Having clarified these parameters, the CHP electricity and heat prices are the following:

$$\text{CHP total electric cost} = \text{CHP max} \cdot \text{Tsim} \cdot \text{CHP electricity price}$$

$$\text{CHP total heat cost} = \text{CHP max} \cdot \text{Tsim} \cdot \text{Heat price}$$

where:

CHP max = maximum electric power of the CHP (kW).

T sim = time of the simulation (h).

The option to simulate without PV system might be taken. In that case, the following prices are calculated:

$$\text{Pay grid batt and CHP} = \text{Grid total power cost} + \text{Grid total energy cost} \\ + \text{CHP total electric cost} - \text{CHP total surplus benefit}$$

where:

Pay grid batt and CHP = price (€) to pay, in the simulation days, when the grid, the battery and the CHP provide all the power to the load.

$$\text{Investment grid batt and CHP} = \text{Battery investment} + \text{CHP investment}$$

where:

Investment grid batt and CHP = sum of the initial investment of the battery and the CHP.

$$\text{Payback grid batt and CHP} = \frac{\text{Investment grid batt and CHP}}{\frac{(\text{Pay grid provide all} - \text{Pay grid batt and CHP}) \cdot 365}{\text{Number days}}}$$

where:

Payback grid batt and CHP = time in which the initial investment is returned (years).

PV SYSTEM

Finally, the PV prices are calculated when the user selects the option to simulate with PV input. The specific PV price is 1250 €/kWp [21], and the user has to introduce the solar peak power (kWp) of the system.

The PV investment (€) is calculated as follows:

$$\text{PV investment} = \text{PV price} \cdot \text{PV kWp}$$

$$[\text{PV investment}] = \frac{€}{\text{kWp}} \cdot \text{kWp} = €$$

The feed-in price of the PV is 0,128 €/kWh [9], but 0,11 €/kWh has been taken as a forward vision value. This price, multiplied by the energy surplus, has a total surplus benefit of:

$$\text{PV total surplus benefit} = \text{PV feed in price} \cdot \text{PV surplus energy}$$

$$[\text{PV total surplus benefit}] = \frac{€}{\text{kWh}} \cdot \text{kWh} = €$$

If the option to simulate without PV system is taken, the following prices are calculated:

$$\text{Pay grid batt CHP and PV} = \text{Pay grid batt and CHP} - \text{PV total surplus benefit}$$

where:
Pay grid batt CHP and PV = price (€) to pay, in the simulation days, when the grid, the battery, the CHP and he PV system provide all the power to the load.

$$\text{Investment grid batt CHP and PV} = \text{Investment grid batt and CHP} + \text{PV investment}$$

where:
Investment grid batt CHP and PV = sum of the initial investment of the battery, the CHP and the PV system.

$$\text{Payback grid batt CHP and PV} = \frac{\text{Investment grid batt CHP and PV}}{\frac{(\text{Pay grid provide all} - \text{Pay grid batt CHP and PV}) * 365}{\text{Number days}}}$$

$$[\text{Payback grid batt CHP and PV}] = \frac{€}{€/a} = a$$

where:

Payback grid batt CHP and PV = time in which the initial investment is returned (years).

5.2.14 Prices 2 Script

The difference between this script and the previous one is the calculation of the battery investment, the CHP heat power and the CHP heat and electric efficiencies.

5.2.14.1 Battery Investment

The user can introduce the battery price or the program can calculate it if the user wishes. Supposing that the program calculates the battery price, one potential equation has been built in an Excel file to calculate it. That price depends on the battery capacity.

To begin with the calculation, two prices from the Table 5.4 have been selected and the battery specific price per kWh for those two prices has been calculated in the Table 5.5.

Table 5.5: Section taken from the Table 5.4.

Values	Price /€	1800000	100000
	Capacity /kWh	1600	40
	Spec. Price /€·kWh^{-1}	1125	2500

The data have been adjusted to a potential equation (dotted line), as shown in the Figure 5.26.

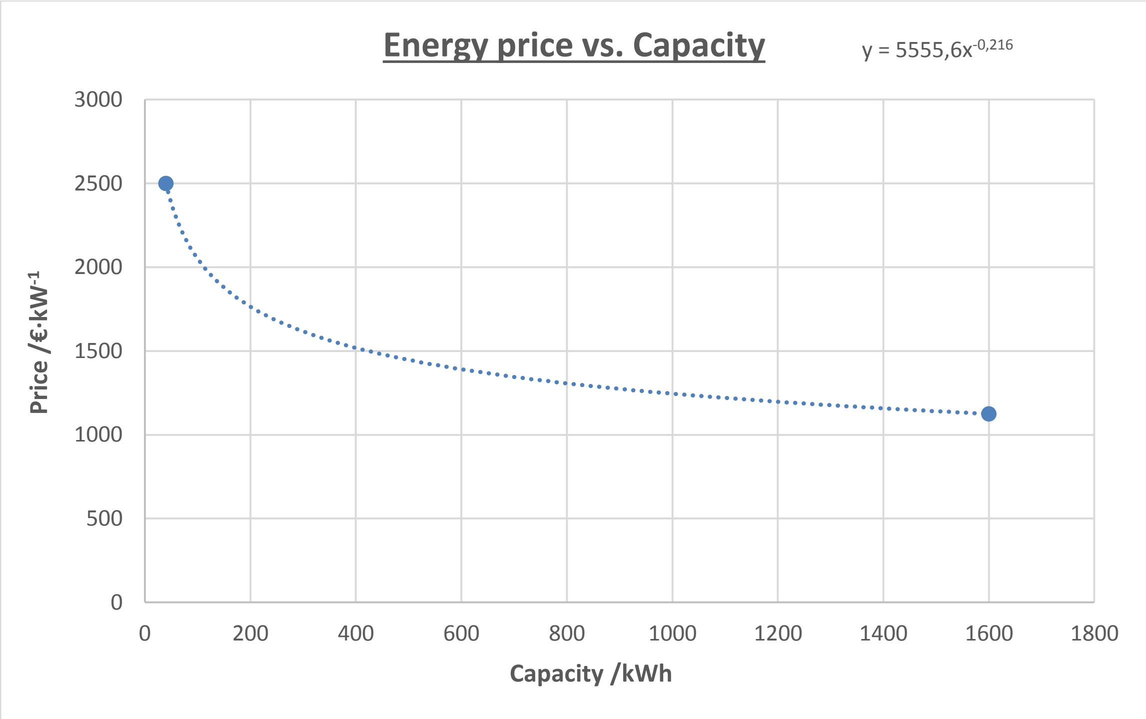

Figure 5.26: Energy price vs. Capacity.

With the potential equation, the price per kWh for the rest of capacities has been calculated in the Table 5.6.

$$\text{Battery price user per kWh} = 5555{,}6 \cdot \text{Battery capacity}^{-0{,}216}$$

where:

Battery price user per kWh = price (€/kWh) of the battery. This price is calculated by the program depending on the battery features which has been introduced by the user.

Table 5.6: Energy prices in €·kWh^{-1} for all the range of capacities.

Capacity / kWh	40	70	100	130	400	800	1600
Price /€·kWh^{-1}	2504,2	2219,1	2054,6	1941,4	1522,9	1311,1	1128,8

Multiplying the battery price per kWh by the battery capacity, the following Table 5.7 is obtained.

Table 5.7: Prices in € for all the range of capacities.

Capacity /kWh	40	70	100	130	400	800	1600
Price /€	100171	155341	205461	252384	609180	1048946	1806180

The Figure 5.27 has been created from the Table 5.7.

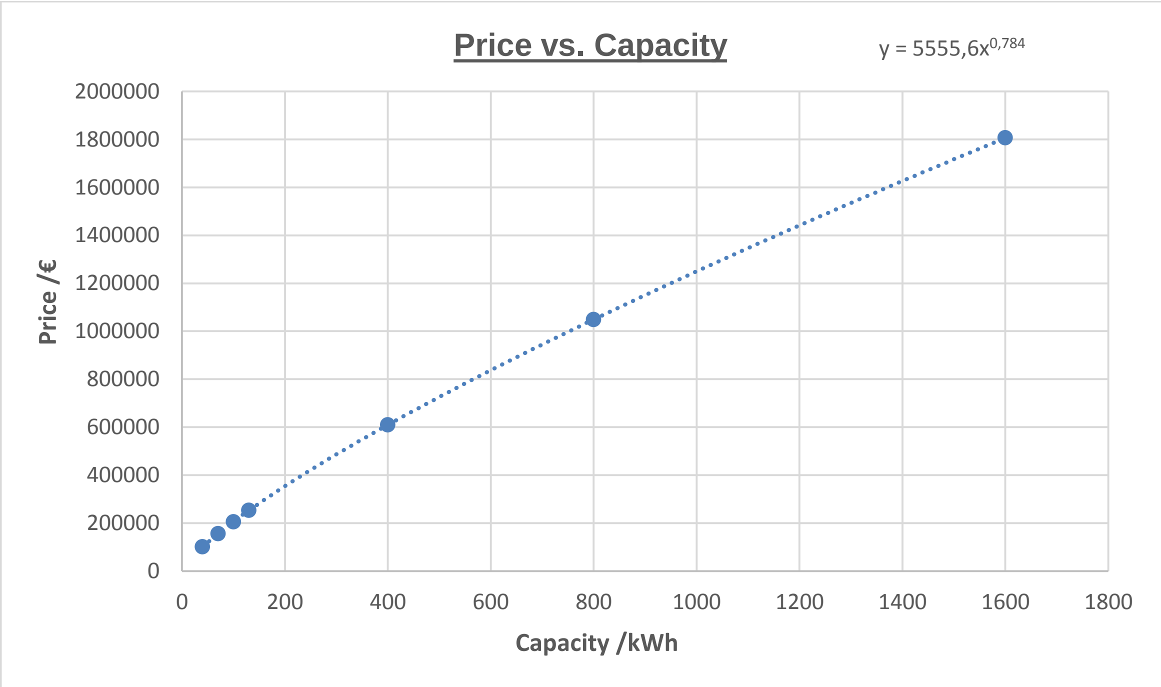

Figure 5.27: Price vs Capacity

To obtain the final equation and, thus, to know the battery price for the user, the data have been adjusted to a potential equation (dotted line), as shown in Figure 5.27.

$$\text{Battery price user} = 5555{,}6 \cdot \text{Battery capacity}^{0{,}784}$$

where:

Battery price user = price (€) of the battery, that is calculated by the program, from the battery characteristics which the user has introduced.

Battery capacity (kWh).

5.2.14.2 CHP Heat Power

CHP heat power is calculated as follows:

$$\text{CHP heat power} = \text{CHP max} \cdot 1{,}2$$

where:

CHP heat power (W).

CHP max = maximum electric power of the CHP (W).

The number 1,2 has been taken because the CHP heat power is normally 1,2 times the CHP max (CHP max is the nominal electric CHP power) [1].

5.2.14.3 CHP Heat and Electric Efficiencies

CHP heat efficiency, always takes the default value 49 % [2].
CHP electric efficiency, is an input data that must be introduced by the user.

5.2.15 Program Results Script

In this script some images and Excel files are automatically created by the Matlab program. All of them are inside a folder called “RESULTS WITH DEFAULT DATA”. At first, six different images are generated. On the top of each one, a graph appears with the CHP, grid supply, charge battery, PV (if it is enabled) and discharge battery data. On the bottom, there is another graph with the state of charge of the battery.

The graphs have been obtained from six simulations with different values of the following parameters:

CHP max = maximum power of the CHP (W).
max discharge power = maximum discharge power of the battery (W).

In the first three graphs, the value of the CHP max is the average of the load data divided by *three* and the max discharge power of the battery is calculated as follows:

First graph: → $\text{max discharge power} = 0{,}10 \cdot \text{maximum load value}$

Second graph: → $\text{max discharge power} = 0{,}15 \cdot \text{maximum load value}$

Third graph: → $\text{max discharge power} = 0{,}20 \cdot \text{maximum load value}$

In the second three graphs, the value of the CHP max is the average of the load data divided by *four* and the max discharge power is calculated as above:

Fourth graph: → $\text{max discharge power} = 0{,}10 \cdot \text{maximum load value}$

Fifth graph: → $\text{max discharge power} = 0{,}15 \cdot \text{maximum load value}$

Sixth graph: → $\text{max discharge power} = 0{,}20 \cdot \text{maximum load value}$

At the end, two Excel files are created, and inside of each one there are three Excel sheets which depend on the maximum discharge power of the battery.
The first one contains all the parameters, data, prices and cost calculations made with the first CHP power value, and the second one the same, but with the second CHP power value.

5.2.16 Program Results 2 Script

In this script, an image and an Excel file can be found inside of the folder “YOUR OWN RESULTS”. Both of them have the same format as in the case of the previous script, and the information shown has been calculated in the same way, but from the introduced data by the user.

5.3 Graphical User Interface

In order to help an inexperienced MTLAB user to run the simulation of the model, a Graphical User Interface is built (GUI).

But, first of all, the user has to make an Excel sheet with the load data of the industry that it wants to simulate, or to copy the data into the data_company file, which is already made. It is important to make sure that the first column corresponds to the power data, and the second one to the PV data, both in kilowatts.

Furthermore, some parameters have to be adjusted in Simulink in order to get the suitable results. The steps to set the parameters are the following:

1. Open the folder Matlab Simulink Program.
2. Double click on Simulink program file. Next screen has to appear:

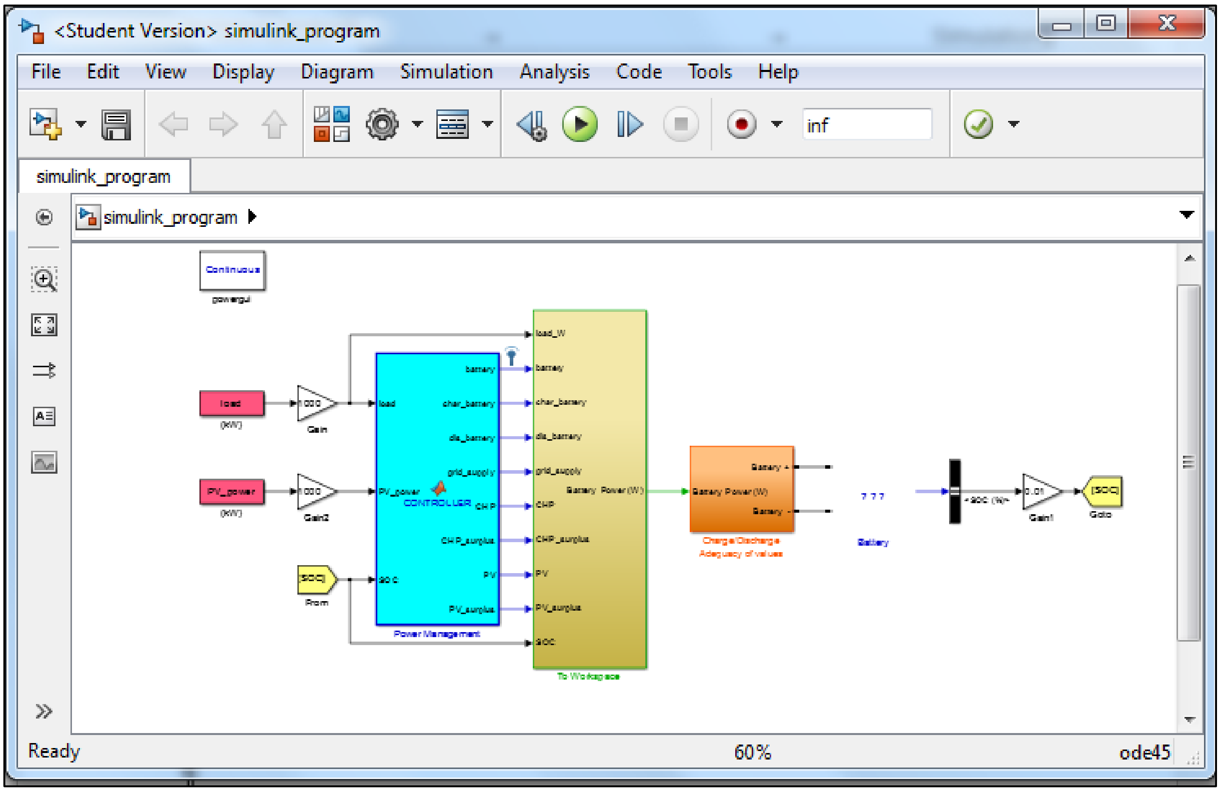

Figure 5.28: Window of the Simulink program file.

3. Click on the settings icon.

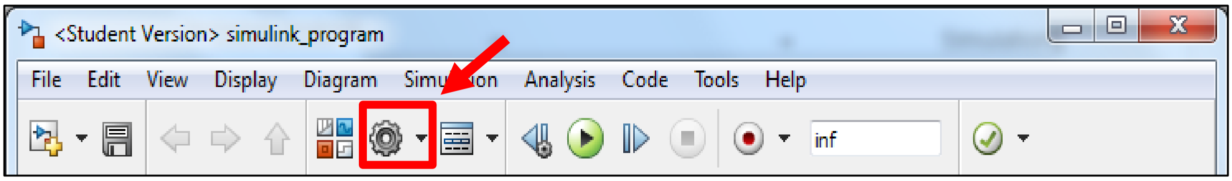

Figure 5.29: Settings icon.

4. Configuration parameters window appears. Select Diagnostics and Connectivity.

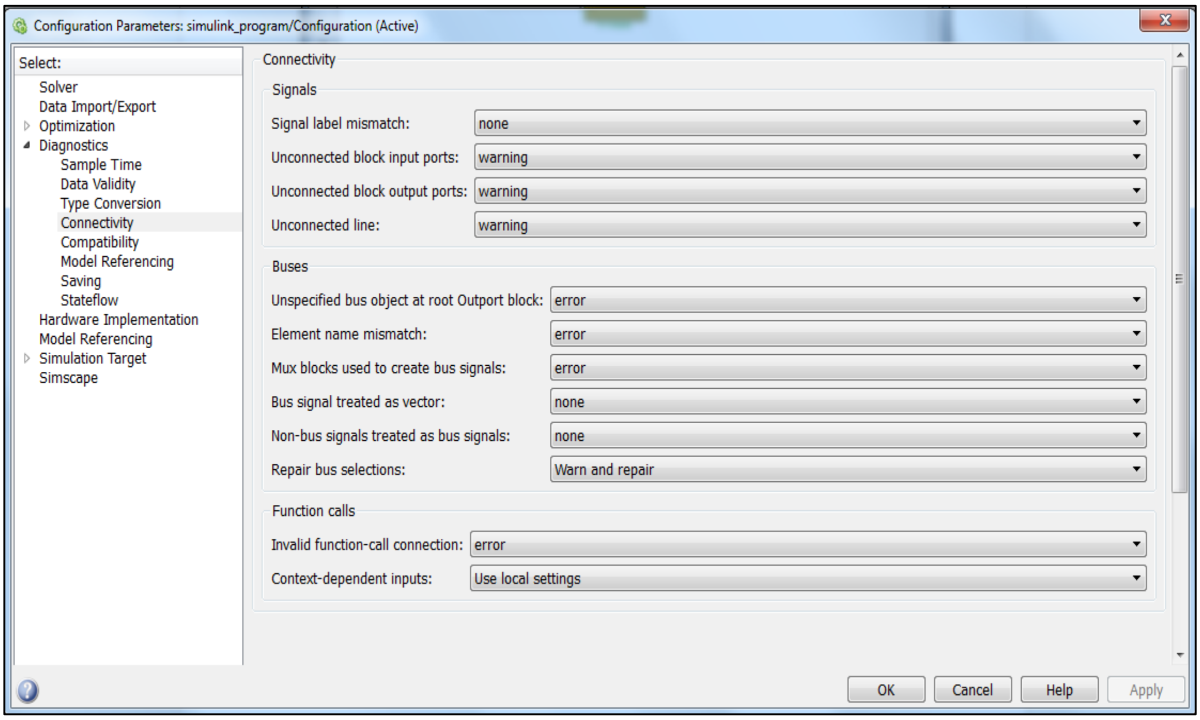

Figure 5.30: Configuration parameters window.

In this window, the following parameters have to be selected.

Table 5.8: Connectivity parameters selected.

Connectivity	**1**	**2**
SIGNALS	Signal label mismatch	none
	Unconnected block input ports	warning
	Unconnected block output ports	warning
	Unconnected line	warning
BUSES	Unspecified bus object at root Outport block	error
	Element name mismatch	error
	Mux blocks used to create bus signals	error
	Bus signal treated as vector	none
	Non-bus signals treated as bus signals	none
	Repair bus selections	Warn and repair
FUNCTION CALLS	Invalid function-call connection	error
	Context-dependent inputs	Use local set-tings

5. Click on OK button and SAVE the model.

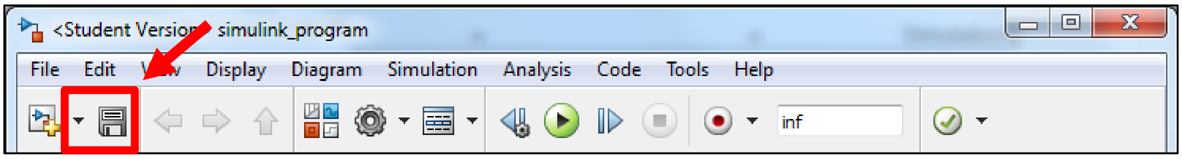

Figure 5.31: Save the settings.

6. Repeat the entire process for the Capacity Simulink Program file.

Once everything is ready for the simulation, the user can close all the windows. If the user closes Matlab, he has to look for the "main program" file in the Matlab Simulink program folder in order to run the simulation. Otherwise, if the user does not close Matlab, he has to look for the "main program" file which is on the "current folder" of Matlab.

Afterwards, several menus and dialog windows are displayed by the GUI. The user has to select the options desired and enter the requested data when they are required.

In the following, some screenshots are presented in order to see the operation of the GUI.

Firstly, after the program run, the window which is shown in the Figure 5.32 appears in order to select the file with the company data.

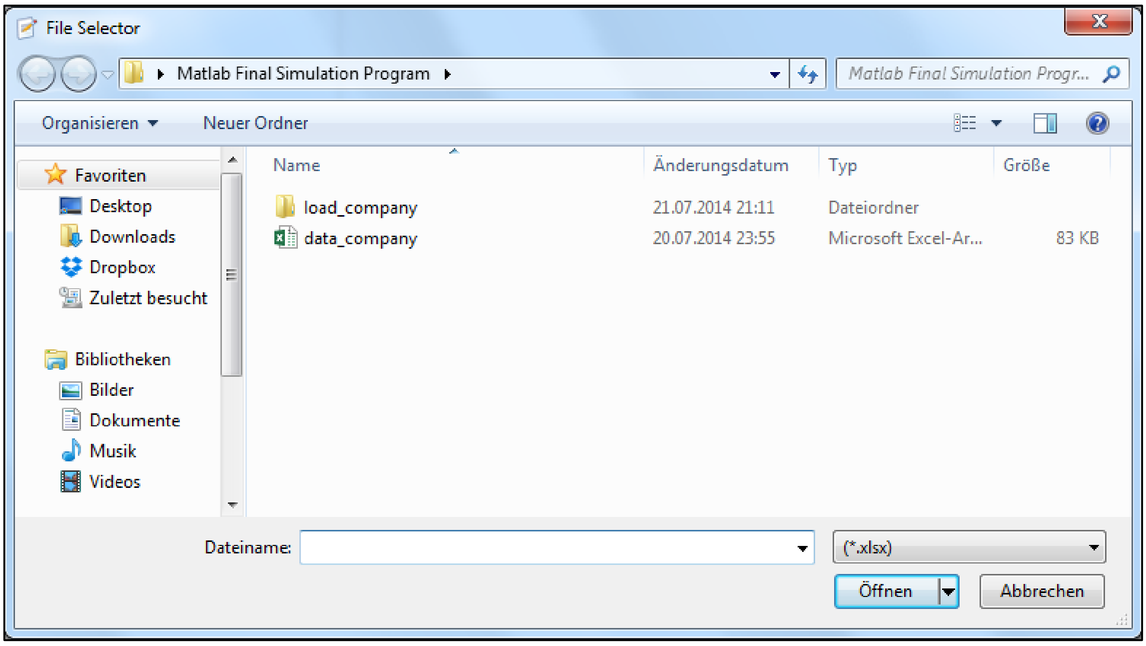

Figure 5.32: Window to select the excel with the company data.

Then, the following windows sequence shows up. The first one is:

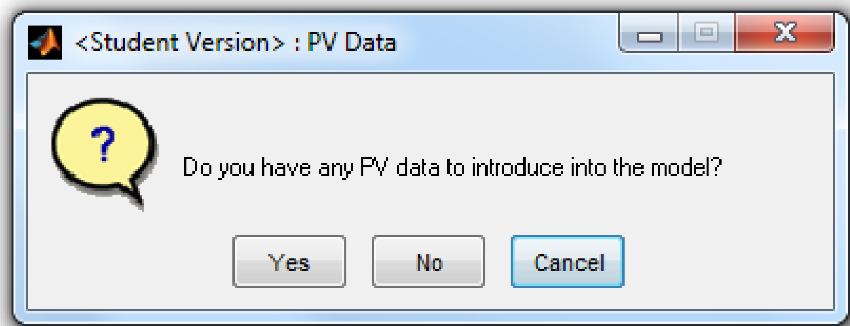

Figure 5.33: PV Data window.

If the user clicks on "yes":

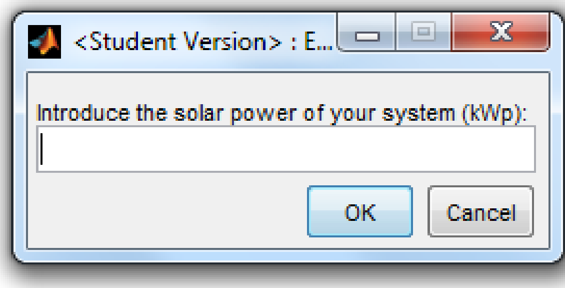

Figure 5.34: Enter the following data window.

If this window has already appeared before, then the value is kept and assigned as a default value. It can be changed by the user. Note that the decimal figures are expressed using a point.

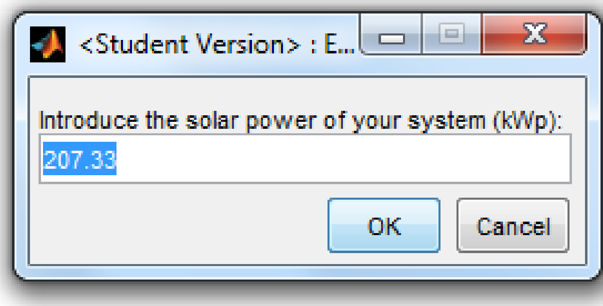

Figure 5.35: Enter the solar power window with a default value.

Figure 5.36 is the next window. This window will also appear if the user clicks on "no" in the first window, Figure 5.33: PV Data window.

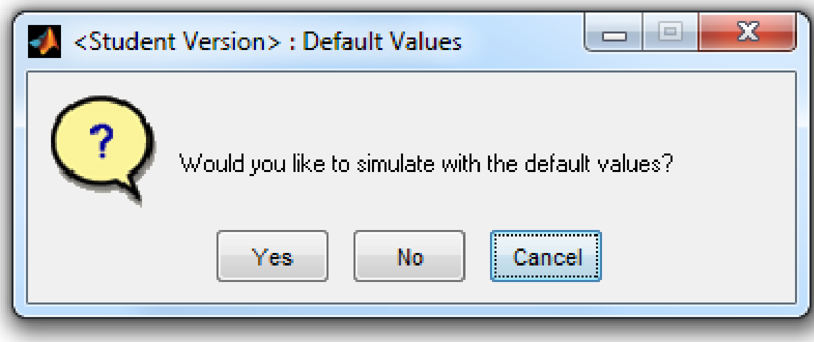

Figure 5.36: Default values window.

If the user clicks on " yes", Figure 5.37 appears and the time step has a default value of 15 minutes.

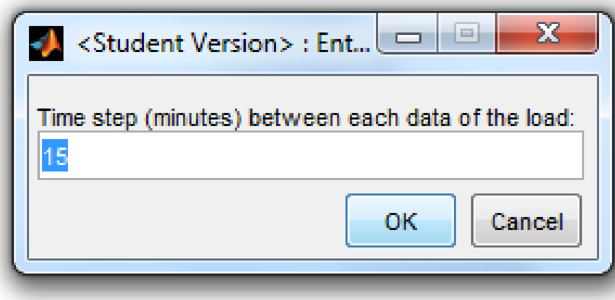

Figure 5.37: Enter the time step window.

If the user selects "no" in the "default values" window, Figure 5.36, the following window appears:

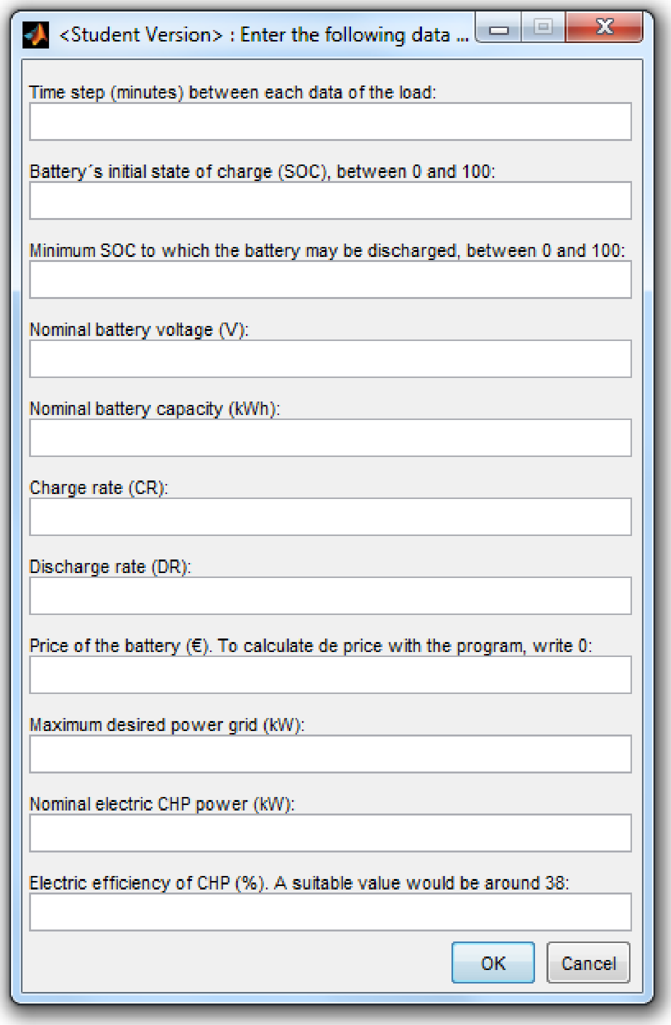

Figure 5.38: Individual user values selection window.

As in the previous windows, if the user has already entered her/his data, in the next simulation these data will be assigned as default values.They can be changed by the user.

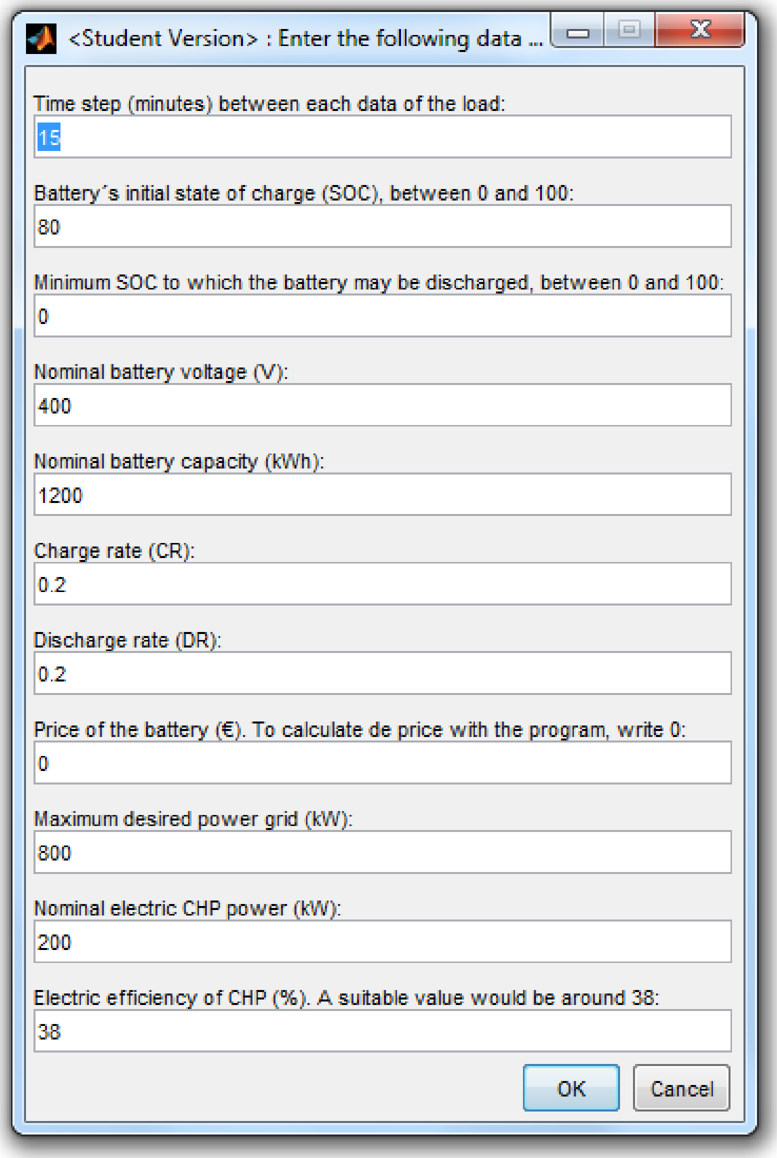

Figure 5.39: Default user values window.

If the button Cancel is selected on one of these windows, the following message appears, Figure 5.40. In his case, the simulation will not be started but cancelled.

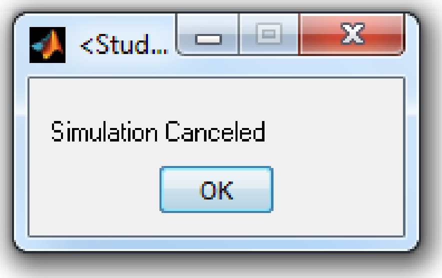

Figure 5.40: Simulation canceled window.

After having filled in all the fields, the simulation starts automatically and a progress bar is displayed to inform about the estimated remaining time.

.

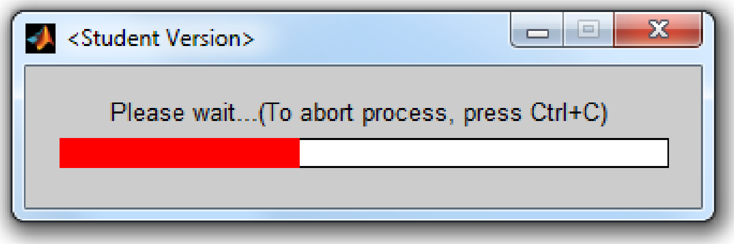

Figure 5.41: Progress bar window.

When the simulation is done, the next window is displayed, see Figure 5.42.

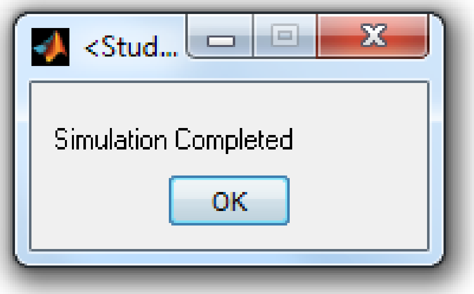

Figure 5.42: Simulation completed window.

Finally, once the simulation process is completed, a new folder is created and saved automatically into the "Matlab simulation program" folder. Depending on the simulation type, if the values have been entered as a default values or by the user, the folder has different names. For a default values simulation, the folder which contains the results is called "RESULTS WITH DEFAULT DATA". Otherwise, the folder is called "YOUR OWN RESULTS". This folder can be renamed later according to the user´s needs.

In the folder called "YOUR OWN RESULTS", there are an Excel file and a graph. The data entered by the user and an economic balance are saved in the excel file. The different parts of the economic balance have already mentioned on the Prices Script. The power balance of the simulation is shown in that graph.

Finally, in the "RESULTS WITH DEFAULT DATA" folder, there are two Excel files and six different graphs. The Excel files contain the parameters calculated by the program, for the battery, CHP and for the grid. Thus, as in the previous folder, an economic balance is obtained.

This folder has two Excel files because the simulation is performed with two different CHP powers. Moreover, for each simulation, three different batteries are selected. As a consequence, each Excel file has three Excel sheets with the different parameters and economic balances. For this very reason, for the power balances, six graphs are obtained.

6 Results

In order to show the good operation of the simulation, the load of a company has been introduced into the program.

The power consumption of the company is simulated for a day to see more clearly the results of the graphs. Note that within the box, the main features of the simulation are shown, they are variables inside of the program.

In the following tables result, the program shows, first of all, the parameters used during the simulation with their corresponding values. Secondly, one can see the power and energy cost of each component and the benefit if they provide benefit. The third table shows the costs of supply all the load with the grid, in other words, without any more component apart from the grid. Finally, the fourth table is a table which includes the payback time for the system.

6.1 Battery Provides Power to the Load

In the first simulation, the system uses the power from grid, and from the battery to supply the required load. The default values have been selected in order to show better how the program works. The following results have been obtained for a Redox Flow Battery.

6.1.1 Battery Power 10 % of the Maximum Power

Battery discharge power = 10 % maximum power peak

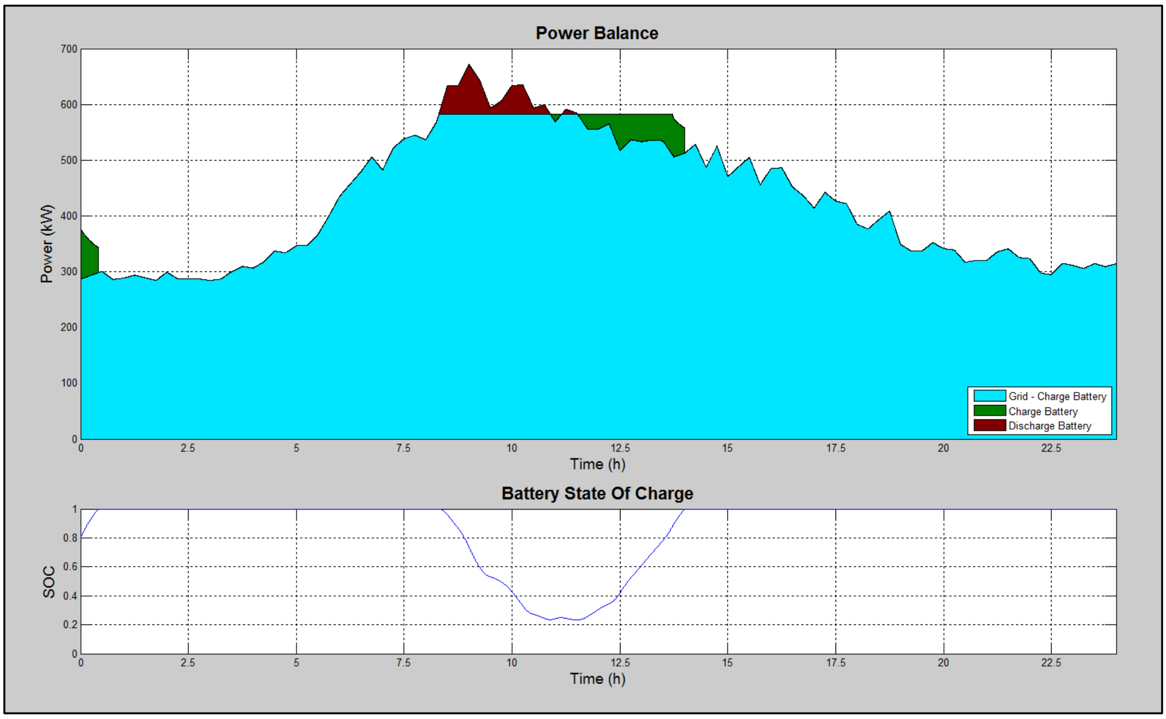

Figure 6.1: Power balance with battery power, 10 % of the maximum power I.

Table 6.1: Data with battery power, 10 % of the maximum power I.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	100	kWh
Charge Rate	0,6	1/h
Discharge Rate	0,6	1/h
Maximum Discharge Power of the Battery	60	kW
Maximum Desired Power Grid	582	kW
Number of days	1	day

Table 6.2: Grid and battery to provide all load without battery I.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	582	kW
	Total Power Cost	100,45	€
ENERGY			
	Energy Price	0,015	€/kWh
	Total Energy Cost	1534,36	€
BATTERY			
	Battery Price	267500	€

Table 6.3: Grid to provide all the load. Battery power, 10 % of the maximum power I.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	671,92	kW
	Total Power Cost	115,97	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	1534,36	€

Table 6.4: Summary with battery power, 10 % of the maximum power I.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	1634,81	€
	Investment	267500	€
GRID SUPPLIES ALL LOAD			
	Money to pay	1650,33	€
PAY-BACK TIME		47,22	years

6.1.2 Battery Power 15 % of the Maximum Power

Battery discharge power = 15 % maximum power peak

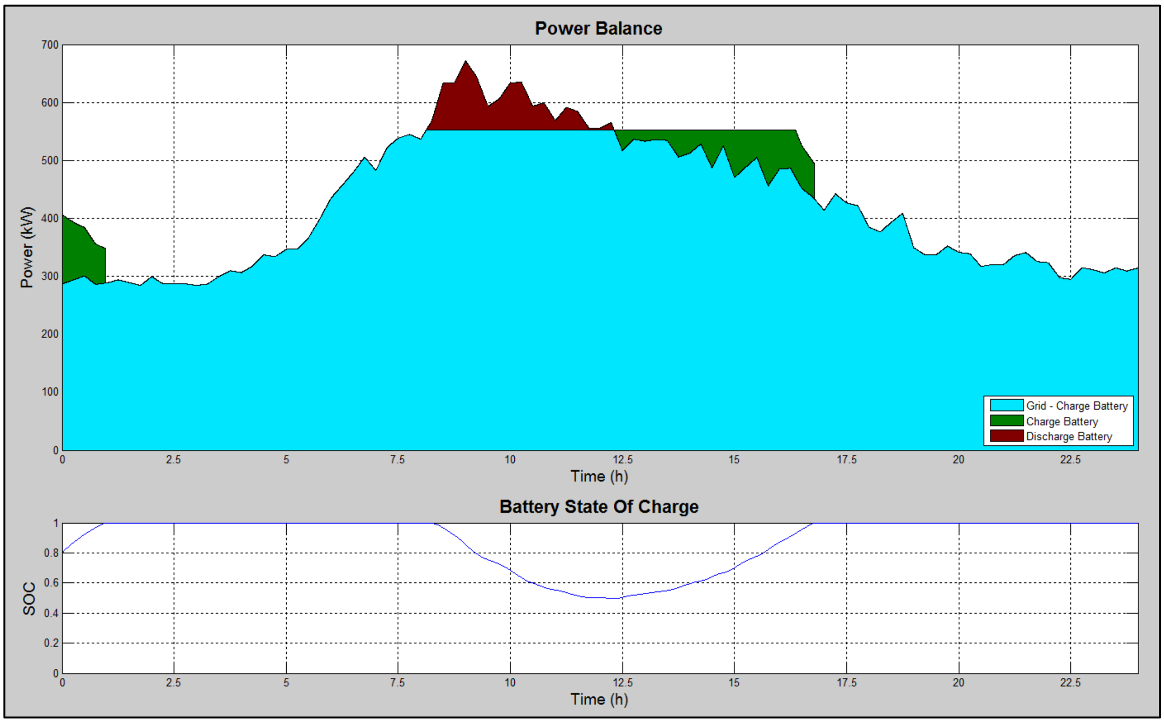

Figure 6.2: Power balance without PV (battery) I.

Table 6.5: Data with battery power, 15 % of the maximum power II.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	130	kWh
Charge Rate	0,69	1/h
Discharge Rate	0,69	1/h
Maximum Discharge Power of the Battery	90	kW
Maximum Desired Power Grid	552	kW
Number of days	1	day

Table 6.6: Grid and battery to provide all load. Battery power, 15 % of the maximum power II.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	552	kW
	Total Power Cost	95,28	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	1534,36	€
BATTERY			
	Battery Price	390132	€

Table 6.7: Grid to provide all the load. Battery power, 15 % of the maximum power II.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	671,96	kW
	Total Power Cost	115,98	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	1534,36	€

Table 6.8: Summary with battery power, 15 % of the maximum power II.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	1629,64	€
	Investment	390132	€
GRID SUPPLIES ALL LOAD			
	Money to pay	1650,34	€
PAY-BACK TIME		51,63	years

6.1.3 Battery Power 20 % of the Maximum Power

Battery discharge power = 20 % maximum power peak

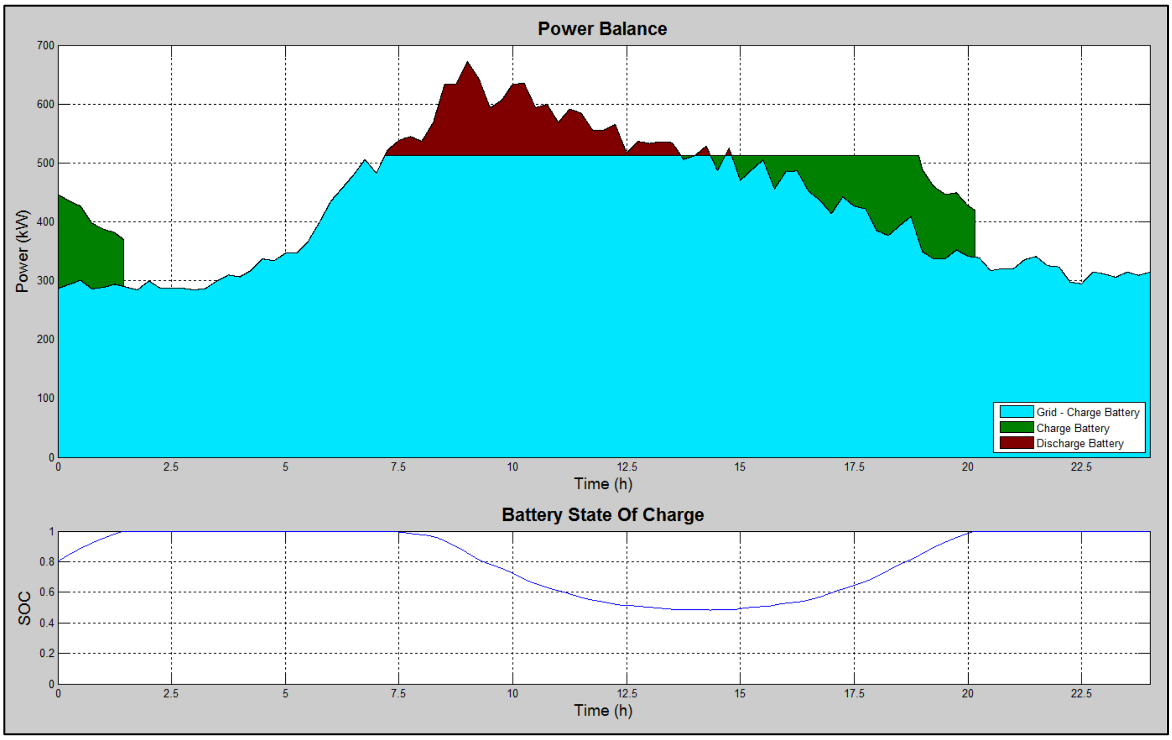

Figure 6.3: Power with battery power, 20 % of the maximum power III.

Table 6.9: Data with battery power, 20 % of the maximum power III.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	400	kWh
Charge Rate	0,3	1/h
Discharge Rate	0,3	1/h
Maximum Discharge Power of the Battery	120	kW
Maximum Desired Power Grid	512	kW
Number of days	1	day

Table 6.10: Grid and battery to provide all load with battery power, 20 % of the maximum power III.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	512	kW
	Total Power Cost	88,37	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	1534,36	€
BATTERY			
	Battery Price	624866	€

Table 6.11: Grid to provide all the load. Battery power, 20 % of the maximum power III.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	671,93	kW
	Total Power Cost	115,98	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	1534,36	€

Table 6.12: Summary with battery power, 20 % of the maximum power III.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	1622,73	€
	Investment	624866	€
GRID SUPPLIES ALL LOAD			
	Money to pay	1650,34	€
PAY-BACK TIME		62	years

On the basis of the simulation results obtained, it can be concluded that, in the industrial sector, the investment of a battery is no an economic solution, because the return of investment time by saving grid power cost is in the range of 45-60 years, for a Redox Flow Battery.

6.2 Grid, CHP and Battery provide Power to the Load

In this simulation, the system uses the power from the CHP, grid, and from the battery to supply the required load. In this case, the default values have been selected and the following results have been obtained.

In the whole paragraph the *threshold* is the sum of the nominal electric power of the CHP and the maximum desired power grid.

6.2.1 CHP 1/3 of Consumption, Battery 10 % of Max. Power

CHP electricity power = average consumption /3

Battery discharge power = 10 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery.*

Threshold = 1 429,1 kW

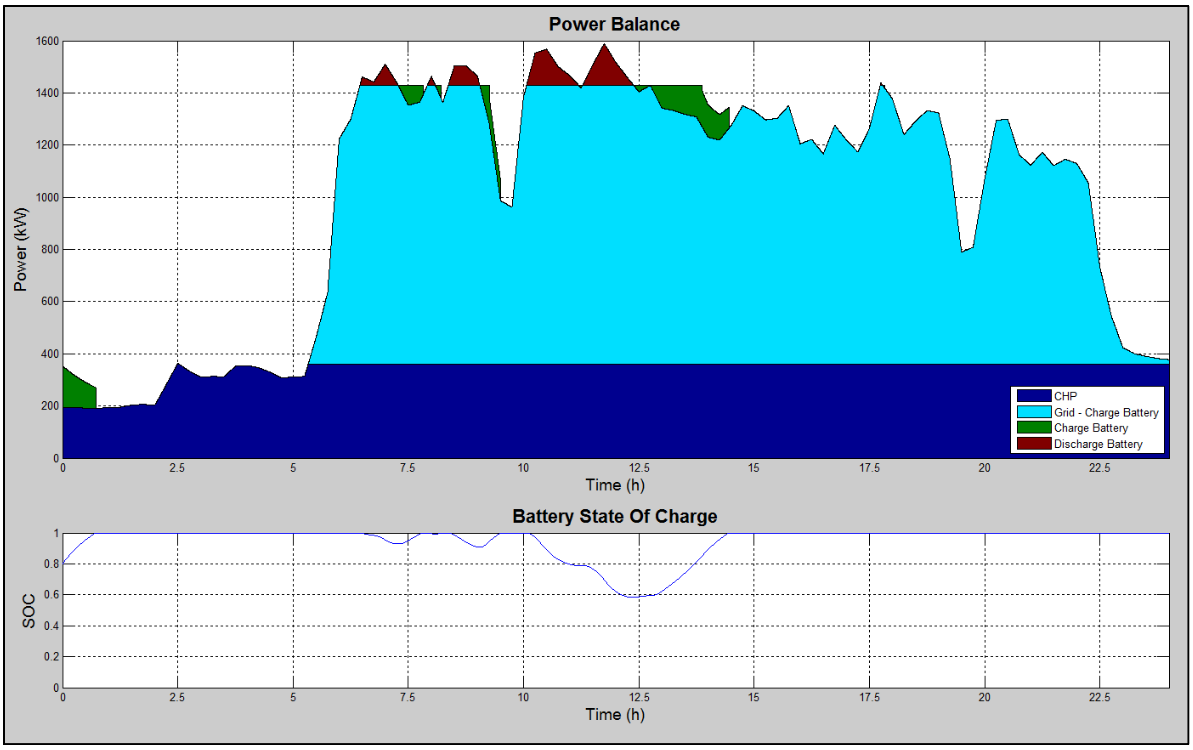

Figure 6.4: Power balance. CHP 1/3 of consumption. Battery 10 % of Max.Power. Without PV I.

Table 6.13: Data. CHP 1/3 of consumption. Battery 10 % Max.Power. Without PV I.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	400	kWh
Charge Rate	0,4	1/h
Discharge Rate	0,4	1/h
Maximum Discharge Power of the Battery	160	kW
Maximum Desired Power Grid	1069,1	kW
Nominal el. CHP Power	360	kW
CHP electric efficiency	42,5	%
CHP heat Power	389	kW
CHP heat efficiency	46	%
Number of days	1	day

Table 6.14: Grid, Battery and CHP to provide load. CHP 1/3 consumption. Battery 10 % of Max.Power. Without PV I.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1069,1	kW
	Total Power Cost	184,52	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2371,88	€
BATTERY			
	Battery Price	738226	€
CHP			
INVESTMENT			
	CHP Price	222635,32	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	39	€
ELECTRICITY AND HEAT			
	Electricity Price	0,042	€/kWh
	Total Electric Cost	367,68	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	466,8	€

Table 6.15: Grid provides load. CHP 1/3 consumption. Battery 10 % of Max.Power. Without PV I

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,80	kW
	Total Power Cost	274,23	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.16: Summary. CHP 1/3 consumption. Battery 10 % of Max.Power. Without PV I.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	2885,09	€
	Investment	960861,32	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,81	€
PAY-BACK TIME		2,66	years

6.2.2 CHP 1/3 of Consumption, Battery 15 % of Max. Power

CHP electricity power = average consumption /3

Battery discharge power = 15 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1 329,1 kW

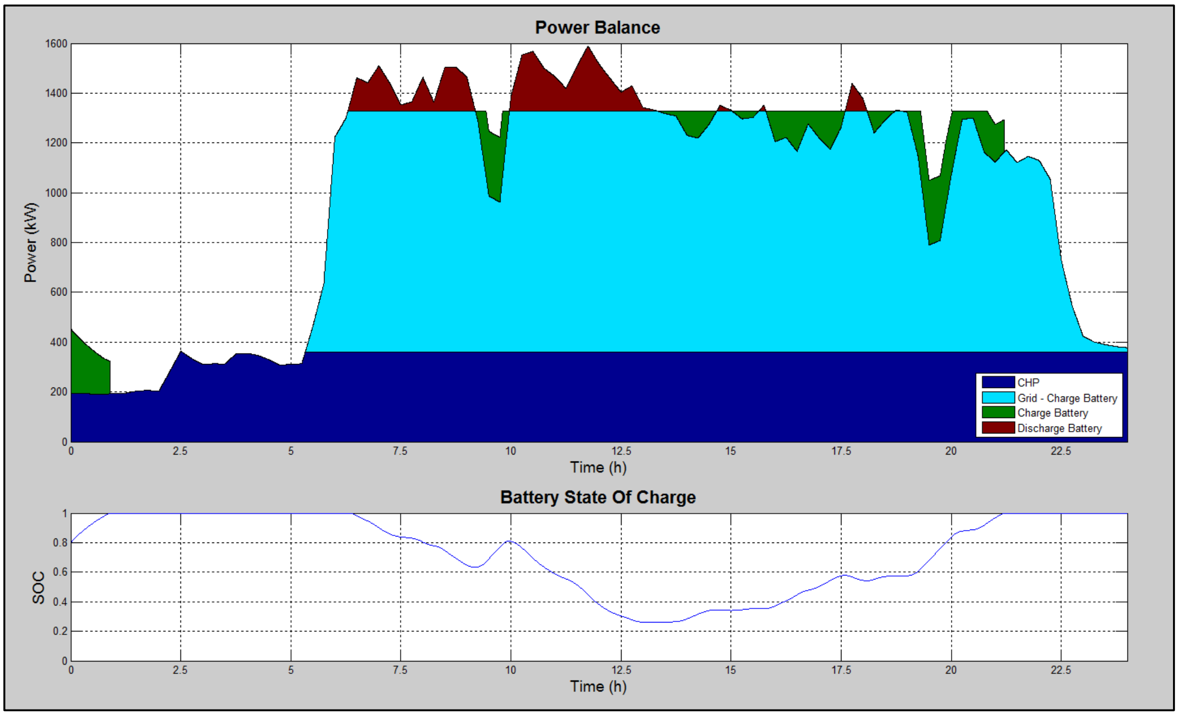

Figure 6.5: Power balance. CHP 1/3 of consumption. Battery 15 % of Max.Power. Without PV II.

Table 6.17: Data. CHP 1/3 of consumption. Battery 15 % of Max.Power. Without PV II.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	800	kWh
Charge Rate	0,325	1/h
Discharge Rate	0,325	1/h
Maximum Discharge Power of the Battery	260	kW
Maximum Desired Power Grid	969,1	kW
Nominal el. CHP Power	360	kW
CHP electric efficiency	42,5	%
CHP heat Power	389	kW
CHP heat efficiency	46	%
Number of days	1	day

Table 6.18: Grid, Battery and CHP provide load. CHP 1/3 consumption. Battery 15 % of Max.Power. Without PV II.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	969,1	kW
	Total Power Cost	167,26	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2374,50	€
BATTERY			
	Battery Price	1437427	€
CHP			
INVESTMENT			
	CHP Price	222635,32	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	32,09	€
ELECTRICITY AND HEAT			
	Electricity Price	0,042	€/kWh
	Total Electric Cost	367,68	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	466,8	€

Table 6.19: Grid provides load. CHP 1/3 consumption. Battery 15 % of Max.Power. Without PV II.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,80	kW
	Total Power Cost	274,23	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.20: Summary. CHP 1/3 consumption. Battery 15 % of Max.Power. Without PV II.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	2877,36	€
	Investment	1660062,32	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,82	€
PAY-BACK TIME		4,56	years

6.2.3 CHP 1/3 of Consumption, Battery 20 % of Max. Power

CHP electricity power = average consumption /3

Battery discharge power = 20 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1 269,1 kW

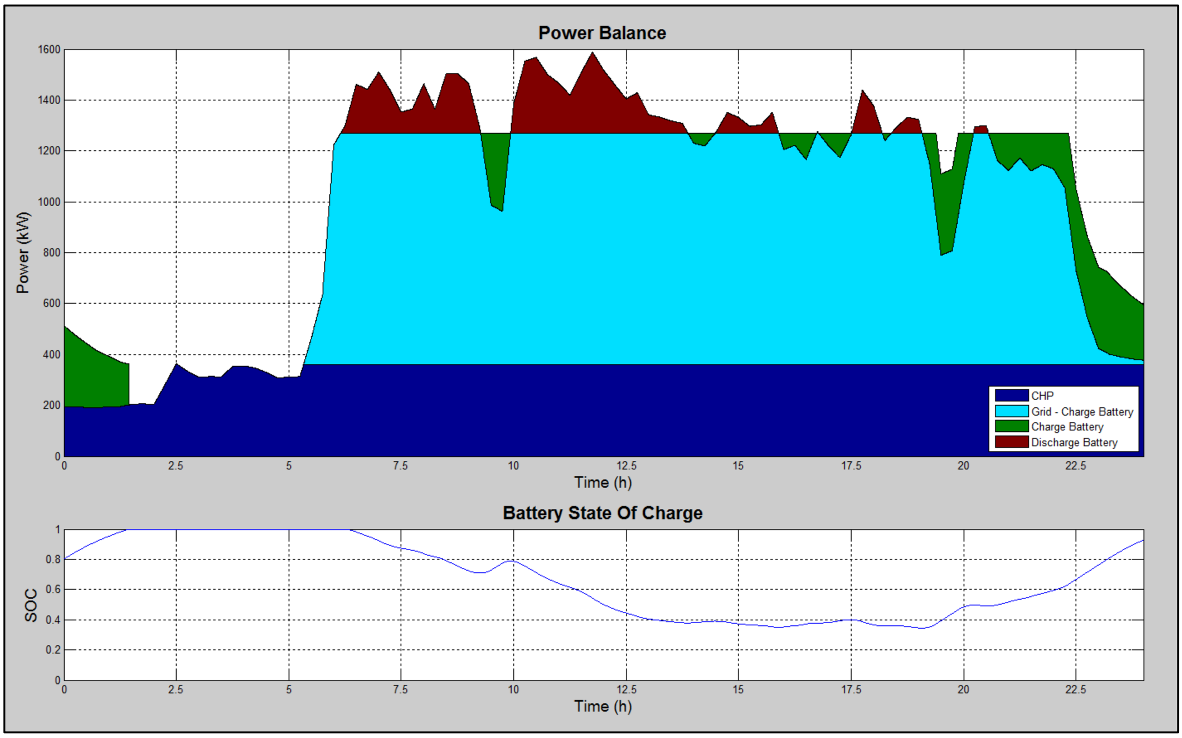

Figure 6.6: Power balance. CHP 1/3 of consumption. Battery 20 % of Max.Power. without PV III.

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Table 6.21: Data. CHP 1/3 of consumption. Battery 20 % of Max.Power. Without PV III.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	1600	kWh
Charge Rate	0,2	1/h
Discharge Rate	0,2	1/h
Maximum Discharge Power of the Battery	320	kW
Maximum Desired Power Grid	909,1	kW
Nominal el. CHP Power	360	kW
CHP electric efficiency	42,5	%
CHP heat Power	389	kW
CHP heat efficiency	46	%
Number of days	1	days

Table 6.22: Grid, Battery and CHP provide the load. CHP 1/3 consumption. Battery 20 % of Max.Power. Without PV III

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	909,1	kW
	Total Power Cost	156,91	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2367,62	€
BATTERY			
	Battery Price	2447266	€
CHP			
INVESTMENT			
	CHP Price	222635,32	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	22,51	€
ELECTRICITY AND HEAT			
	Electricity Price	0,042	€/kWh
	Total Electric Cost	367,68	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	466,8	€

Table 6.23: Grid provides load. CHP 1/3 consumption. Battery 20 % of Max.Power. Without PV III.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,91	kW
	Total Power Cost	274,25	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.24: Summary. CHP 1/3 consumption. Battery 20 % of Max.Power. Without PV III.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	2869,71	€
	Investment	2669901,32	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,83	€
PAY-BACK TIME		7,28	years

6.2.4 CHP 1/4 of Consumption, Battery 10 % of Max. Power

CHP electricity power = average consumption /4

Battery discharge power = 10 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1 429,1 kW

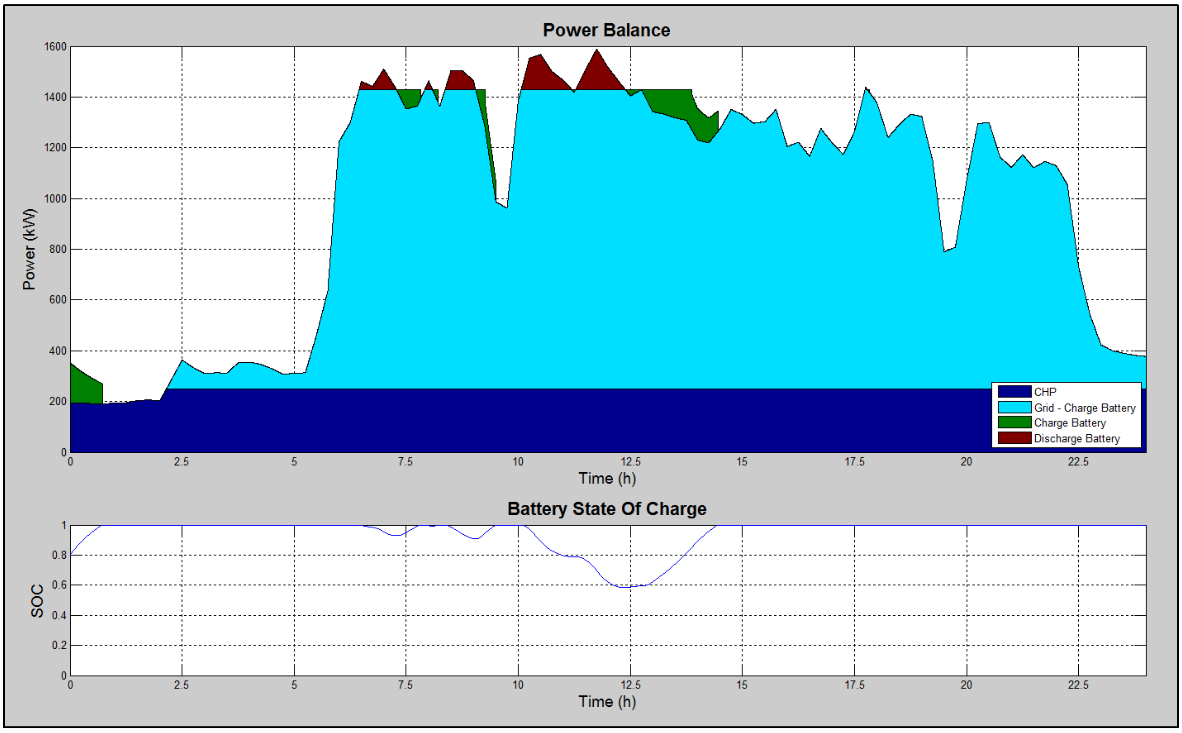

Figure 6.7: Power balance. CHP 1/4 of consumption. Battery 10 % of Max. Power. Without PV IV.

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Table 6.25: Data. CHP 1/4 of consumption. Battery 10 % of Max. Power. Without PV IV.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	400	kWh
Charge Rate	0,4	1/h
Discharge Rate	0,4	1/h
Maximum Discharge Power of the Battery	160	kW
Maximum Desired Power Grid	1179,1	kW
Nominal el. CHP Power	250	kW
CHP electric efficiency	37,5	%
CHP heat Power	312	kW
CHP heat efficiency	46,8	%
Number of days	1	day

Table 6.26: Grid, Battery and CHP provide the load CHP 1/4 of consumption. Battery 10 % of Max. Power. Without PV IV.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1179,1	kW
	Total Power Cost	203,51	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2722,45	€
BATTERY			
	Battery Price	738226	€
CHP			
INVESTMENT			
	CHP Price	182916,34	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	7,20	€
ELECTRICITY AND HEAT			
	Electricity Price	0,054	€/kWh
	Total Electric Cost	328,13	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	374,4	€

Table 6.27: Grid provides load. CHP 1/4 consumption. Battery 10 % of Max. Power. Without PV IV..

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,80	kW
	Total Power Cost	274,23	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.28: Summary. CHP 1/4 of consumption. Battery 10 % of Max. Power. Without PV IV.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	3246,89	€
	Investment	921142,34	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,81	€
PAY-BACK TIME		4,02	years

6.2.5 CHP 1/4 of Consumption, Battery 15 % of Max. Power

CHP electricity power = average consumption /4

Battery discharge power = 15 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1 329,1 kW

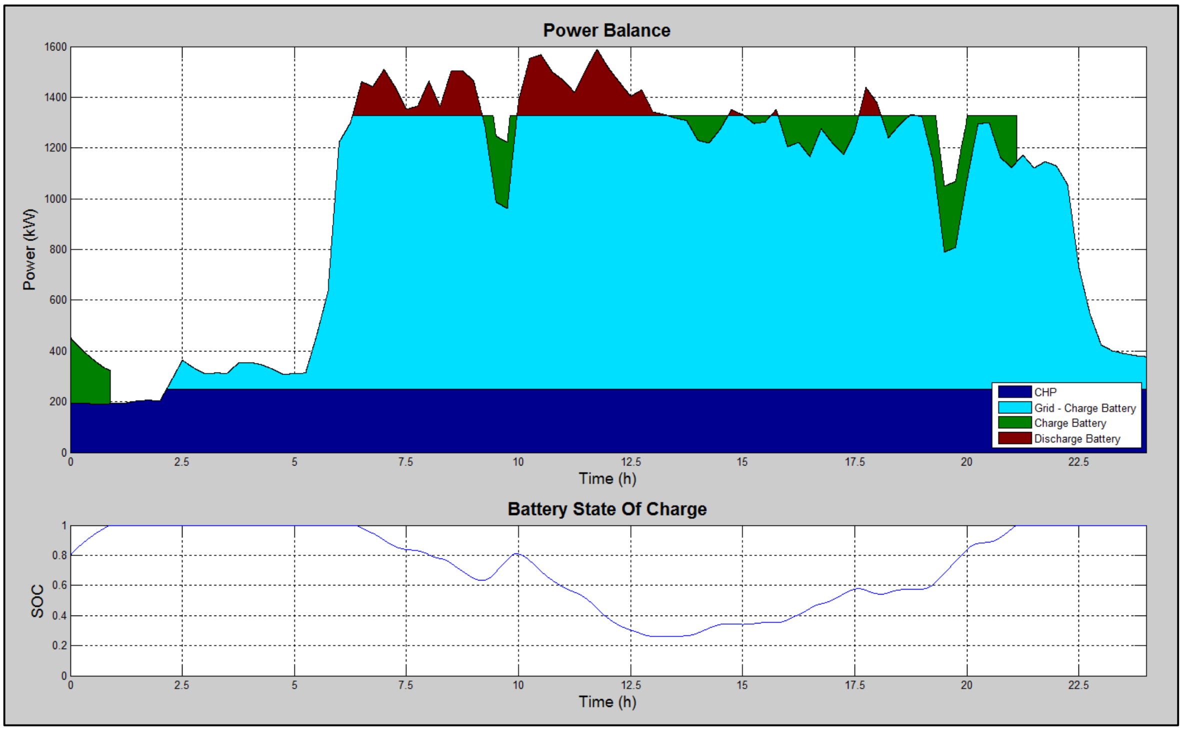

Figure 6.8: Power balance. CHP 1/3 of consumption. Battery 15 % of Max.Power. Without PV V.

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Table 6.29: Data. CHP 1/3 of consumption. Battery 15 % of Max.Power. Without PV V.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	800	kWh
Charge Rate	0,325	1/h
Discharge Rate	0,325	1/h
Maximum Discharge Power of the Battery	260	kW
Maximum Desired Power Grid	1079,1	kW
Nominal el. CHP Power	250	kW
CHP electric efficiency	37,5	%
CHP heat Power	312	kW
CHP heat efficiency	46,8	%
Number of days	1	day

Table 6.30: Grid, Battery and CHP provide the load. CHP 1/3 of consumption. Battery 15 % of Max.Power. Without PV V.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1079,1	kW
	Total Power Cost	186,25	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2733,48	€
BATTERY			
	Battery Price	1437427	€
CHP			
INVESTMENT			
	CHP Price	182916,34	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	6,18	€
ELECTRICITY AND HEAT			
	Electricity Price	0,054	€/kWh
	Total Electric Cost	328,13	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	374,4	€

Table 6.31: Grid provides load. CHP 1/3 of consumption. Battery 15 % of Max.Power. Without PV V.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,85	kW
	Total Power Cost	274,24	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.32: Summary. CHP 1/3 of consumption. Battery 15 % of Max.Power. Without PV V.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	3241,69	€
	Investment	1620343,34	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,82	€
PAY-BACK TIME		7,02	years

6.2.6 CHP 1/4 of Consumption, Battery 20 % of Max. Power

CHP electricity power = average consumption /4

Battery discharge power = 20 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1 269,1 kW

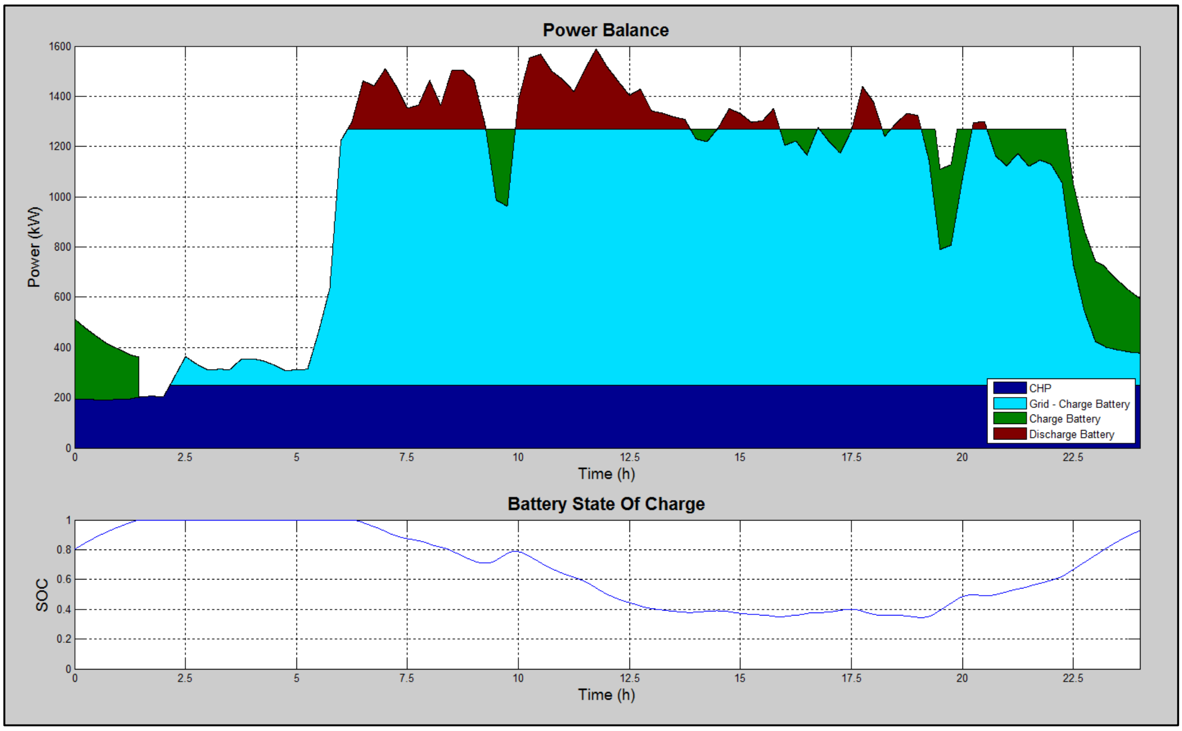

Figure 6.9: Power balance. CHP 1/3 of consumption. Battery 20 % of Max.Power. Without PV VI.

Table 6.33: Data. CHP 1/3 of consumption. Battery 20 % of Max.Power. Without PV VI.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	1600	kWh
Charge Rate	0,2	1/h
Discharge Rate	0,2	1/h
Maximum Discharge Power of the Battery	320	kW
Maximum Desired Power Grid	1019,1	kW
Nominal el. CHP Power	250	kW
CHP electric efficiency	37,5	%
CHP heat Power	312	kW
CHP heat efficiency	46,8	%
Number of days	1	day

Table 6.34: Grid, Battery and CHP provide the load. CHP 1/3 of consumption. Battery 20 % of Max.Power. Without PV VI..

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1019,1	kW
	Total Power Price	175,89	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Price	2735,79	€
BATTERY			
	Battery Price	2447266	€
CHP			
INVESTMENT			
	CHP Price	182916,34	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	3,02	€
ELECTRICITY AND HEAT			
	Electricity Price	0,054	€/kWh
	Total Electric Cost	328,13	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	374,4	€

Table 6.35: Grid provides load. CHP 1/3 consumption. Battery 20 % of Max.Power. Without PV VI..

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,91	kW
	Total Power Cost	274,25	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.36: Summary .CHP 1/3 of consumption. Battery 20 % of Max.Power. Without PV VI.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	3236,79	€
	Investment	2630182,34	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,83	€
PAY-BACK TIME		11,31	years

In this case, the integration of a cogeneration system, working together with the battery, can provide additional savings, making the payback time shorter.

6.3 Grid, CHP, Battery and Solar Panels provide power to the load.

In this case, the consumption of the same company is simulated, but the company is supposed to possess some **solar panels** (207.33 kWp). As in the other case, the default values have been selected in order to show better how the program works. The following results have been obtained.

In the whole paragraph the *threshold* is the sum of the nominal electric power of the CHP and the maximum desired power grid.

6.3.1 CHP 1/3 of Consumption, Battery 10 % of Max. Power

CHP electricity power = average consumption /3

Battery discharge power = 10 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold =1 429,1kW

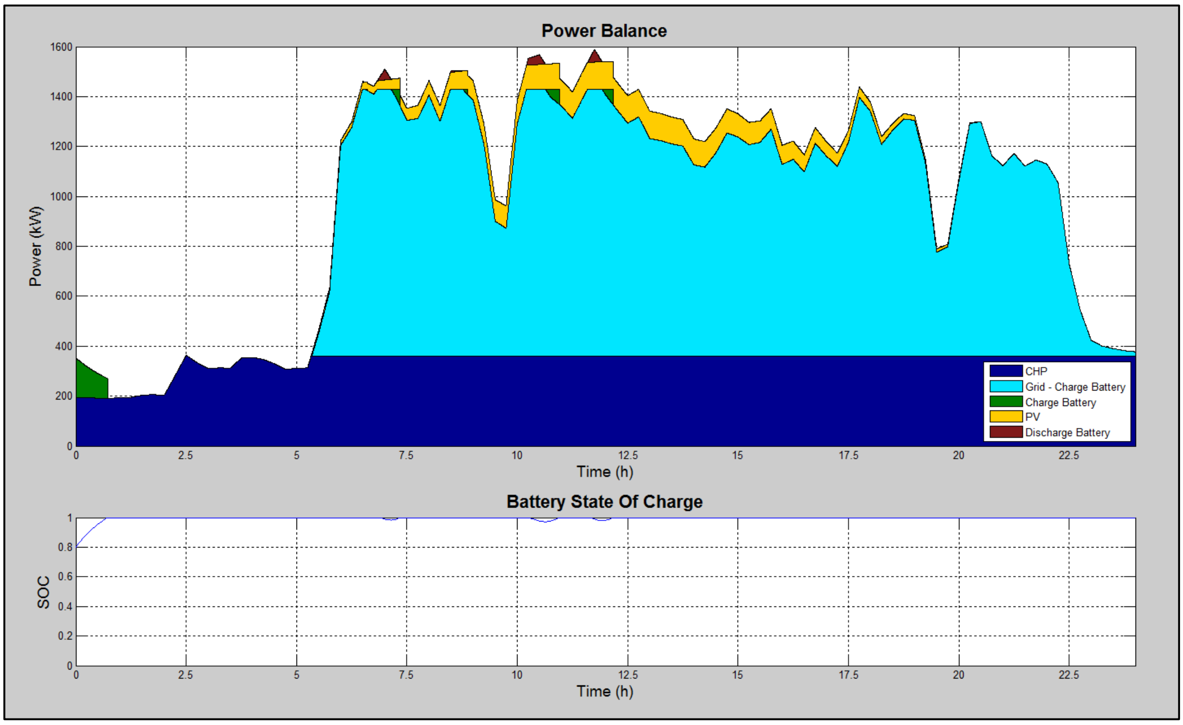

Figure 6.10: Power balance. CHP 1/3 of consumption. Battery 10 % of Max.Power. With PV I.

Table 6.37: Data. CHP 1/3 of consumption. Battery 10 % of Max.Power. With PV I.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	400	kWh
Charge Rate	0,4	1/h
Discharge Rate	0,4	1/h
Maximum Discharge Power of the Battery	160	kW
Maximum Desired Power Grid	1069,1	kW
Nominal el. CHP Power	360	kW
CHP electric efficiency	42,5	%
CHP heat Power	389	kW
CHP heat efficiency	46	%
Number of days	1	day

Table 6.38: Grid, Battery, CHP and PV provide the load. CHP 1/3 of consumption. Battery 10 % of Max.Power. With PV I.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1069,1	kW
	Total Power Price	184,53	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2221,14	€
BATTERY			
	Battery Price	738226	€
CHP			
INVESTMENT			
	CHP Price	222635,32	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	39,01	€
ELECTRICITY AND HEAT			
	Electricity Price	0,042	€/kWh
	Total Electric Cost	367,68	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	466,8	€
PV			
INVESTMENT			
	PV Price	259162,5	€
SURPLUS			
	Feed in Price	0,1	€/kWh
	Total Surplus Benefit	0,63	€

Table 6.39: Grid provides load. CHP 1/3 of consumption. Battery 10 % of Max.Power. With PV I.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,92	kW
	Total Power Cost	274,25	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.40: Summary. CHP 1/3 of consumption. Battery 10 % of Max.Power. With PV I..

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	2733,71	€
	Investment	1220023,82	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,83	€
PAY-BACK TIME		2,93	years

6.3.2 CHP 1/3 of Consumption, Battery 15 % of Max. Power

CHP electricity power = average consumption /3

Battery discharge power = 15 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1 329,1 kW

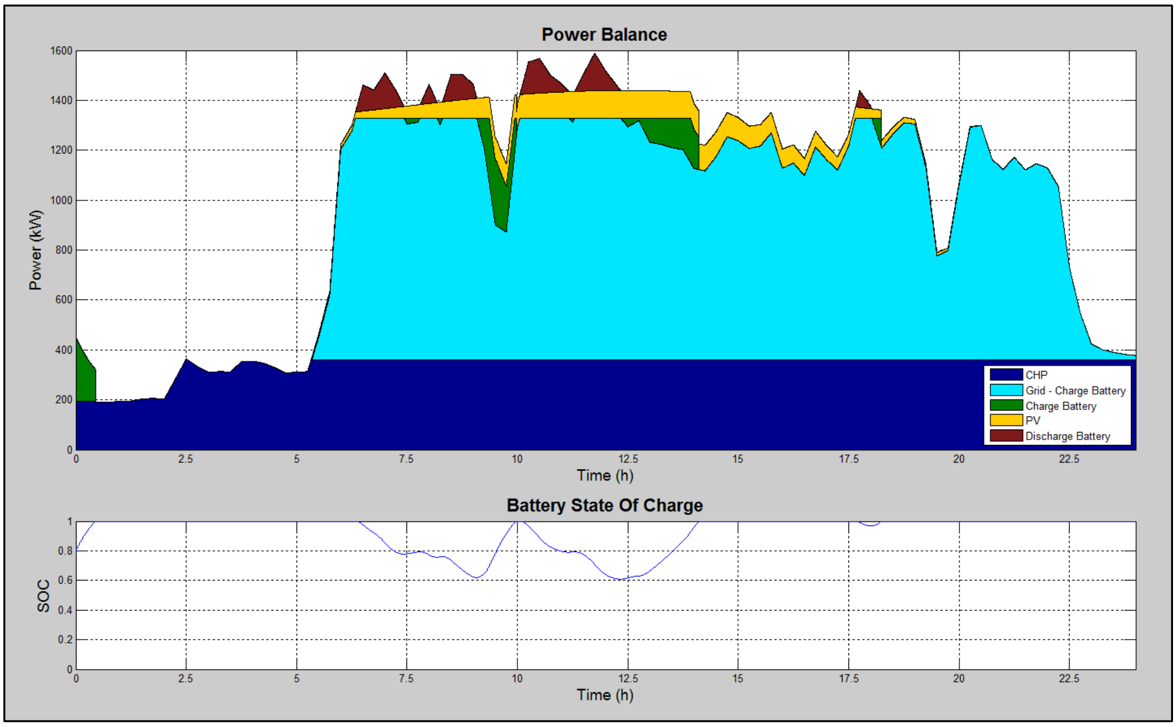

Figure 6.11: Power balance CHP 1/3 of consumption. Battery 15 % of Max.Power. With PV II.

Table 6.41: Data. CHP 1/3 of consumption. Battery 15 % of Max.Power. With PV II

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	400	kWh
Charge Rate	0,65	1/h
Discharge Rate	0,65	1/h
Maximum Discharge Power of the Battery	260	kW
Maximum Desired Power Grid	969,1	kW
Nominal el. CHP Power	360	kW
CHP electric efficiency	42,5	%
CHP heat Power	389	kW
CHP heat efficiency	46	%
Number of days	1	day

Table 6.42: Grid, Battery, CHP and PV provide the load. CHP 1/3 of consumption. Battery 15 % of Max.Power. With PV II.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	969,1	kW
	Total Power Cost	167,27	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2222,01	€
BATTERY			
	Battery Price	1021626	€
CHP			
INVESTMENT			
	CHP Price	222635,32	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	39,94	€
ELECTRICITY AND HEAT			
	Electricity Price	0,042	€/kWh
	Total Electric Cost	367,68	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	466,8	€
PV			
INVESTMENT			
	PV Price	259162,5	€
SURPLUS			
	Feed in Price	0,1	€/kWh
	Total Surplus Benefit	0,63	€

Table 6.43: Grid provides load II. CHP 1/3 of consumption. Battery 15 % of Max.Power. With PV II

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,76	kW
	Total Power Cost	274,22	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.44: Summary. CHP 1/3 of consumption. Battery 15 % of Max.Power. With PV II.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	2717,04	€
	Investment	1503423,82	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,81	€
PAY-BACK TIME		3,56	years

6.3.3 CHP 1/3 of Consumption, Battery 20 % of Max. Power

CHP electricity power = average consumption /3

Battery discharge power = 20 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1 269,1 kW

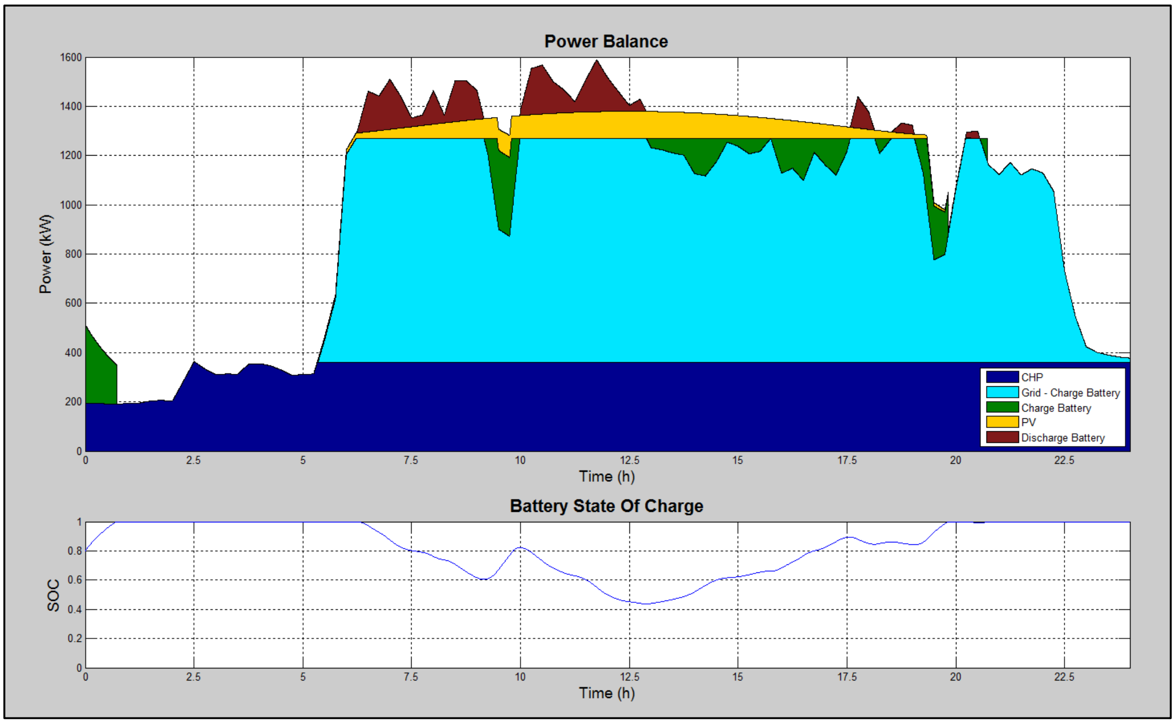

Figure 6.12: Power balance. CHP 1/3 of consumption. Battery 20 % of Max.Power. With PV III.

Table 6.45: Data. CHP 1/3 of consumption. Battery 20 % of Max.Power. With PV III.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	800	kWh
Charge Rate	0,4	1/h
Discharge Rate	0,4	1/h
Maximum Discharge Power of the Battery	320	kW
Maximum Desired Power Grid	909,1	kW
Nominal el. CHP Power	360	kW
CHP electric efficiency	42,5	%
CHP heat Power	389	kW
CHP heat efficiency	46	%
Number of days	1	day

Table 6.46: Grid, Battery, CHP and PV provide the load. CHP 1/3 of consumption. Battery 20 % of Max.Power. With PV III.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	909,1	kW
	Total Power Cost	159,91	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2228,02	€
BATTERY			
	Battery Price	1683223	€
CHP			
INVESTMENT			
	CHP Price	222635,32	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	35,02	€
ELECTRICITY AND HEAT			
	Electricity Price	0,042	€/kWh
	Total Electric Cost	367,68	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	466,8	€
PV			
INVESTMENT			
	PV Price	259162,5	€
SURPLUS			
	Feed in Price	0,1	€/kWh
	Total Surplus Benefit	0,63	€

Table.6.47: Grid provides load. CHP 1/3 of consumption. Battery 20 % of Max.Power. With PV III.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,77	kW
	Total Power Cost	274,22	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.48: Summary. CHP 1/3 of consumption. Battery 20 % of Max.Power. With PV III.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	2716,93	€
	Investment	2165020,82	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,81	€
PAY-BACK TIME		5,13	years

6.3.4 CHP 1/4 of Consumption, Battery 10 % of Max. Power

CHP electricity power = average consumption /4
Battery discharge power = 10 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1429,1 kW

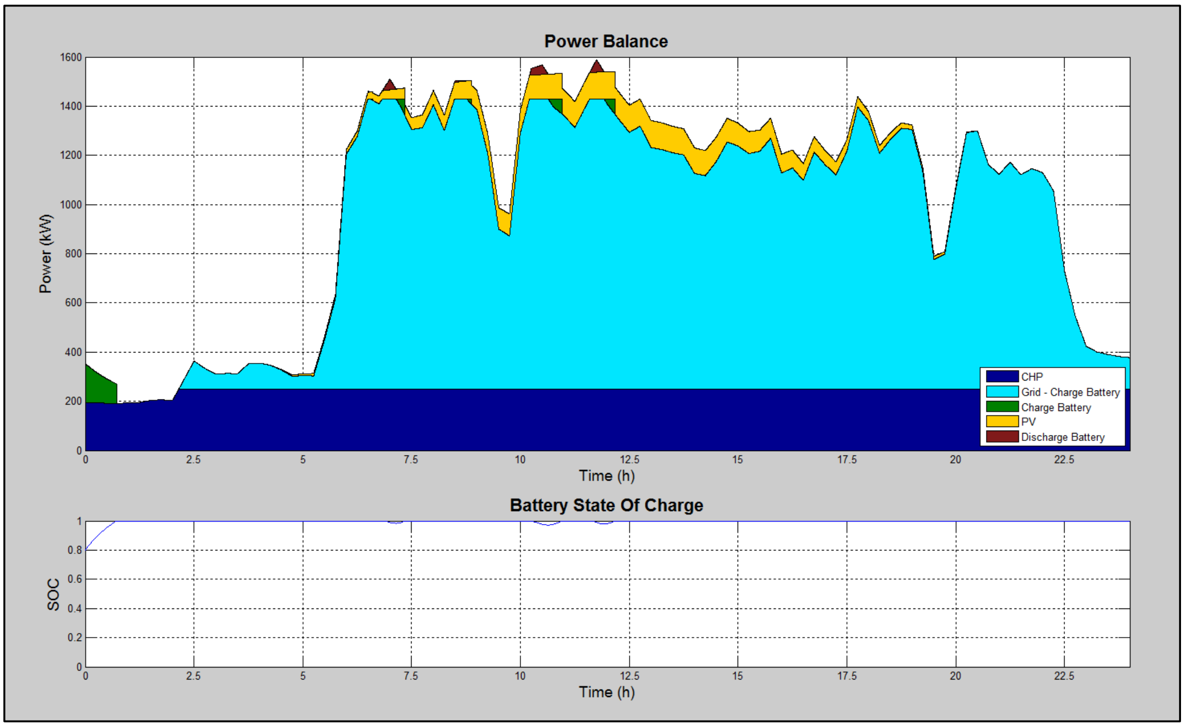

Figure 6.13: Power balance. CHP 1/4 of consumption. Battery 10 % of Max.Power. With PV IV.

Table 6.49: Data. CHP 1/4 of consumption. Battery 10 % of Max.Power. With PV IV.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	400	kWh
Charge Rate	0,4	1/h
Discharge Rate	0,4	1/h
Maximum Discharge Power of the Battery	160	kW
Maximum Desired Power Grid	1179,1	kW
Nominal el. CHP Power	250	kW
CHP electric efficiency	37,5	%
CHP heat Power	312	kW
CHP heat efficiency	46,8	%
Number of days	1	day

Table 6.50: Grid, Battery, CHP and PV provide the load. CHP 1/4 of consumption. Battery 10 % of Max.Power. With PV IV.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1179,1	kW
	Total Power Cost	203,51	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2570,84	€
BATTERY			
	Battery Price	738226	€
CHP			
INVESTMENT			
	CHP Price	182916,34	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	7,20	€
ELECTRICITY AND HEAT			
	Electricity Price	0,054	€/kWh
	Total Electric Cost	328,13	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	374,4	€
PV			
INVESTMENT			
	PV Price	259162,5	€
SURPLUS			
	Feed in Price	0,1	€/kWh
	Total Surplus Benefit	0	€

Table 6.51: Grid provides load. CHP 1/4 of consumption. Battery 10 % of Max.Power. With PV IV.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,92	kW
	Total Power Cost	274,25	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.52: Summary. CHP 1/4 of consumption. Battery 10 % of Max.Power. With PV IV.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	3095,28	€
	Investment	1180304,84	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,83	€
PAY-BACK TIME		4,15	years

6.3.5 CHP 1/4 of Consumption, Battery 15 % of Max. Power

CHP electricity power = average consumption /4

Battery discharge power = 15 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1 329,1 kW

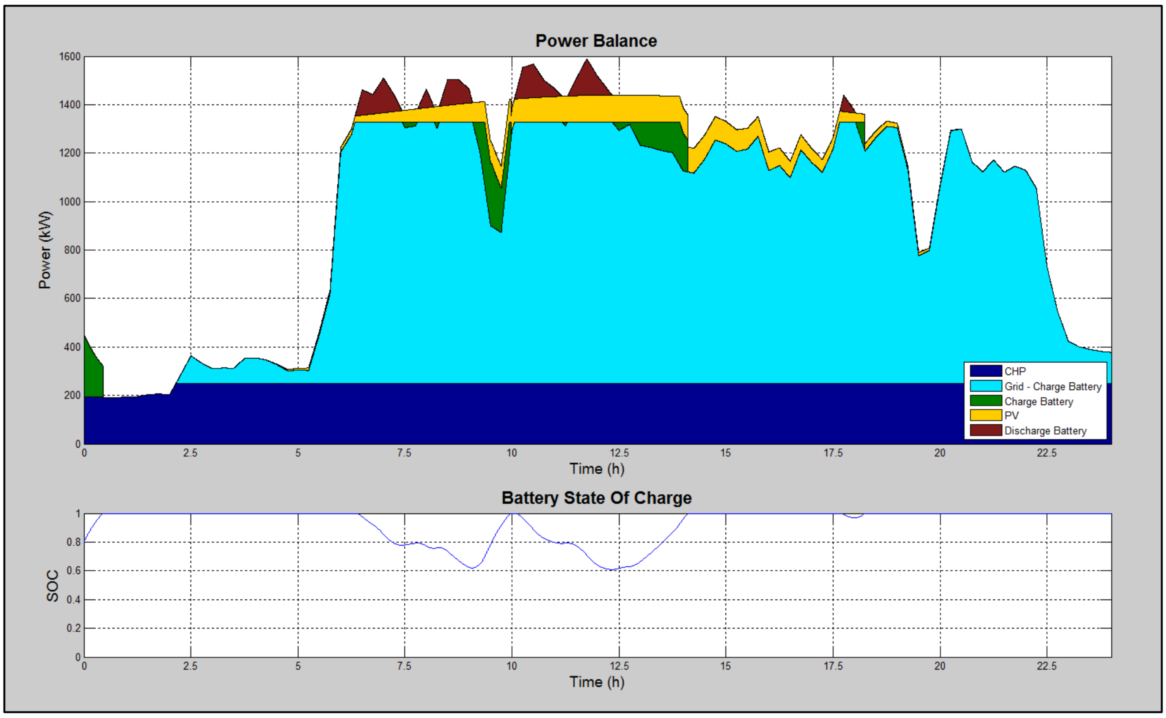

Figure 6.14: Power balance. CHP 1/4 of consumption. Battery 15 % of Max.Power. With PV V.

Table 6.53: Data. CHP 1/4 of consumption. Battery 15 % of Max.Power. With PV V.

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	400	kWh
Charge Rate	0,65	1/h
Discharge Rate	0,65	1/h
Maximum Discharge Power of the Battery	260	kW
Maximum Desired Power Grid	1079,1	kW
Nominal el. CHP Power	250	kW
CHP electric efficiency	37,5	%
CHP heat Power	312	kW
CHP heat efficiency	46,8	%
Number of days	1	day

Table 6.54: Grid, Battery, CHP and PV provide the load. CHP 1/4 of consumption. Battery 15 % of Max.Power. With PV V

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1079,1	kW
	Total Power Cost	186,25	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2573,33	€
BATTERY			
	Battery Price	1021626	€
CHP			
INVESTMENT			
	CHP Price	182916,34	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	8,91	€
ELECTRICITY AND HEAT			
	Electricity Price	0,054	€/kWh
	Total Electric Cost	328,13	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	374,4	€
PV			
INVESTMENT			
	PV Price	259162,5	€
SURPLUS			
	Feed in Price	0,1	€/kWh
	Total Surplus Benefit	0	€

Table 6.55: Grid provides load. CHP 1/4 of consumption. Battery 15 % of Max.Power. With PV V.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,91	kW
	Total Power Cost	274,25	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.56: Summary. CHP 1/4 of consumption. Battery 15 % of Max.Power. With PV V.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	3078,79	€
	Investment	1463704,84	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,83	€
PAY-BACK TIME		5,04	years

6.3.6 CHP 1/4 of Consumption, Battery 20 % of Max. Power

CHP electricity power = average consumption /4

Battery discharge power = 20 % maximum power peak

Recommended Battery Type for this simulation: *Redox Flow Battery*

Threshold = 1269,1 kW

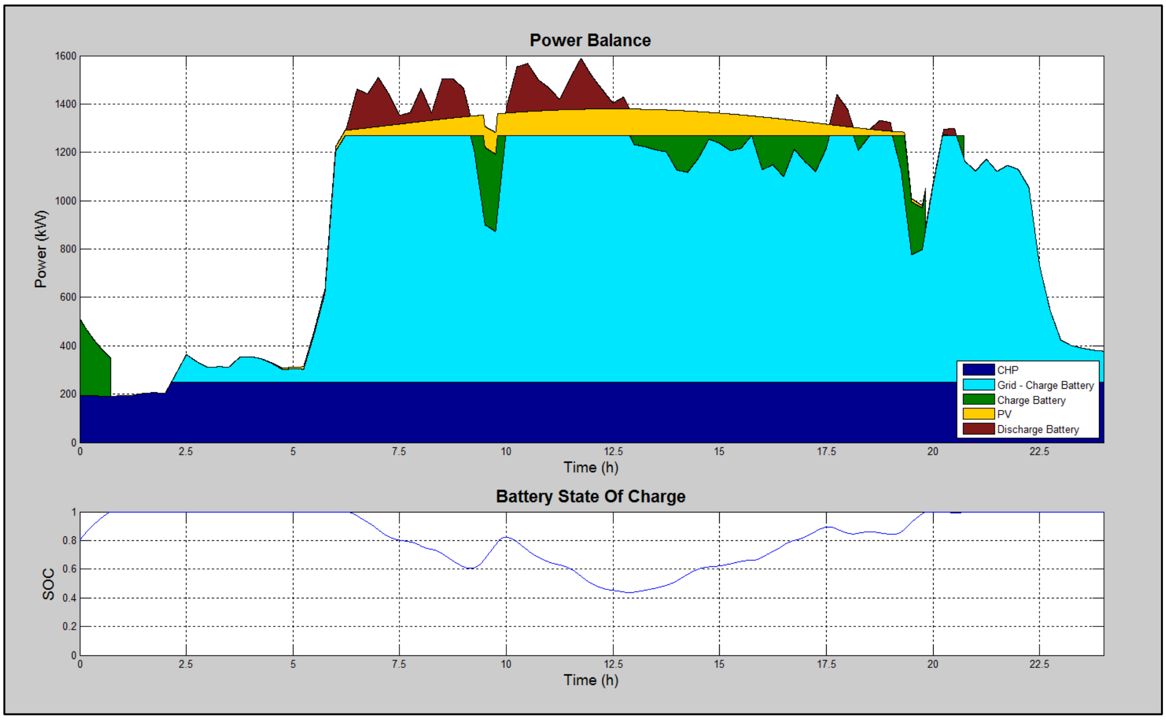

Figure 6.15: Power Balance. CHP 1/4 of consumption. Battery 20 % of Max.Power. With PV VI.

Table 6.57: Data. CHP 1/4 of consumption. Battery 20 % of Max.Power. With PV VI

Parameters	Values	Units
Time Step	15	min
Initial SOC	80	%
Minimum SOC	0	%
Nominal Battery Voltage	400	V
Battery Capacity	800	kWh
Charge Rate	0,4	1/h
Discharge Rate	0,4	1/h
Maximum Discharge Power of the Battery	320	kW
Maximum Desired Power Grid	1019,1	kW
Nominal el. CHP Power	250	kW
CHP electric efficiency	37,5	%
CHP heat Power	312	kW
CHP heat efficiency	46,8	%
Number of days	1	day

Table 6.58: Grid, Battery, CHP and PV provide the load. CHP 1/4 of consumption. Battery 20 % of Max.Power. With PV VI.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1019,1	kW
	Total Power Cost	175,90	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2583,31	€
BATTERY			
	Battery Price	1683223	€
CHP			
INVESTMENT			
	CHP Price	182916,34	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	7,20	€
ELECTRICITY AND HEAT			
	Electricity Price	0,054	€/kWh
	Total Electric Cost	328,13	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	374,4	€
PV			
INVESTMENT			
	PV Price	259162,5	€
SURPLUS			
	Feed in Price	0,1	€/kWh
	Total Surplus Benefit	0	€

Table 6.59: Grid providesl load. CHP 1/4 of consumption. Battery 20 % of Max.Power. With PV VI.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,77	kW
	Total Power Cost	274,22	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.60: Summary. CHP 1/4 of consumption. Battery 20 % of Max.Power. With PV VI.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	3080,19	€
	Investment	2125301,84	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,81	€
PAY-BACK TIME		7,33	years

In this case,comparing this results with the results without PV data, it can be seen that including solar panels has not evident differences in the economic balances when the discharge power is the lowest, otherwise, it has.

6.4 Estimated Optimum Solution

Finally, from the simulations above, an example will be explained that could be followed to calculate the parameters of the different components of the system. The values of the different elements are **introduced by the user**.

Looking at the six different simulations without PV power, the one that has the least Payback is the one in which the CHP is the average of the load divided by three, and the maximum discharge power is 10% of the maximum value of the load. The same happens in the six simulations with PV power.

Now, comparing the two minimum values of payback, it can be seen that the lowest is the one that does not have PV power. This happens for the PV power data entered by default, which come from a 207.33 kWp installation. For other data of peak power, the result of the payback might have been different. To enter some different PV data, the value of the data must increase or decrease in the column of the PV power (in the Excell sheet), to the same extent as the value of peak power of the alleged installation.

As it has been already mentioned and trying to find the optimum solution, the selected result is the shortest payback time without PV power. The data of this simulation are found in Table 6.13. The user should be guided by this information in order to introduce his own data.

In order to go on with the example, one may assume that the user has already a battery which costs 870 000 €,Table 5.4, and has a CHP of 400 kW.

The battery has a discharge power of 200 kW and a capacity of 400 kWh, that means:

$$\mathrm{DR} = \mathrm{CR} = \frac{200\ \mathrm{kW}}{400\ \mathrm{kWh}} = 0{,}5\ \mathrm{h}^{-1}$$

After that, the simulation starts with the following data:

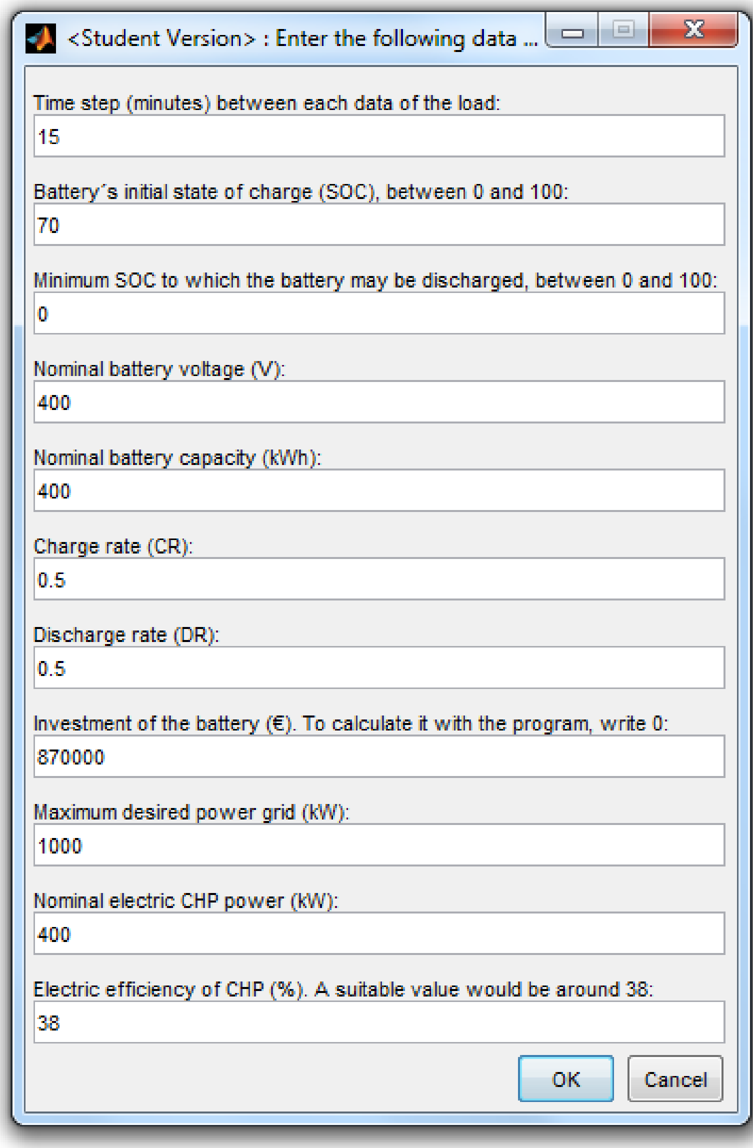

Figure 6.16: Data of a simulation example.

In the whole paragraph the *threshold* is the sum of the nominal electric power of the CHP and the maximum desired power grid.

The results of the simulation are the following:

6.4.1 Estimated Optimum Solution. Max. Desired Power Grid 1000 kW

Threshold = 1 400 kW

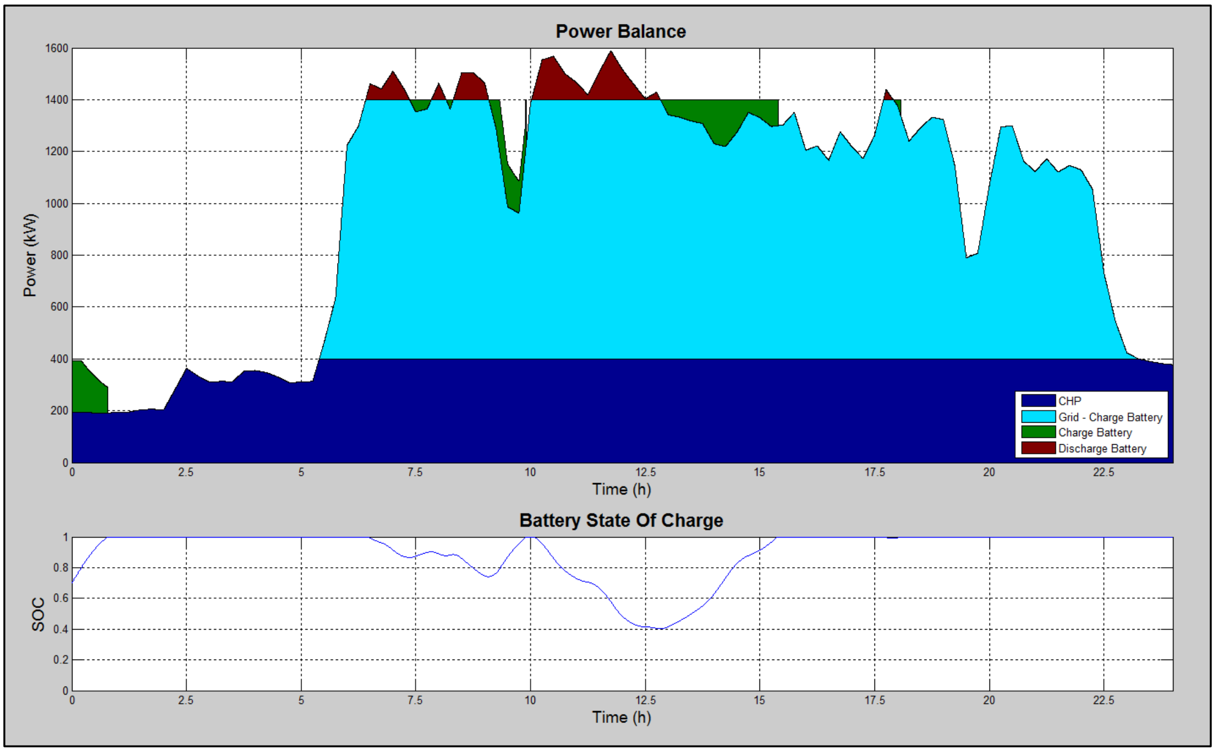

Figure 6.17: Power balance. Estimated optimum solution. Max. Desired power grid 1 000 kW.

Table 6.61: Grid, Battery and CHP provide the load. Estimated optimum solution. Max. Desired power grid 1 000 kW.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1000	kW
	Total Power Cost	172,60	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2261,57	€
BATTERY			
	Battery Price	870000	€
CHP			
INVESTMENT			
	CHP Price	235642,04	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	58,17	€
ELECTRICITY AND HEAT			
	Electricity Price	0,029	€/kWh
	Total Electric Cost	282,84	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	576	€

Table 6.62: Grid to provide all load. Estimated optimum solution. Max. Desired power grid 1 000 kW.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,94	kW
	Total Power Cost	274,25	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Table 6.63: Summary. Estimated optimum solution. Max. Desired power grid 1 000 kW.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	2658,84	€
	Investment	1105642,04	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,84	€
PAY-BACK TIME		2,49	years

In the Figure 6.17 of this simulation, one can see that the battery is not providing its maximum discharge power. For that reason, the value of the grid could be decreased in order to run again the simulation and see what happens.

The next simulation is made with the same values as previously but with a max desired power grid of 970 kW.

6.4.2 Estimated Optimum Solution. Max. Desired Power Grid 970 kW

Threshold = 1 370kW

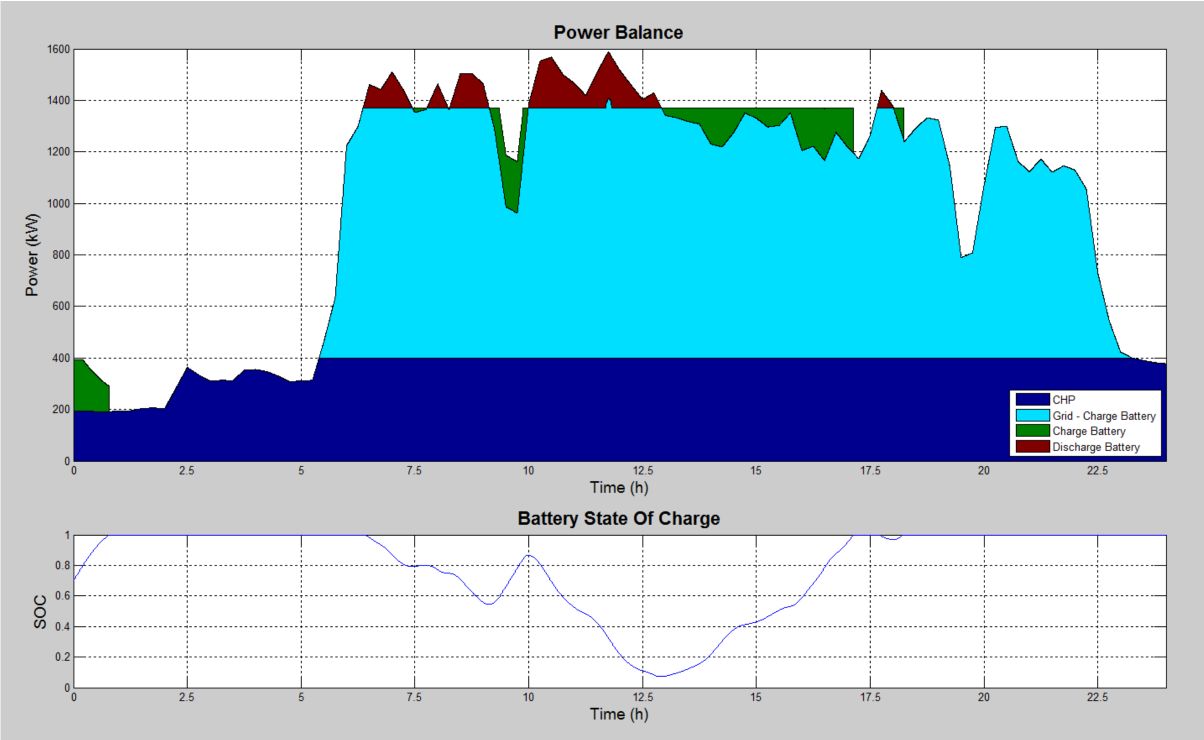

Figure 6.18: Power balance. Estimated optimum solution. Max. Desired power grid 970 kW.

In order to show that the previous solution is really nearly optimum, the threshold now was lowered in this section. The objective was to save even more grid power, thus more money. The results show, that under these conditions, the grid power consumption cannot be kept velow the threshold any longer. See Figure 6.18.

Table 6.64: Grid, Battery and CHP provide the load. Estimated optimum solution. Max. Desired power grid 970 kW.

GRID			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1007,79	kW
	Total Power Cost	173,94	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	2261,50	€
BATTERY			
	Battery Price	870000	€
CHP			
INVESTMENT			
	CHP Price	235642,0441	€
SURPLUS			
	Feed in Price	0,105	€/kWh
	Total Surplus Benefit	58,17	€
ELECTRICITY AND HEAT			
	Electricity Price	0,029	€/kWh
	Total Electric Cost	282,84	€
	Heat Price	0,05	€/kWh
	Total Heat Cost	576	€

Table 6.65: Grid to provide all load. Estimated optimum solution. Max. Desired power grid 970 kW.

GRID TO PROVIDE ALL LOAD			
	Parameters	**Values**	**Units**
POWER			
	Power Price	63	€/kW
	Max. Value	1588,76	kW
	Total Power Cost	274,22	€
ENERGY			
	Energy Price	0,15	€/kWh
	Total Energy Cost	3599,58	€

Tabelle 6.66: Summary. Estimated optimum solution. Max. Desired power grid 970 kW.

SUMMARY			
	Parameters	**Values**	**Units**
GRID WITH BATT AND CHP			
	Money to pay	2660,11	€
	Investment	1105642,04	€
GRID SUPPLIES ALL LOAD			
	Money to pay	3873,80	€
PAY-BACK TIME		2,49	years

In this case, the grid is suppling more power than desired, therefore, a new value, between 970 and 1000 kW should be chosen as a new desired max. grid power in order to get the accurate value.

It is easy to see that iincluding the cogeneration system has a really important effect because with it, the investment is payed back earllier. Finally, for each simulation, it is posible to see that the smallest battery is the best option.

7 Conclusion and Prospects

Conclusion

The integration between the different elements which make up the simulation model of the system, together with the demand and generation profiles, from different industrial sector companies, has been carried out successfully.

As has been shown in the previous chapter, with the use, in the industrial sector, of a suitable battery in order to avoid power peaks, a small amount of money can be saved.
On the other hand, the integration of a cogeneration system, working together with the battery, can provide additional savings, making the payback time shorter.

The use of redox flow batteries is technically a good option for the companies, as long as they are frequently employed, because this type of batteries has practically no ageing. Otherwise, the use of another type of battery would be more economic, because the investment of redox flow batteries is 7 times more expensive.

It should be added that during the implementation of this project, a great challenge, such as the learning of the programming of Simulink/Matlab, has been achieved.

Moreover, some difficulties concerning the research of the accurate information have been overcome.

Finally, it is worth mentioning that, the main drawback during this work was to find a Redox Flow battery model because it is a relatively new technology.

Prospects

As perspectives of the future work of this project, the following improvements are suggested:

- Building a Redox Flow Battery model, which makes the simulation more realistic.
- Development of a model with solar panels in order to incorporate them into the program.
- Utilization of the thermal power of the cogeneration system in order to use it in the economic balance calculation.
- Making a broader economic balance through the calculation of more parameters of economic interest
- Integration of electricity prices, in different countries, in order to make the program more international and standardized.

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Appendix

Appendix 1: Main Program Code

```
%% MAIN PROGRAM
input_data;
if strcmp(answer, 'Yes')
    for run = 1:2
         for sub_run = 10:5:20
            selection;
            simulink_model;
            prices;
            program_results;
         end
    end
elseif strcmp(answer, 'No')
    conditioning_of_values;
    simulink_model;
    prices2;
    program_results2;
end
```

Appendix 2: Input Data Code

```
%% INPUT DATA
%% Fresh start
close all, clc, clearvars -except data1 PV_kWp1
[filename, pathname] = uigetfile({'*.xlsx';'*.xls'},'File Selector');
%% check if Load/PV data has been loaded
if ~exist('load', 'var'),
    import_data_company;
    v = 1;
    t(:,1) = v * (1:size(t));
    load(:,1) = t(:,1);
    load(:,2) = LoadkW(:,1);
end
% Construct a questdlg with three options
pvexist = questdlg('Do you have any PV data to introduce into the 
model?',...
    'PV Data','Yes','No', 'Cancel','Cancel');
% Handle response
switch pvexist
    case 'Yes'
         temporal00 = {'Introduce the solar power of your system 
(kWp):'};
         dlg_title = 'Enter the following data     ';
         num_lines = 1;
         if exist('PV_kWp1','var'),
             def = PV_kWp1;
             PV_kWp1 = inputdlg(temporal00,dlg_title,num_lines,def);
         else
             PV_kWp1 = inputdlg(temporal00,dlg_title,num_lines);
         end
         PV_kWp = str2num(cell2mat(PV_kWp1));
         if ~exist('PV_power', 'var')
             PV_power(:,1) = t(:,1);
             PV_power(:,2) = PVkW(:,1);
         end
    case 'No'
         if ~exist('PV_power', 'var')
             PV_power(:,1) = t(:,1);
             PV_power(:,2) = (0);
         end
    case 'Cancel'
         h = msgbox('Simulation canceled');
         error('The simulation has been canceled');
end
%% Define the variables
% Construct a questdlg with three options
answer = questdlg('Would you like to simulate with the default values?',
...
    'Default Values','Yes','No','Cancel','Cancel');
% Handle response
if strcmp(answer, 'Yes')
     temporal0 = {'Time step (minutes) between each data of the load:'};
     dlg_title = 'Enter the following data     ';
     num_lines = 1;
     def1 ={'15'};
     T1 = inputdlg(temporal0,dlg_title,num_lines,def1);
     T = str2num(cell2mat(T1));
     T = T * 60;
     SOC_initial = 80;
```

```
     maximum = 1000 * max(load(:,2));
     average = 1000 * mean(load(:,2));
     difference = maximum - average;

elseif strcmp(answer, 'No')
    temporal = {'Time step (minutes) between each data of the load:',
    'Battery´s initial state of charge (SOC), between 0 and 100:',
    'Minimum SOC to which the battery may be discharged, between 0 and
100:',
    'Nominal battery voltage (V):',
    'Nominal battery capacity (kWh):',
    'Charge rate (CR):',
    'Discharge rate (DR):',
    'Investment of the battery (€). To calculate it with the program,
write 0:',
    'Maximum desired power grid (kW):',
    'Nominal electric CHP power (kW):',
    'Electric efficiency of CHP (%). A suitable value would be around
     38:'};
    dlg_title = 'Enter the following data     ';
    num_lines = 1;
    if exist('data1','var'),
         def2 = data1;
         data1 = inputdlg(temporal,dlg_title,num_lines,def2);
    else
         data1 = inputdlg(temporal,dlg_title,num_lines);
    end
    if isempty (data1)
        h = msgbox('Simulation Canceled');
        error('your quitting error message');
    end
    Data = str2double(data1);
    T = Data(1) * 60;
    SOC_initial = Data(2);
    SOC_min = Data(3);
    SOC_min = SOC_min/100;
    if SOC_min < 0.00011
        SOC_min = 0.00011;
    end
    nominal_battery_voltage = Data(4);
    battery_capacity = Data(5)/nominal_battery_voltage*1000;
    c_charge = Data(6);
    c_discharge = Data(7);
    battery_investment_user = Data(8);
    max_desired_power_grid = Data(9);
    CHP_max = Data(10);
    CHP_electric_efficiency = Data(11)/100;
    max_desired_power_grid = max_desired_power_grid * 1000;
    CHP_max = CHP_max * 1000;
    nominal_discharge_battery_current=c_discharge * battery_capacity;
    max_discharge_power = nominal_battery_voltage ...
        * nominal_discharge_battery_current;
    nominal_charge_battery_current = c_charge * battery_capacity;
    max_charge_power = nominal_battery_voltage ...
        * nominal_charge_battery_current;
else strcmp(answer, 'Cancel')
    h = msgbox('Simulation canceled');
    error('your quitting error message');
end

h = waitbar(0,'Please wait...(To abort process, press Ctrl+C)');
```

Appendix 3: Selection Code

```
%% SELECTION
%% CHP_catalogue
CHP_max = average/run+2);
CHP_catalogue;
%% battery_discharge_power_catalogue
max_discharge_power = sub_run * maximum/100;
battery_discharge_power_catalogue;
max_desired_power_grid = maximum - CHP_max - max_discharge_power;
nominal_battery_voltage = 400;
%% battery_capacity_min
battery_capacity_min;
c_discharge = (max_discharge_power/nominal_battery_voltage)/battery_ca-
pacity;
c_charge = c_discharge;
nominal_discharge_battery_current = c_discharge * battery_capacity;
nominal_charge_battery_current = c_charge * battery_capacity;
max_charge_power = nominal_battery_voltage * nominal_charge_battery_cur-
rent;
%% day_max_capacity_calc
cond_values_and_day_max_capacity_calc;
t_sim_day = size(day_load_max, 1);
keep_running = 1;
while keep_running
    sim('capacity_simulink_program.slx', t_sim_day);
    if strcmp(battery_type, 'redox flow')
        if min(SOC.Data) <= 0.01 || SOC.Data(length(SOC.Data)) <
SOC.Data(1)
            change_capacity;
            c_discharge = (max_discharge_power/nominal_battery_voltage)
                  .../battery_capacity;
            c_charge=c_discharge;
            nominal_discharge_battery_current = c_discharge*battery_ca-
pacity;
            nominal_charge_battery_current=c_charge*battery_capacity;
            max_charge_power = nominal_battery_voltage ...
                *nominal_charge_battery_current;
        else
            keep_running = 0;
        end
    end
if strcmp(battery_type, 'lead acid')
        if min(SOC.Data) <= 0.4 || SOC.Data(length(SOC.Data))<SOC.Data(1)
            change_capacity;
            c_discharge = (max_discharge_power/nominal_battery_voltage)
                  .../battery_capacity;
            c_charge=c_discharge;
            nominal_discharge_battery_current = c_discharge ...
                * battery_capacity;
            nominal_charge_battery_current = c_charge ...
                * battery_capacity;
            max_charge_power = nominal_battery_voltage ...
                * nominal_charge_battery_current;
        else keep_running = 0;
        end
    end
end
```

Appendix 4: CHP Catalogue Code

```
%% CHP CATALOGUE
CHP_range = [20,50,100,140,200,220,240,250,360,400,450,527,550,600, ...
    637,800,835,845,1067,1130,1200,1413,1560,2000]*1000; % Catalogue
for i = 1:length(CHP_range)
    if i == length(CHP_range)
        CHP_max = CHP_range(i);
    end
    if CHP_max <= CHP_range(i)
        CHP_max = CHP_range(i);
        break
    end
    if CHP_max > CHP_range(i) && CHP_max < CHP_range (i+1)
        if CHP_max - CHP_range(i) <= CHP_range(i+1) - CHP_max
            CHP_max = CHP_range(i);
            break
        else
            CHP_max = CHP_range(i+1);
            break
        end
    end
end

CHP_electric_effi-
ciency_range=[31.5,34.5,36.9,36.5,37.4,39.6,36,37.5,42.5,...
 38.8,41,39.8,42.6,42,40.5,42.4,40,42.7,41,42.9,43.7,42.9,43.3,43.6]/100;
CHP_heat_power_range=[43,100,130,207,256,253,370,312,389,504,480,625,...
    585,654,731,856,986,865,1208,1155,1195,1442,1584,1990]*1000;
CHP_heat_effi-
ciency_range=[73.1,68.5,47.9,53.9,47.9,45.5,55.5,46.8,46,48.9,...
   43.8,47.2,45.3,45.8,46.5,45.3,47.2,43.8,46.4,43.8,43.5,43.8,43.9,43.4]
.../100;
CHP_electric_efficiency=CHP_electric_efficiency_range ...
    (find(CHP_range==CHP_max));
CHP_heat_power=CHP_heat_power_range(find(CHP_range==CHP_max));
CHP_heat_efficiency=CHP_heat_efficiency_range(find(CHP_range ==
CHP_max));
```

Appendix 5: Battery Discharge Power Catalogue Code

```
%% BATTERY DISCHARGE POWER CATALOGUE
% Catalogue
batery_discharge_power_range = [10,20,30,60,90,120,160,200,260,320]*1000;
for i = 1:length(batery_discharge_power_range)
    if i == length(batery_discharge_power_range)
        max_discharge_power = batery_discharge_power_range(i);
    end
    if max_discharge_power <= batery_discharge_power_range(i)
        max_discharge_power = batery_discharge_power_range(i);
        break
    end
    if max_discharge_power > batery_discharge_power_range(i) && ...
            max_discharge_power < batery_discharge_power_range (i+1)
        max_discharge_power = batery_discharge_power_range(i+1);
        break
    end
end
```

Appendix 6: Battery Capacity Minimum Code

```
%% BATTERY CAPACITY MINIMUM
% Determine the battery capacity
if max_discharge_power == 10000 || max_discharge_power == 20000 || ...
        max_discharge_power == 30000
    battery_capacity = 40000/nominal_battery_voltage;
end

if max_discharge_power == 60000
    battery_capacity = 100000/nominal_battery_voltage;
end

if max_discharge_power == 90000
    battery_capacity = 130000/nominal_battery_voltage;
end

if  max_discharge_power == 120000 || max_discharge_power == 160000 || ...
    max_discharge_power == 200000 || max_discharge_power == 260000
    battery_capacity = 400000/nominal_battery_voltage;
end

if max_discharge_power == 320000
    battery_capacity = 800000/nominal_battery_voltage;
end
```

Appendix 7: Conditioning of Values and Day of Maximum Energy Code

```
%% CONDITIONING OF VALUES AND DAY MAXIMUM CAPACITY CALCULATION
steps_day = 86400/T;
number_days = round(length(load)/steps_day);
if number_days > 1
    % In case some data have not been entered, that means that the last
    % data measures are missed, they are filled with the last value of
    % the load or PV power
    if length(load) ~= steps_day*number_days
        diferencia = steps_day*number_days - length(load);
        if diferencia > 0
            for i=(length(load) + 1):(length(load) + diferencia)
                load(i,1)= i;
                load(i,2) = load(i-1,2);
                PV_power(i,1)= i;
                PV_power(i,2) = PV_power(i-1,2);
            end
        end
    end
    energy_battery_total = zeros(1, number_days);
    days_use_battery = 0;
    for j=1:number_days
        use_battery = zeros(1, number_days);
        energy_battery = 0;
        for i=1:steps_day
            if load(i + steps_day*(j-1),2)*1000 > (max_desired_power_grid
             ...+ CHP_max + PV_power(i + steps_day*(j-1),2))
                energy = T * (load(i + steps_day*(j-1),2)*1000 ...
                    - max_desired_power_grid ...
                    - CHP_max-PV_power(i+steps_day*(j-1),2));
                use_battery(i) =  1;
            else
                energy = 0;
                use_battery(i) =  0;
            end
            energy_battery = energy_battery + energy;
        end
        energy_battery_total(j) = energy_battery;
        if sum(use_battery) ~= 0
            days_use_battery = days_use_battery + 1;
        end
    end

    % It tells you the column where the day,
    % in which more energy is consumed, is located
    day_of_maximum_energy = find(energy_battery_total== ...
        max(energy_battery_total));
    day_of_maximum_energy = day_of_maximum_energy(1);
    initial_step = (day_of_maximum_energy - 1) * steps_day + 1;
    final_step = day_of_maximum_energy * steps_day;

    more_steps = 1;
    while load(final_step+more_steps,2) * 1000 ...
            < (max_desired_power_grid+CHP_max)
        more_steps = more_steps + 1;
    end
```

```
    more_steps = more_steps - 1;

    if exist('day_load_max','var'),
       clear day_load_max;
    end
    day_load_max(:,1)=load(initial_step : (final_step + more_steps), 1);
    day_load_max(:,2)=load(initial_step : (final_step + more_steps), 2);

    % In a year, means more than two days per week
    if days_use_battery > 0.285 * number_days
        battery_type = 'redox flow';
        SOC_min = 0.00011;
    else
        battery_type = 'lead acid';
        SOC_min = 0.4;
    end

else
    day_load_max(:,1) = load(:,1);
    day_load_max(:,2) = load(:,2);
    battery_type = 'redox flow';
    SOC_min = 0.00011;
end
```

Appendix 8: Change Capacity Code

```
%% CHANGE CAPACITY
capacity = 'default';

if max_discharge_power == 10000 || max_discharge_power == 20000 ...
        || max_discharge_power == 30000
    capacity = 'range_1';
end
if max_discharge_power == 60000
    capacity = 'range_2';
end
if max_discharge_power == 90000
    capacity = 'range_3';
end
if max_discharge_power == 120000
    capacity = 'range_4';
end
if max_discharge_power == 160000 || max_discharge_power == 200000 ...
        || max_discharge_power == 260000
    capacity = 'range_5';
end
if max_discharge_power == 320000
    capacity = 'range_6';
end

switch capacity
    case 'range_1'
        battery_capacity_range = [40,70,100,130]*1000 ...
            /nominal_battery_voltage;
        actual_capacity=find(battery_capacity_range == battery_capacity);
        if actual_capacity == 4
            battery_capacity = battery_capacity_range(4);
            keep_running = 0;
        else
            battery_capacity=battery_capacity_range(actual_capacity + 1);
        end
    case 'range_2'
        battery_capacity_range=[100,130,400]*1000 ...
            /nominal_battery_voltage;
        actual_capacity=find(battery_capacity_range == battery_capacity);
        if actual_capacity == 3
            battery_capacity = battery_capacity_range(3);
            keep_running = 0;
        else
            battery_capacity=battery_capacity_range(actual_capacity + 1);
        end
    case 'range_3'
        battery_capacity_range = [130,400,800]*1000 ...
            /nominal_battery_voltage;
        actual_capacity=find(battery_capacity_range == battery_capacity);
        if actual_capacity == 3
            battery_capacity = battery_capacity_range(3);
            keep_running = 0;
        else
            battery_capacity=battery_capacity_range(actual_capacity + 1);
        end
    case 'range_4'
        battery_capacity_range = [400,800]*1000/nominal_battery_voltage;
```

```
        actual_capacity=find(battery_capacity_range == battery_capacity);
        if actual_capacity == 2
            battery_capacity = battery_capacity_range(2);
            keep_running = 0;
        else
            battery_capacity=battery_capacity_range(actual_capacity + 1);
        end
    case 'range_5'
        battery_capacity_range = [400,800,1600]*1000 ...
            /nominal_battery_voltage;
        actual_capacity=find(battery_capacity_range == battery_capacity);
        if actual_capacity == 3
            battery_capacity = battery_capacity_range(3);
            keep_running = 0;
        else
            battery_capacity=battery_capacity_range(actual_capacity + 1);
        end
    case 'range_6'
        battery_capacity_range = [800,1600]*1000/nominal_battery_voltage;
        actual_capacity=find(battery_capacity_range == battery_capacity);
        if actual_capacity == 2
            battery_capacity = battery_capacity_range(2);
            keep_running = 0;
        else
            battery_capacity=battery_capacity_range(actual_capacity + 1);
        end
    otherwise
        disp('error');
end
```

Appendix 9: Conditioning of Values Code

```
%% CONDITIONING OF VALUES
steps_day = 86400/T;
number_days = round(length(load)/steps_day);
if number_days > 1
    % In case some data have not been entered, that means that the last
    % data measures are missed, they are filled with the last value of
    % the load or PV power
    if length(load)~= steps_day*number_days
        diferencia = steps_day*number_days - length(load);
        if diferencia > 0
            for i=(length(load) + 1):(length(load) + diferencia)
                load(i,1)= i;
                load(i,2) = load(i-1,2);
                PV_power(i,1)= i;
                PV_power(i,2) = PV_power(i-1,2);
            end
        end
    end
    energy_battery_total = zeros(1, number_days);
    days_use_battery = 0;
    for j=1:number_days
        use_battery = zeros(1, number_days);
        energy_battery = 0;
        for i=1:steps_day
            if load(i + steps_day*(j-1),2)*1000 > (max_desired_power_grid
                    ...+ CHP_max + PV_power(i + steps_day*(j-1),2))
                energy = T * (load(i + steps_day*(j-1),2)*1000 ...
                    - max_desired_power_grid ...
                    - CHP_max-PV_power(i+steps_day*(j-1),2));
                use_battery(i) =  1;
            else
                energy = 0;
                use_battery(i) =  0;
            end
            energy_battery = energy_battery + energy;
        end
        energy_battery_total(j) = energy_battery;
        if sum(use_battery) ~= 0
            days_use_battery = days_use_battery + 1;
        end
    end

    % In a year, means more than two days per week
    if days_use_battery > 0.285 * number_days
        battery_type = 'redox flow';
    else
        battery_type = 'lead acid';
    end

else
    day_load_max(:,1) = load(:,1);
    day_load_max(:,2) = load(:,2);
    battery_type = 'non';
end
```

Appendix 10: Simulink Model Code

```
%% SIMULINK MODEL
t_sim = v * size(load, 1);
sim('simulink_program.slx', t_sim);
```

Appendix 11: Power Management Function Code

```
function [battery,char_battery,dis_battery,grid_supply,CHP, ...
    CHP_surplus,PV,PV_surplus] = CONTROLLER(load,PV_power,SOC)

%#codegen
eml.extrinsic('evalin')

%% initialization of variables
battery = 0;
grid_supply = 0;
CHP = 0;
PV = 0;
dis_battery = 0;
char_battery = 0;
max_desired_power_grid = 0;
CHP_max = 0;
max_charge_power = 0;
max_discharge_power = 0;
SOC_min = 0;
PV_surplus = 0;
CHP_surplus = 0;

%% variables from the workspace
max_desired_power_grid = evalin('base', 'max_desired_power_grid');
CHP_max = evalin('base', 'CHP_max');
max_charge_power = evalin('base', 'max_charge_power');
max_discharge_power = evalin('base', 'max_discharge_power');
SOC_min = evalin('base', 'SOC_min');

%% calculation
needed_extra_power = load - CHP_max - PV_power - max_desired_power_grid;

%% charge battery
line_charge = -2.5*max_charge_power*SOC +3*max_charge_power;
if SOC >= 0.8
     max_charge_power = line_charge;
end

%% discharge battery
line_discharge = 1.25*max_discharge_power*SOC +0.5*max_discharge_power;
if SOC <= 0.4
     max_discharge_power = line_discharge;
end

%% determine your needs and resources
if load - CHP_max - PV_power > max_desired_power_grid
    support = 1;
```

```
else support = 0;
end

if SOC > SOC_min
    battery_available = 1;
else battery_available = 0;
end

if SOC >= 1
    battery_full = 1;
else battery_full = 0;
end

if max_discharge_power >= needed_extra_power
    battery_support = 1;
else battery_support = 0;
end

if max_desired_power_grid - (load - CHP_max - PV_power) >= max_charge_power
    charge_battery_limit = 1;
else charge_battery_limit = 0;
end

if CHP_max > load
    CHP_to_battery = 1;
else CHP_to_battery = 0;
end

if CHP_max - load >= max_charge_power
    CHP_to_battery_limit = 1;
else CHP_to_battery_limit = 0;
end

if load > CHP_max + PV_power
    extra_power_grid = 1;
else extra_power_grid = 0;
end

if CHP_max + PV_power - load >= max_charge_power
    CHP_PV_to_battery_limit = 1;
else CHP_PV_to_battery_limit = 0;
end

%% determine your rules
state = 'default';

if support && battery_available && battery_support
    state = 'battery_supplies_all_surplus'; end

if support && battery_available && ~battery_support
    state = 'CHP_PV_battery_extrapower_grid'; end

if support && ~battery_available
    state = 'CHP_PV_and_extrapower_grid'; end

if ~support && battery_full && extra_power_grid
    state = 'CHP_PV_and_extrapower_grid'; end

if ~support && battery_full && ~extra_power_grid && CHP_to_battery
```

```
    state = 'CHP_supplies_load'; end

if ~support && battery_full && ~extra_power_grid && ~CHP_to_battery
    state = 'CHP_and_PV_supply_all'; end

if ~support && ~battery_full && extra_power_grid && charge_battery_limit
    state = 'grid_to_charge_battery_limit'; end

if ~support && ~battery_full  && extra_power_grid && ~charge_battery_limit
    state = 'grid_to_charge_battery_rest'; end

if ~support && ~battery_full && ~extra_power_grid && CHP_to_battery ...
        && CHP_to_battery_limit
    state = 'CHP_to_charge_battery_limit'; end

if ~support && ~battery_full  && ~extra_power_grid && CHP_to_battery ...
        && ~CHP_to_battery_limit && CHP_PV_to_battery_limit
    state = 'CHP_and_PV_to_charge_battery_limit'; end

if ~support && ~battery_full  && ~extra_power_grid && CHP_to_battery ...
        && ~CHP_to_battery_limit && ~CHP_PV_to_battery_limit
    state = 'CHP_PV_and_grid_to_charge_battery_limit'; end

if ~support && ~battery_full  && ~extra_power_grid && ~ CHP_to_battery ...
        && CHP_PV_to_battery_limit
    state = 'CHP_and_PV_to_charge_battery_limit'; end

if ~support && ~battery_full  && ~extra_power_grid && ~ CHP_to_battery ...
        && ~CHP_PV_to_battery_limit
    state = 'CHP_PV_and_grid_to_charge_battery_limit'; end

%% define the states
switch state

     case 'battery_supplies_all_surplus'
         grid_supply = max_desired_power_grid;
         battery = - needed_extra_power;
         CHP = CHP_max;
         PV = PV_power;
     case 'CHP_PV_battery_extrapower_grid'
         grid_supply = load - CHP_max - PV_power - max_discharge_power;
         battery = - max_discharge_power;
         CHP = CHP_max;
         PV = PV_power;
     case 'CHP_PV_and_extrapower_grid'
         grid_supply = load - CHP_max - PV_power;
         battery = 0;
         CHP = CHP_max;
         PV = PV_power;
     case 'CHP_supplies_load'
         battery = 0;
         CHP = load;
         CHP_surplus = CHP_max - load;
         PV_surplus = PV_power;
     case 'CHP_and_PV_supply_all'
         CHP = CHP_max;
         PV = load - CHP_max;
         PV_surplus = PV_power - (load - CHP_max);
     case 'grid_to_charge_battery_limit'
```

```
        grid_supply = load - CHP_max - PV_power + max_charge_power;
        battery = max_charge_power;
        CHP = CHP_max;
        PV = PV_power;
    case 'grid_to_charge_battery_rest'
        grid_supply = max_desired_power_grid;
        battery = max_desired_power_grid - (load - CHP_max - PV_power);
        CHP = CHP_max;
        PV = PV_power;
    case 'CHP_to_charge_battery_limit'
        battery = max_charge_power;
        CHP = load + max_charge_power;
        CHP_surplus = CHP_max - (load + max_charge_power);
        PV_surplus = PV_power;
    case 'CHP_and_PV_to_charge_battery_limit'
        battery = max_charge_power;
        CHP = CHP_max;
        PV = load - CHP_max + max_charge_power;
        PV_surplus = PV_power - (load - CHP_max + max_charge_power);
    case 'CHP_PV_and_grid_to_charge_battery_limit'
        grid_supply = load - CHP_max - PV_power + max_charge_power;
        battery = max_charge_power;
        CHP = CHP_max;
        PV = PV_power;
    otherwise
        disp('error');
end


%% variables for graphing
if battery < 0
    dis_battery = - battery;
else
    char_battery = battery;
end

end
```

Appendix 12: Prices Code

```
%% PRICES
kWh = 1/(3600*1000);

%% GRID TO PROVIDE ALL THE LOAD
%  Power
grid_power_price = 63; % €/kW
maximum_value_load = max(load_W.Data)/1000;
grid_to_load_total_power_cost = grid_power_price * maximum_value_load ...
    /365 *number_days;

%  Energy
grid_energy_price = 0.15; % €/kWh
grid_to_load_total_energy_cost = 0;
for n=2:length(load_W.Data)
    a = n-1;
    grid_to_load_total_energy_cost = grid_to_load_total_energy_cost ...
        +T * load_W.Data(n) * (load_W.Time(n) - load_W.Time(a));
end
grid_to_load_total_energy_cost = grid_to_load_total_energy_cost ...
    * kWh * grid_energy_price;

pay_grid_provide_all = grid_to_load_total_power_cost ...
    + grid_to_load_total_energy_cost;

%% GRID
%  Grid power
grid_power_price = 63; % €/kW
maximum_value_grid = max(grid_supply.Data)/1000;
grid_total_power_cost = grid_power_price * maximum_value_grid ...
    /365 *number_days;

%  Grid energy
grid_energy_price = 0.15; % €/kWh
grid_total_energy_cost = 0;
for n=2:length(grid_supply.Data)
    a = n-1;
    grid_total_energy_cost = grid_total_energy_cost ...
        +T *grid_supply.Data(n)*(grid_supply.Time(n)-grid_sup-
ply.Time(a));
end
grid_total_energy_cost = grid_total_energy_cost * kWh * grid_en-
ergy_price;

%%  BATTERY
battery_capacity_kWh = battery_capacity/1000*nominal_battery_voltage;

if battery_capacity_kWh == 40;
     battery_investment = 4000*max_discharge_power/1000 + 60000;
end
if battery_capacity_kWh == 70;
    battery_investment = 3700*max_discharge_power/1000 + 78000;
end
if battery_capacity_kWh == 100;
    battery_investment = 2600*max_discharge_power/1000 + 111500;
end
if battery_capacity_kWh == 130;
```

```
     battery_investment = 3094.4*max_discharge_power/1000 + 111636;
end
if battery_capacity_kWh == 400;
    battery_investment = 2834*max_discharge_power/1000 + 284786;
end
if battery_capacity_kWh == 800;
     battery_investment = 4096.6*max_discharge_power/1000 + 372311;
end
if battery_capacity_kWh == 1600;
    battery_investment = 5850.3*max_discharge_power/1000 + 575170;
end
if strcmp(battery_type, 'lead acid')
    battery_investment = battery_investment/7;
end

%% CHP
% CHP investment
CHP_investment = CHP_max/1000 * (9332.6*(CHP_max/1000)^-0.4611);

% CHP surplus
feed_in_price_CHP = 0.105; % €/kWh
CHP_total_surplus_benefit = 0;
for n=2:length(CHP_surplus.Data)
    a = n-1;
    CHP_total_surplus_benefit = CHP_total_surplus_benefit ...
        +T*CHP_surplus.Data(n)*(CHP_surplus.Time(n)-CHP_surplus.Time(a));
end
CHP_total_surplus_benefit=CHP_total_surplus_bene-
fit*kWh*feed_in_price_CHP;

% CHP electricity and heat prices
Top = 8000; % Operation time per year (h/a)
% Heat energy produced in a year (kWhth/a)
Eh = CHP_heat_power/1000 * Top * CHP_heat_efficiency;
gas_boiler_efficiency = 0.9;
gas_price = 0.045; % €/kWh
heat_price = gas_price / gas_boiler_efficiency; % €/kWhth
% Electric energy produced in a year (kWhe/a)
Ee = CHP_max/1000 * Top * CHP_electric_efficiency;
Ta = 1; % Amortization time, payback time of the investment
Cop = 2.3133/100 * (CHP_max/1000)^-0.141;%Operational annual cost(€/kWhe)
CHP_electricity_price=(CHP_investment/Ta+Cop*Ee-Eh*heat_price)/Ee;%€/kWhe
CHP_total_electric_cost=T*CHP_max*length(load)*kWh*CHP_electricity_price;
CHP_total_heat_cost=T*CHP_heat_power*length(load)*kWh*heat_price;

pay_grid_batt_and_CHP = grid_total_power_cost + grid_total_energy_cost
              ...+ CHP_total_electric_cost - CHP_total_surplus_benefit;
investment_grid_batt_and_CHP = battery_investment + CHP_investment;
pay_back_grid_batt_and_CHP = investment_grid_batt_and_CHP ...
    /((pay_grid_provide_all - pay_grid_batt_and_CHP)*365/number_days);

%% PV
if strcmp(pvexist, 'Yes')
% PV investment
    PV_price = 1250; % €/kWp
    PV_investment = PV_price * PV_kWp;
% PV surplus
    feed_in_price_PV = 0.11; % €/kWh
    PV_total_surplus_benefit = 0;
    for n=2:length(PV_surplus.Data)
```

```
        a = n-1;
        PV_total_surplus_benefit = PV_total_surplus_benefit ...
            +T *PV_surplus.Data(n) *(PV_surplus.Time(n) ...
            - PV_surplus.Time(a));
    end
    PV_total_surplus_benefit = PV_total_surplus_benefit * kWh ...
        *feed_in_price_PV;
    pay_grid_batt_CHP_and_PV = pay_grid_batt_and_CHP - ...
        PV_total_surplus_benefit;
    investment_grid_batt_CHP_and_PV = investment_grid_batt_and_CHP ...
        + PV_investment;
    pay_back_grid_batt_CHP_and_PV = investment_grid_batt_CHP_and_PV ...
        /((pay_grid_provide_all - pay_grid_batt_CHP_and_PV) ...
        * 365/number_days);
end
```

Appendix 13: Prices 2 Code

```
%% PRICES 2
kWh = 1/(3600*1000);

%% GRID TO PROVIDE ALL THE LOAD
%  Power
grid_power_price = 63; % €/kW
maximum_value_load = max(load_W.Data)/1000;
grid_to_load_total_power_cost = grid_power_price * maximum_value_load ...
    /365 *number_days;

%  Energy
grid_energy_price = 0.15; % €/kWh
grid_to_load_total_energy_cost = 0;
for n=2:length(load_W.Data)
    a = n-1;
    grid_to_load_total_energy_cost = grid_to_load_total_energy_cost ...
        +T * load_W.Data(n) * (load_W.Time(n) - load_W.Time(a));
end
grid_to_load_total_energy_cost = grid_to_load_total_energy_cost ...
    * kWh * grid_energy_price;

pay_grid_provide_all = grid_to_load_total_power_cost ...
    + grid_to_load_total_energy_cost;

%% GRID
%  Grid power
grid_power_price = 63; % €/kW
maximum_value_grid = max(grid_supply.Data)/1000;
grid_total_power_cost = grid_power_price * maximum_value_grid ...
    /365 *number_days;

%  Grid energy
grid_energy_price = 0.15; % €/kWh
grid_total_energy_cost = 0;
for n=2:length(grid_supply.Data)
    a = n-1;
    grid_total_energy_cost = grid_total_energy_cost ...
        +T *grid_supply.Data(n) *(grid_supply.Time(n) ...
        - grid_supply.Time(a));
end
grid_total_energy_cost = grid_total_energy_cost * kWh * grid_en-
ergy_price;
%%  BATTERY
if battery_investment_user == 0
    battery_capacity_kWh = battery_capacity/1000*nominal_battery_voltage;
    battery_investment_user = 5555.6*battery_capacity_kWh^0.784;
end

if strcmp(battery_type, 'lead acid')
    battery_investment_user = battery_investment_user/7;
end
%% CHP
% CHP investment
CHP_investment = CHP_max/1000 * (9332.6*(CHP_max/1000)^-0.4611);
% CHP surplus
feed_in_price_CHP = 0.105; % €/kWh
```

```
CHP_total_surplus_benefit = 0;
for n=2:length(CHP_surplus.Data)
    a = n-1;
    CHP_total_surplus_benefit = CHP_total_surplus_benefit ...
        +T *CHP_surplus.Data(n) *(CHP_surplus.Time(n) - ...
        CHP_surplus.Time(a));
end
CHP_total_surplus_benefit=CHP_total_surplus_bene-
fit*kWh*feed_in_price_CHP;
% CHP electricity and heat prices
Top = 8000; % Operation time per year (h/a)
CHP_heat_power = CHP_max * 1.2;
CHP_heat_efficiency = 0.49;
% Heat energy produced in a year (kWhth/a)
Eh = CHP_heat_power/1000 * Top * CHP_heat_efficiency;
gas_boiler_efficiency = 0.9;
gas_price = 0.045; % €/kWh
heat_price = gas_price / gas_boiler_efficiency; % €/kWhth
% Electric energy produced in a year (kWhe/a)
Ee = CHP_max/1000 * Top * CHP_electric_efficiency;
Ta = 1; % Amortization time, payback time of the investment
Cop = 2.3133/100 * (CHP_max/1000)^-0.141;%Operational annual cost
(€/kWhe)
CHP_electricity_price = (CHP_investment/Ta + Cop*Ee ...
    - Eh*heat_price)/Ee; % €/kWhe
CHP_total_electric_cost = T*CHP_max*length(load)*kWh*CHP_electric-
ity_price;
CHP_total_heat_cost = T*CHP_heat_power*length(load)*kWh*heat_price;

pay_grid_batt_and_CHP = grid_total_power_cost + grid_total_energy_cost
...
    + CHP_total_electric_cost - CHP_total_surplus_benefit;
investment_grid_batt_and_CHP = battery_investment_user + CHP_investment;
pay_back_grid_batt_and_CHP = investment_grid_batt_and_CHP ...
    /((pay_grid_provide_all - pay_grid_batt_and_CHP)*365/number_days);
%% PV
if strcmp(pvexist, 'Yes')
% PV investment
    PV_price = 1250; % €/kWp
    PV_investment = PV_price * PV_kWp;
% PV surplus
    feed_in_price_PV = 0.11; % €/kWh
    PV_total_surplus_benefit = 0;
    for n=2:length(PV_surplus.Data)
        a = n-1;
        PV_total_surplus_benefit = PV_total_surplus_benefit ...
            +T *PV_surplus.Data(n) *(PV_surplus.Time(n) - ...
            PV_surplus.Time(a));
    end
    PV_total_surplus_benefit = PV_total_surplus_benefit * kWh ...
        * feed_in_price_PV;
    pay_grid_batt_CHP_and_PV = pay_grid_batt_and_CHP - ...
        PV_total_surplus_benefit;
    investment_grid_batt_CHP_and_PV = investment_grid_batt_and_CHP ...
        + PV_investment;
    pay_back_grid_batt_CHP_and_PV = investment_grid_batt_CHP_and_PV ...
        /((pay_grid_provide_all - pay_grid_batt_CHP_and_PV) * ...
        365/number_days);
end
```

Appendix 14: Program Results Code

```
%% PROGRAM RESULTS
% graphs
hl = figure;
set(hl,'visible','off');
if strcmp(pvexist, 'Yes')
    X = load_W.Time*T/3600;
    grid_new = grid_supply.Data - char_battery.Data;
    Y = [CHP.Data,grid_new,char_battery.Data,PV.Data, ...
    dis_battery.Data]/1000;
    subplot (20,1,[1 13]);
    harea = area(X, Y);
    x_step_tick = number_days * 2.5;
    set(gca, 'XTick', [0:x_step_tick:length(load)])
    set(harea(2),'FaceColor',[0 .9 1]);
    set(harea(3),'FaceColor',[0 .5 0]);
    set(harea(4),'FaceColor',[1 .8 0]);
    set(harea(5),'FaceColor',[.5 .1 .1]);
    title ('Power Balance','FontSize', 12,'FontWeight','bold')
    xlabel('Time (h)','FontSize', 10)
    ylabel('Power (kW)','FontSize', 10)
    hleg1 = legend('CHP','Grid - Charge Battery', ...
        'Charge Battery','PV','Discharge Battery');
    set(hleg1,'FontSize', 7,'Location','SouthEast')
else
    X = load_W.Time*T/3600;
    grid_new = grid_supply.Data - char_battery.Data;
    Y = [CHP.Data,grid_new,char_battery.Data,dis_battery.Data]/1000;
    subplot (20,1,[1 13]);
    harea = area(X, Y);
    x_step_tick = number_days * 2.5;
    set(gca, 'XTick', [0:x_step_tick:length(load)])
    set(harea(3),'FaceColor',[0 .5 0]);
    title ('Power Balance','FontSize', 12,'FontWeight','bold')
    xlabel('Time (h)','FontSize', 10)
    ylabel('Power (kW)','FontSize', 10)
    hleg2 = legend('CHP','Grid - Charge Battery','Charge Battery', ...
        'Discharge Battery');
    set(hleg2,'FontSize', 7,'Location','SouthEast')
end
grid on

subplot (20,1,[17 20])
plot(SOC)
xlim([0 length(load)])
x_step_tick = number_days * 10;
set(gca, 'XTick', [0:x_step_tick:length(load)])
x_step_label = number_days*2.5;
set(gca,'XTickLabel',[0;x_step_label;2*x_step_label; ...
    3*x_step_label;4*x_step_label;5*x_step_label; ...
    6*x_step_label;7*x_step_label;8*x_step_label;9*x_step_label])
ylim([0 1])
set(gca,'YTick',[0;0.2;0.4;0.6;0.8;1])
title ('Battery State Of Charge','FontSize', 12,'FontWeight','bold')
xlabel('Time (h)','FontSize', 10)
ylabel('SOC','FontSize', 10)
grid on
```

```
mkdir('RESULTS WITH DEFAULT DATA');
saveas(hl,['Power_Balance CHP' num2str(run) '_Battery' ...
    num2str(sub_run)],'jpg');
movefile('*.jpg','RESULTS WITH DEFAULT DATA');

% text in Excel
header = {'','Recommended Battery Type',battery_type};
classinfo = {'Parameters','Values','Units'; 'Time Step',T/60,'min'; ...
    'Initial SOC',SOC_initial,'%'; 'Minimum SOC',SOC_min*100,'%'; ...
    'Nominal Battery Voltage',nominal_battery_voltage,'V'; ...
    'Battery Capacity',battery_capacity*nominal_battery_voltage/1000, ...
    'kWh'; 'Charge Rate',c_charge,'1/h'; ...
    'Discharge Rate',c_discharge,'1/h'; ...
    'Maximum Discharge Power of the Battery',max_discharge_power/1000, ...
    'kW'; 'Maximum Desired Power Grid',max_desired_power_grid/1000,'kW';
...
    'Nominal el. CHP Power',CHP_max/1000,'kW'; ...
    'CHP electric efficiency',CHP_electric_efficiency*100,'%'; ...
    'CHP heat Power',CHP_heat_power/1000,'kW'; ...
    'CHP heat efficiency',CHP_heat_efficiency*100,'%'; ...
    'Number of days',number_days,'days'};
headergridtoload = {'GRID TO PROVIDE ALL LOAD'};
gridpricetoload = {'Power','','',''; '','Parameters','Values','Units'; ...
    '','Power  Price',63,'€/kW';  '','Max.  Value',maximum_value_load,'kW';
...
    '','Total Power Price',grid_to_load_total_power_cost,'€'; ...
    'Energy','','',''; '','Parameters','Values','Units'; ...
    '','Energy Price',0.15,'€/kWh'; ...
    '','Total Energy Price',grid_to_load_total_energy_cost,'€'};
headergrid = {'GRID'};
gridprice = {'Power','','',''; '','Parameters','Values','Units'; ...
    '','Power  Price',63,'€/kW';  '','Max.  Value',maximum_value_grid,'kW';
...
    '','Total Power Price',grid_total_power_cost,'€'; ...
    'Energy','','',''; '','Parameters','Values','Units'; ...
    '','Energy Price',0.15,'€/kWh'; ...
    '','Total Energy Price',grid_total_energy_cost,'€'};
if strcmp(pvexist, 'Yes')
    headerPV = {'PV'};
    PVprice  =  {'Investment','','','';  '','Parameters','Values','Units';
...
        '','PV Price',PV_investment,'€'; 'Surplus','','',''; ...
        '','Parameters','Values','Units'; '','Feed in Price',0.1,'€/kWh';
...
        '','Total Surplus Price',PV_total_surplus_benefit,'€'};
end
headerbattery = {'BATTERY'};
batteryprice = {'Parameters','Values','Units'; ...
    'Battery Price',battery_investment,'€'};
headerCHP = {'CHP'};
CHPprice = {'Investment','','',''; '','Parameters','Values','Units'; ...
    '','CHP Price',CHP_investment,'€'; 'Surplus','','',''; ...
    '','Parameters','Values','Units';  '','Feed  in  Price',0.105,'€/kWh';
...
    '','Total Surplus Price',CHP_total_surplus_benefit,'€'; ...
    'Electricity and Heat','','',''; '','Parameters','Values','Units'; ...
    '','Electricity Price',CHP_electricity_price,'€/kWh'; ...
    '','Total Electric Price',CHP_total_electric_cost,'€'; ...
    '','Heat Price',heat_price,'€/kWh'; ...
    '','Total Heat Price',CHP_total_heat_cost,'€'};
summary = {'','SUMMARY',''; '','',''; 'GRID SUPPLIES ALL LOAD','',''; ...
```

```
    'MONEY TO PAY',pay_grid_provide_all,'€'};
if strcmp(pvexist, 'No')
    summary2 = {'GRID WITH BATT AND CHP','',''; ...
        'MONEY TO PAY',pay_grid_batt_and_CHP,'€'; ...
        'INVESTMENT',investment_grid_batt_and_CHP,'€'};
    summary3 = {'PAY-BACK',pay_back_grid_batt_and_CHP,'years'};
end
if strcmp(pvexist, 'Yes')
    summary2 = {'GRID WITH BATT, CHP AND PV','',''; ...
        'MONEY TO PAY',pay_grid_batt_CHP_and_PV,'€'; ...
        'INVESTMENT',investment_grid_batt_CHP_and_PV,'€'};
    summary3 = {'PAY-BACK',pay_back_grid_batt_CHP_and_PV,'years'};
end

xlswrite(['CHP_' num2str(run)],header,...
    ['battery ' num2str(sub_run)]);
xlswrite(['CHP_' num2str(run)],classinfo,...
    ['battery ' num2str(sub_run)],'B3');
xlswrite(['CHP_' num2str(run)],headergridtoload,...
    ['battery ' num2str(sub_run)],'B19');
xlswrite(['CHP_' num2str(run)],gridpricetoload,...
    ['battery ' num2str(sub_run)],'C20');
xlswrite(['CHP_' num2str(run)],headergrid,...
    ['battery ' num2str(sub_run)],'H1');
xlswrite(['CHP_' num2str(run)],gridprice,...
    ['battery ' num2str(sub_run)],'I2');
if strcmp(pvexist, 'Yes')
    xlswrite(['CHP_' num2str(run)],headerPV,...
        ['battery ' num2str(sub_run)],'H31');
    xlswrite(['CHP_' num2str(run)],PVprice,...
        ['battery ' num2str(sub_run)],'I32');
end
xlswrite(['CHP_' num2str(run)],headerbattery,...
    ['battery ' num2str(sub_run)],'H12');
xlswrite(['CHP_' num2str(run)],batteryprice,...
    ['battery ' num2str(sub_run)],'I13');
xlswrite(['CHP_' num2str(run)],headerCHP,...
    ['battery ' num2str(sub_run)],'H16');
xlswrite(['CHP_' num2str(run)],CHPprice,...
    ['battery ' num2str(sub_run)],'I17');
xlswrite(['CHP_' num2str(run)],summary,...
    ['battery ' num2str(sub_run)],'N1');
xlswrite(['CHP_' num2str(run)],summary2,...
    ['battery ' num2str(sub_run)],'N6');
xlswrite(['CHP_' num2str(run)],summary3,...
    ['battery ' num2str(sub_run)],'N10');

if run == 2 && sub_run == 20
    movefile('*.xls','RESULTS WITH DEFAULT DATA');
    steps = 1000;
    for step = 1:steps
        waitbar(step / steps)
    end
    close(h)
    msgbox('Simulation Completed','Success');
end
```

Appendix 15: Program Results 2 Code

```
%% PROGRAM RESULTS 2
% graphs
hl = figure;
set(hl,'visible','off');
if strcmp(pvexist, 'Yes')
    X = load_W.Time*T/3600;
    grid_new = grid_supply.Data - char_battery.Data;
    Y = [CHP.Data,grid_new,char_battery.Data,PV.Data,dis_battery.Data]
            .../1000;
    subplot (20,1,[1 13]);
    harea = area(X, Y);
    x_step_tick = number_days * 2.5;
    set(gca, 'XTick', [0:x_step_tick:length(load)])
    set(harea(2),'FaceColor',[0 .9 1]);
    set(harea(3),'FaceColor',[0 .5 0]);
    set(harea(4),'FaceColor',[1 .8 0]);
    set(harea(5),'FaceColor',[.5 .1 .1]);
    title ('Power Balance','FontSize', 12,'FontWeight','bold')
    xlabel('Time (h)','FontSize', 10)
    ylabel('Power (kW)','FontSize', 10)
    hleg1 = legend('CHP','Grid - Charge Battery','Charge Battery','PV',
            ...'Discharge Battery');
    set(hleg1,'FontSize', 7,'Location','SouthEast')
else
    X = load_W.Time*T/3600;
    grid_new = grid_supply.Data - char_battery.Data;
    Y = [CHP.Data,grid_new,char_battery.Data,dis_battery.Data]/1000;
    subplot (20,1,[1 13]);
    harea = area(X, Y);
    x_step_tick = number_days * 2.5;
    set(gca, 'XTick', [0:x_step_tick:length(load)])
    set(harea(3),'FaceColor',[0 .5 0]);
    title ('Power Balance','FontSize', 12,'FontWeight','bold')
    xlabel('Time (h)','FontSize', 10)
    ylabel('Power (kW)','FontSize', 10)
    hleg2 = legend('CHP','Grid - Charge Battery','Charge Battery', ...
        'Discharge Battery');
    set(hleg2,'FontSize', 7,'Location','SouthEast')
end
grid on

subplot (20,1,[17 20])
plot(SOC)
xlim([0 length(load)])
x_step_tick = number_days * 10;
set(gca, 'XTick', [0:x_step_tick:length(load)])
x_step_label = number_days*2.5;
set(gca,'XTickLabel',[0;x_step_label;2*x_step_label; ...
    3*x_step_label;4*x_step_label;5*x_step_label; ...
    6*x_step_label;7*x_step_label;8*x_step_label;9*x_step_label])
ylim([0 1])
set(gca,'YTick',[0;0.2;0.4;0.6;0.8;1])
title ('Battery State Of Charge','FontSize', 12,'FontWeight','bold')
xlabel('Time (h)','FontSize', 10)
ylabel('SOC','FontSize', 10)
grid on
```

```
mkdir('YOUR OWN RESULTS');
saveas(hl, 'Power_Balance', 'jpg');
movefile('Power_Balance.jpg','YOUR OWN RESULTS');

% text in Excel
header = {'','Recommended Battery Type',battery_type};
classinfo = {'Parameters','Values','Units'; 'Time Step',T/60,'min'; ...
    'Initial SOC',SOC_initial,'%'; 'Minimum SOC',SOC_min*100,'%'; ...
    'Nominal Battery Voltage',nominal_battery_voltage,'V'; ...
    'Battery Capacity',battery_capacity*nominal_battery_voltage/1000, ...
    'kWh'; 'Charge Rate',c_charge,'1/h'; ...
    'Discharge Rate',c_discharge,'1/h'; ...
    'Maximum Discharge Power of the Battery',max_discharge_power/1000,
 ...'kW'; 'Maximum Desired Power Grid',max_desired_power_grid/1000,'kW';
 ...'Nominal el. CHP Power',CHP_max/1000,'kW'; ...
    'CHP electric efficiency',CHP_electric_efficiency*100,'%'; ...
    'CHP heat Power',CHP_heat_power/1000,'kW'; ...
    'CHP heat efficiency',CHP_heat_efficiency*100,'%'; ...
    'Number of days',number_days,'days'};
headergridtoload = {'GRID TO PROVIDE ALL LOAD'};
gridpricetoload = {'Power','','',''; '','Parameters','Values','Units';
... '','Power Price',63,'€/kW'; '','Max. Value',maximum_value_load,'kW';
... '','Total Power Price',grid_to_load_total_power_cost,'€'; ...
    'Energy','','',''; '','Parameters','Values','Units'; ...
    '','Energy Price',0.15,'€/kWh'; ...
    '','Total Energy Price',grid_to_load_total_energy_cost,'€'};
headergrid = {'GRID'};
gridprice = {'Power','','',''; '','Parameters','Values','Units'; ...
    '','Power Price',63,'€/kW'; '','Max. Value',maximum_value_grid,'kW';
... '','Total Power Price',grid_total_power_cost,'€'; ...
    'Energy','','',''; '','Parameters','Values','Units'; ...
    '','Energy Price',0.15,'€/kWh'; ...
    '','Total Energy Price',grid_total_energy_cost,'€'};
if strcmp(pvexist, 'Yes')
    headerPV = {'PV'};
    PVprice = {'Investment','','',''; '','Parameters','Values','Units';
... '','PV Price',PV_investment,'€'; 'Surplus','','',''; ...
        '','Parameters','Values','Units'; '','Feed in Price',0.1,'€/kWh';
... '','Total Surplus Price',PV_total_surplus_benefit,'€'};
end
headerbattery = {'BATTERY'};
batteryprice = {'Parameters','Values','Units'; ...
    'Battery Price',battery_investment_user,'€'};
headerCHP = {'CHP'};
CHPprice = {'Investment','','',''; '','Parameters','Values','Units'; ...
    '','CHP Price',CHP_investment,'€'; 'Surplus','','',''; ...
    '','Parameters','Values','Units'; '','Feed in Price',0.105,'€/kWh';
... '','Total Surplus Price',CHP_total_surplus_benefit,'€'; ...
    'Electricity and Heat','','',''; '','Parameters','Values','Units';
... '','Electricity Price',CHP_electricity_price,'€/kWh'; ...
    '','Total Electric Price',CHP_total_electric_cost,'€'; ...
    '','Heat Price',heat_price,'€/kWh'; ...
    '','Total Heat Price',CHP_total_heat_cost,'€'};
summary = {'','SUMMARY',''; '','',''; 'GRID SUPPLIES ALL LOAD','',''; ...
    'MONEY TO PAY',pay_grid_provide_all,'€'};
if strcmp(pvexist, 'No')
    summary2 = {'GRID WITH BATT AND CHP','',''; ...
        'MONEY TO PAY',pay_grid_batt_and_CHP,'€'; ...
        'INVESTMENT',investment_grid_batt_and_CHP,'€'};
    summary3 = {'PAY-BACK',pay_back_grid_batt_and_CHP,'years'};
end
```

```
if strcmp(pvexist, 'Yes')
    summary2 = {'GRID WITH BATT, CHP AND PV','',''; ...
        'MONEY TO PAY',pay_grid_batt_CHP_and_PV,'€'; ...
        'INVESTMENT',investment_grid_batt_CHP_and_PV,'€'};
    summary3 = {'PAY-BACK',pay_back_grid_batt_CHP_and_PV,'years'};
end

xlswrite('results',header,'simulation');
xlswrite('results',classinfo,'simulation','B3');
xlswrite('results',headergridtoload,'simulation','B19');
xlswrite('results',gridpricetoload,'simulation','C20');
xlswrite('results',headergrid,'simulation','H1');
xlswrite('results',gridprice,'simulation','I2');
if strcmp(pvexist, 'Yes')
    xlswrite('results',headerPV,'simulation','H31');
    xlswrite('results',PVprice,'simulation','I32');
end
xlswrite('results',headerbattery,'simulation','H12');
xlswrite('results',batteryprice,'simulation','I13');
xlswrite('results',headerCHP,'simulation','H16');
xlswrite('results',CHPprice,'simulation','I17');
xlswrite('results',summary,'simulation','N1');
xlswrite('results',summary2,'simulation','N6');
xlswrite('results',summary3,'simulation','N10');

movefile('results.xls','YOUR OWN RESULTS');
steps = 1000;
for step = 1:steps
    waitbar(step / steps)
end
close(h)
msgbox('Simulation Completed','Success');
```