Technical study of self-sufficient building

Using PV and Hydrogen

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Abstract

The increase of carbon dioxide in the atmosphere and the scarcity of raw materials lead to the development of new forms of energy generation and storage. This document studies the possibility of self-sufficient buildings using the sun's energy for power generation and hydrogen as a storage source. The proposed system must be capable of being self-sufficient, providing the necessary electrical and thermal energy for the comfort of a home located in the city of Munich, Germany. To obtain the necessary electrical energy, the system will have a photovoltaic field and a combined heat power. In turn, to supply the thermal demand, a heat pump and a boiler are included in the system. The variability of renewable energy will be managed by the different forms of storage, it is intended to include a battery system, a hot water tank and a hydrogen tank. For the correct integration of hydrogen, the system includes an electrolyser which use the excess of electrical generation to produce hydrogen, in addition, both the combined heat power and the boiler will be able to use the stored hydrogen as a fuel. According to the simulations, it is concluded that a house with an annual electricity consumption of 5.400 kW and a thermal load of 15.651 kWh can be self-sufficient using the proposed model an even more allows a total of 6.238 kWh to be delivered to the grid.

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Nomenclature

Acronyms / Abbreviations

AFC	Alkaline
ALK	Alkaline water electrolysis
BTM	Behind the meter
CHP	Combined Heat Power
EOY	End Of Year
EVs	Electric Vehicles
FTM	In-front-of-the-meter
HP	Heat Pump
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
MCFC	Molten carbonate
NG	Natural Gas
NREL	National Renewable Energy Laboratory
PAFC	Phosphoric acid
PEMFC	Proton exchange membrane Fuel Cell
PEM	Proton Exchange Membrane Electrolyzer
PHEVs	Plug-in Hybrid Electric Vehicles
PV	Photovoltaic
Soc	State of Charge

SOEC	Solid Oxide Electrolyzer cell
SOFC	Solid oxide
TES	Total Energy Supply

Chapter 1

Introduction

In the residential sector, the energy consumption of homes is concentrated in two major agents, electricity appliances and air conditioning [8]. Currently the most common ways of providing the energy needed for comfort in homes comes from fossil fuels, the most commonly used being oil and gas. In 2020, 59% of the european union's energy was generate by these two fossil fuels [9]. The use of fossil fuels for energy generation has drawbacks such as the emission of greenhouse gases and the variability of supply and demand [10]. This last aspect is an issue of great relevance nowadays worldwide and particularly at European level. The Russia-Ukraine war has created a sustained instability in recent months that has driven up commodity prices. Russia as one of the main exporters of fuels in the region has put in check the economies of the countries of the European Union, because of this the affected countries have had to adopt new strategies to supply their needs, in this aspect highlights Germany which is the largest consumer of energy per capita of the European Union and its energy depends heavily on the supply of Russia [11]. In 2020, 66,1% of Germany's gas imports came from Russia. The war situation has forced the European country to take extreme measures and it has set a 15% reduction in consumption between August 2022 and March 2023, to avoid gas shortages and spiraling prices. All these economic and environmental issues lead the scientific community to point to different forms of energy generation. Among the new technologies with greater use and development for energy generation are wind and solar power. According to the International Energy Agency (IEA) [12], solar power growth has been above forecasts in recent years, with 2021 figures revealing a capacity installed of 160 GW just this year. utility-scale solar projects continue to be the sector with the greatest development, contributing 60% of the total installed capacity. This is mainly due to the fact that in most cases it is the most profitable option to increase energy production for many countries. On the other hand, countries such as China, India and the EU continue to promote policies for the development of photovoltaic installations in the residential and commercial sectors.On wind energy, in

2021 the installed wind energy capacity was 110 GW and it is expected that in the next few years the installed capacity will be 75 GW per year.

Even when the generation problem seems to be resolved, the scientific community is facing a new challenge that comes from the variability of natural resources and leads to the investigation of storage forms that allow the management of the generated energy. There are several forms of energy storage [13] among which are: pumped hydroelectric, compressed air, flywheels [14], batteries, thermal energy storage just to mention a few. These forms of storage allow the accumulation of energy and with this to be able to manage it efficiently. Of the storage technologies mentioned, the most common in the residential sector are batteries [15], however, they are still expensive and are considered to be short term storage. This particular point has prompted the search for different technologies that allow for long term storage, this is where hydrogen plays an important role [16], [17]. In recent decades, the development of hydrogen as an energy vector has suffered ups and downs, however, the latest summits for climate change point to it as a key element for the integration of renewable energies. Currently, world hydrogen production is around 70 million tons per year being most of this produced and consumed in the same place [18]. Even though hydrogen is a widely developed technology, it still has problems that prevent it from fully expanding. Within the low points is the cost, storage and transport.

The integration of a system composed of photovoltaic generation and mixed storage of batteries and hydrogen represents a challenge that could cover the energy needs of homes and make them self-sufficient.

In this document, an analysis of the aforementioned integration is carried out. In addition, the system will integrate a heat pump for heating and a combined heat power unit for electricity generation powered by hydrogen [19].

Chapter 2

Problem Statement - Natural Gas (NG) Dependency

The global energy scenario continues to be led by fossil fuels. According to IEA figures, global energy production in 2019 (see Fig.2.1) was led by oil with 187.364.800 TJ, second was coal with 163.375.732 TJ and third was natural gas with 140.784.380 TJ. These three fossil fuels are responsible for more than 70% of the world's energy production, making them indispensable for most of the countries.

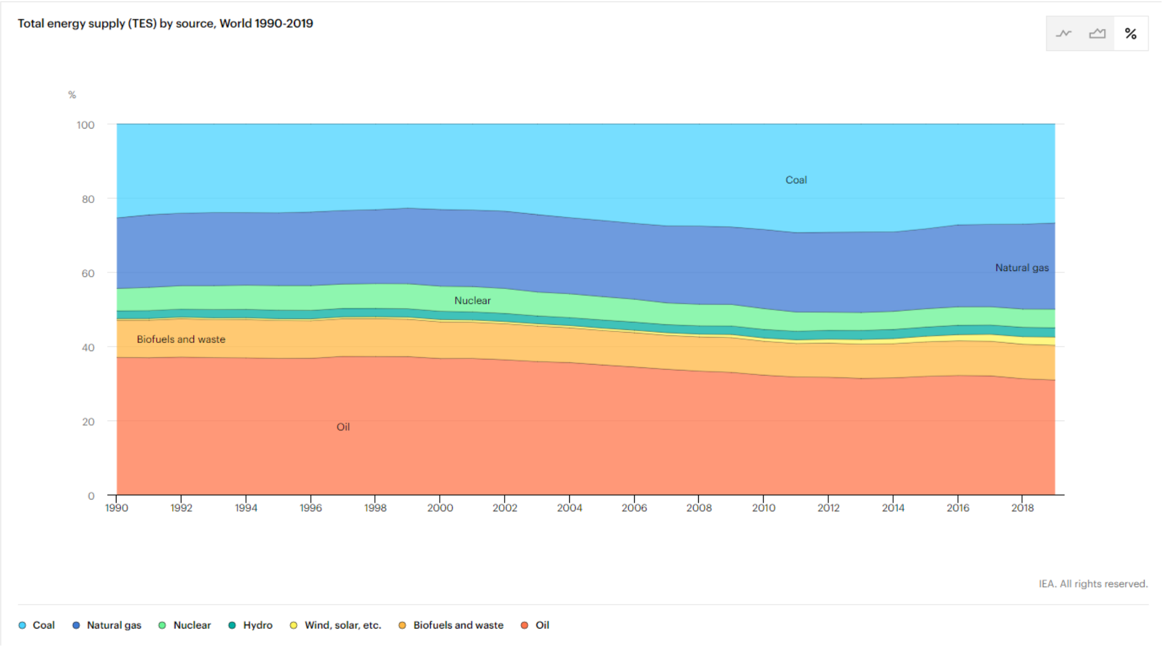


Figure 2.1 Total energy supply (TES) by source, World 1990-2019 [1].

With this in mind, the main objective of this work is to find a way to eliminate or at least reduce the dependence on these fossil fuels. For this purpose, the European continent and more specifically Germany will be taken as a case study.

The current energy situation in Germany is very similar to the worldwide trend with a supremacy of fossil fuels as energy source followed by wind, nuclear power, solar, biomass (wood and biofuels) and hydro. Among fossil fuels, oil produced 3.954.458 TJ of energy in 2020 and natural gas generated 3.118.859 TJ in the same year (See Fig.2.2).

Germany's energy plan underwent a major change at the end of 2010, when it launched the Energiewende meaning "energy turnaround" or "energy transformation", a major plan to make its energy system, which is mainly supplied by renewable energy sources, more efficient. The country has adopted a strategy for an energy pathway to 2050, which includes an accelerated phase-out of nuclear power by 2022.

Energiewende sets as objectives for 2030 that half of the country's energy production comes from natural resources and in 2038 the elimination of the use of coal as an energy source. On the other hand, it intends to install 20 GW of offshore wind by 2030 and 40 GW by 2040. Added to this is 5 GW in green hydrogen.

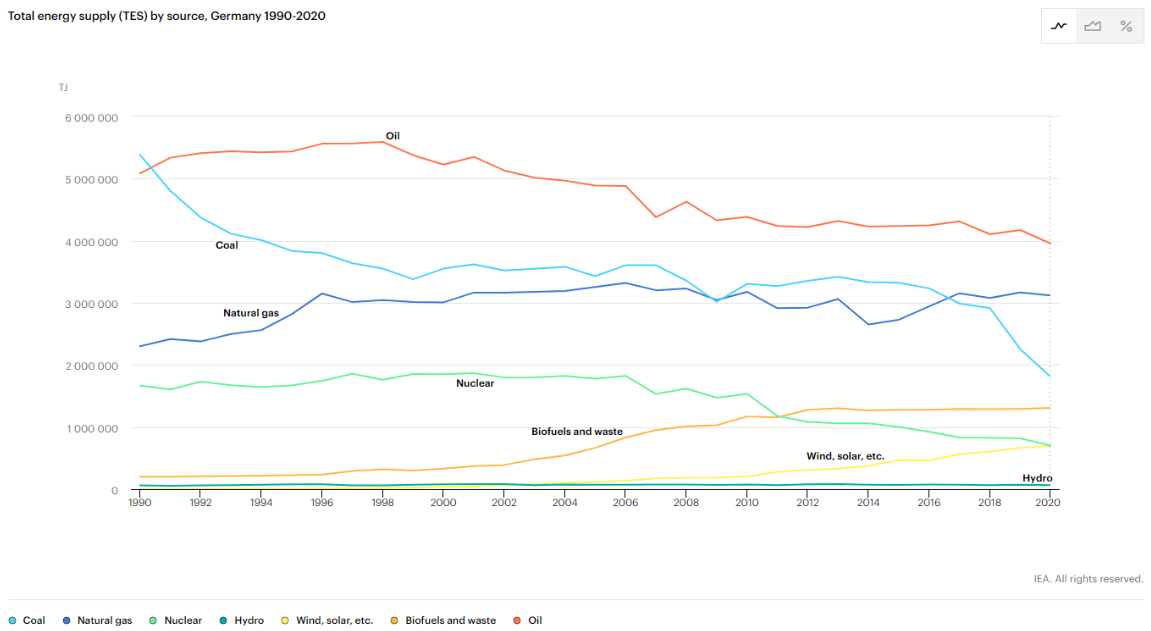


Figure 2.2 Total energy supply (TES) by source, Germany 1990-2020.

Even though energy policies have set ambitious and strict targets, Germany is still dependent on fossil fuels and, moreover, most of its energy is imported. According to EUROSTAT [20], in 2021, the energy imported by Germany was 63,7%.

In the year 2016 Germany was the fourth-largest consumer of coal in the world [21]. The low prices of coal imports led to the total closure of the mines of this mineral in 2018. This fact has led to Germany importing all its coal, reaching 31,8 MT in 2020. The main suppliers were Russia (45,4%), North America (18,3%) and Australia (12,3%) [20].

In addition to coal, natural gas is another of Germany's important imports. This fossil fuel was responsible for a quarter of the energy production in 2020 and 95% of the total NG was imported from another country. The figures form 2020 shows that 66,1% of gas imports come from Russia, 20,8% from Norway and 11,6% from The Netherlands (See Fig. 2.3).

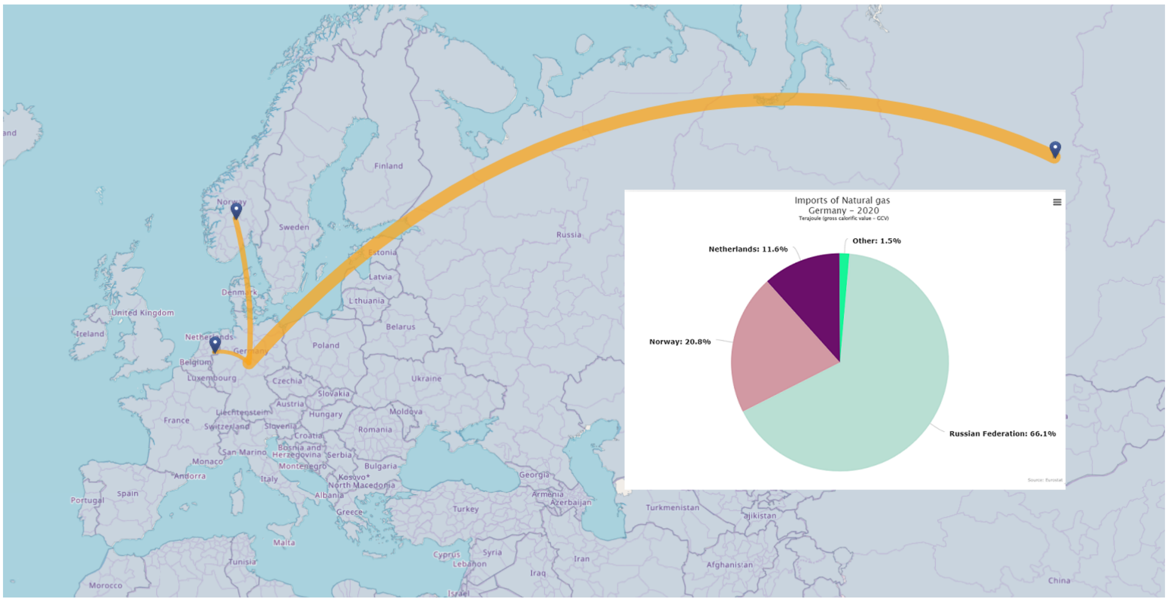


Figure 2.3 Imports of natural gas, Germany 2020.

Germany depends on Russia for about 33% of its total energy consumption. Substituting Russian imports of coal and oil is not the major challenge. Sufficient world market capacity exists from other oil and coal exporting countries to make up the shortfall. The greater challenge is to find short-run substitutes for Russian gas, which accounts for about 15% of Germany's total energy consumption. Owing to the existing pipeline network and limited terminal capacities, a short-term substitution via LNG is challenging, while raising pipeline imports from other countries is also subject to limitations [22].

Natural gas is a very important energy source in Germany for both electricity generation and heat production. Electricity generation by natural gas in 2020 reached 99.540 GWh and was the third largest source of electricity generation after coal and wind (See Fig. 2.4). On the other hand, natural gas was Germany's largest heat pro-

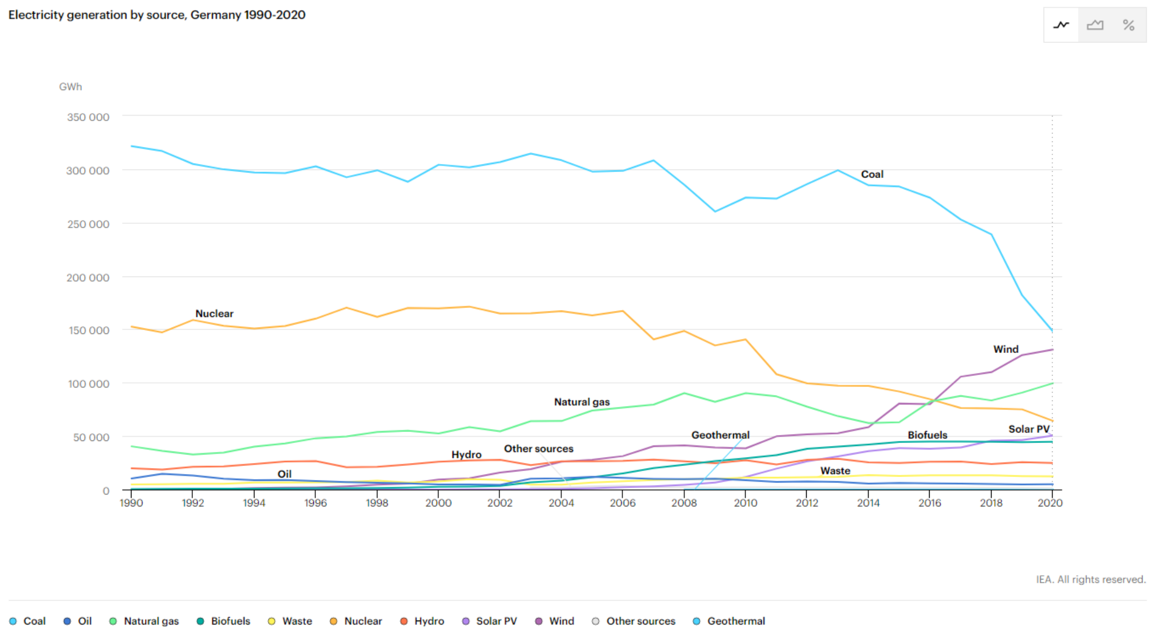


Figure 2.4 Electricity generation by source, Germany 1990-2020 [1].

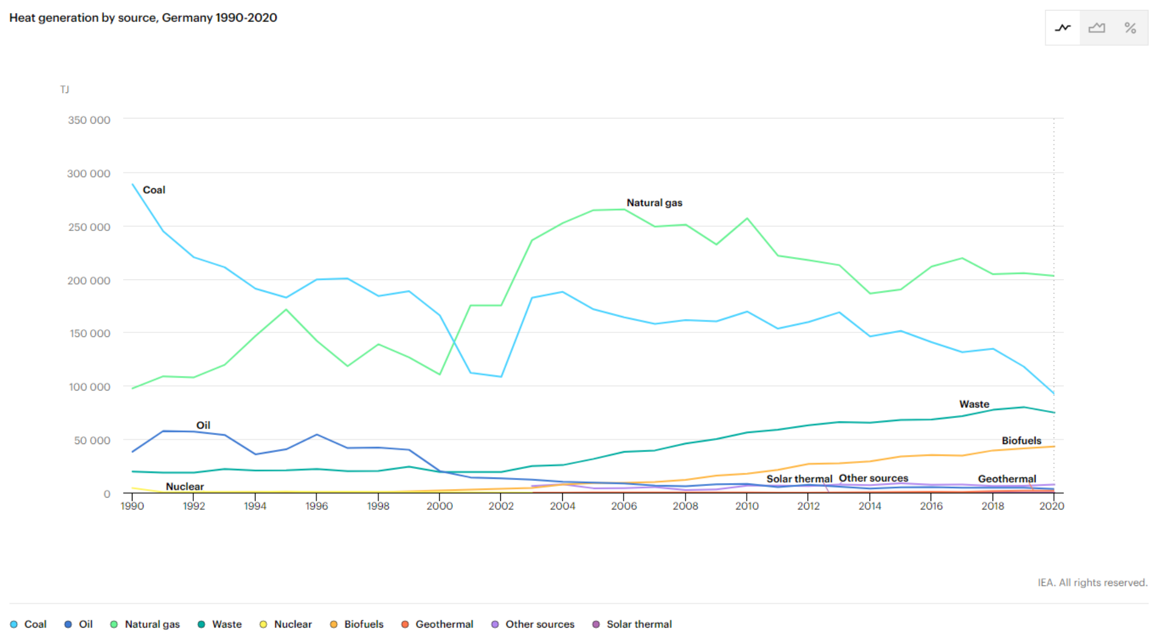


Figure 2.5 Heat generation by source, Germany 1990-2020 [1].

ducer in 2020, generating twice as much heat as coal with an annual output of 202.913 TJ (See Fig.2.5). It is important to point out that gas consumption in the residential sector exceeds gas consumption in the industrial sector, which could be explained by the fact that within residential use, natural gas was the largest producer of heat in 2020, with almost 50% of homes heated by this fuel (See Fig. 2.6).

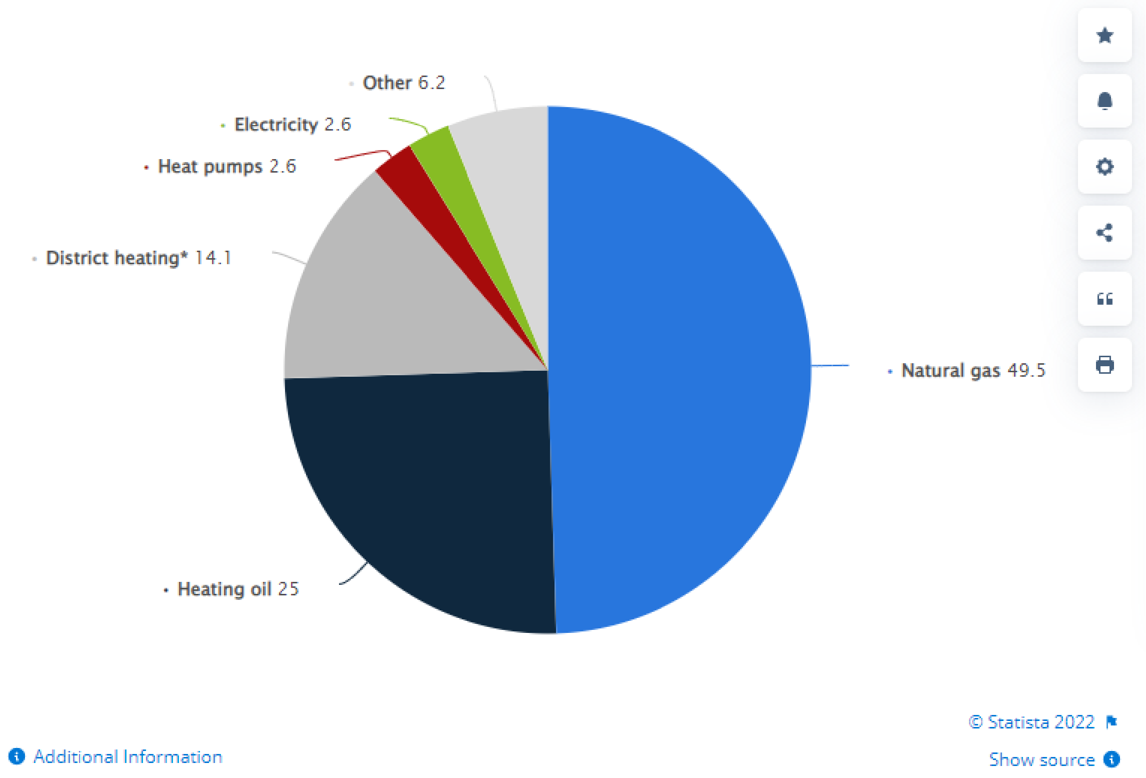


Figure 2.6 Distribution of household heating sources in Germany in 2020 [2].

According to figures from the German Energy Agency (DENA) [23] the three main energy consumers in Germany are trailing transport, industry and in third place with a 26% from the total the residential sector. DENA also points out that almost 84% of the energy consumed by the residential sector is for heating and hot water needs (Fig. 2.7). With this information, it is considered appropriate to propose a change in the forms of energy generation for residential use and more specifically to aim at the elimination of natural gas from homes through other forms of electricity generation, heat production and energy storage. The modification of residential energy production would bring significant changes in the overall result due to its large influence on the overall balance of energy consumption. The following chapter proposes an alternative to achieve these objectives.

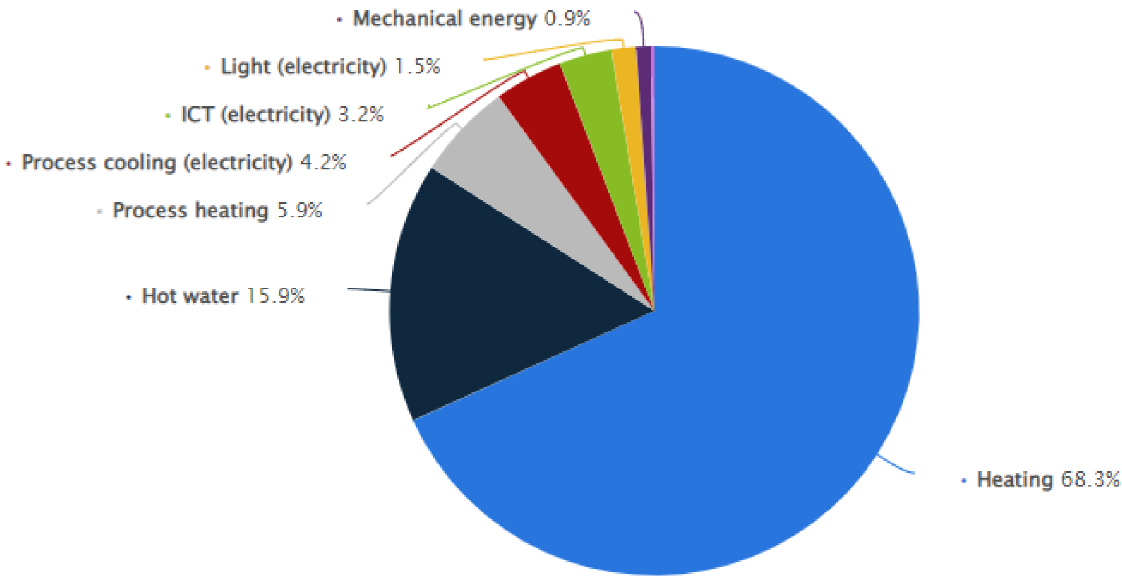


Figure 2.7 Share of final energy consumption in residential buildings in Germany in 2020, by end use [3].

Chapter 3

Methodology

In order to reduce dependence on fossil fuels, a system that eliminates the use of natural gas heaters and replaces them with heat pumps is proposed. In this way the residential sector, which is one of the largest consumers of natural gas, could drastically reduce its consumption. An overview of the proposed system can be seen in Figure 3.1. The system would be mainly composed of a photovoltaic field, heat pump, batteries, combined heat power and hydrogen generation and storage system. The diagram also proposes a small boiler that would act as an emergency system. Figure 3.1 also shows the presence of the electrical grid and the gas network, however, these would only be used in case of emergency and to discharge excess electricity or hydrogen.

The following is a description of the different components of the proposed system, which will be responsible for the generation of heat and electricity.

3.1 Electricity and Heat Generation

3.1.1 PV field

Edmond Becquerel in 1839 was the first scientist to discover the photovoltaic effect and is credited with the discovery of electricity generation by solar panels [24]. The photovoltaic effect is produced in semiconductor materials that in contact with the sun generate electric current. The process of energy generation takes place in the solar cells, the solar panel is formed by a set of cells. Silicon is the most widely used element for the manufacture of solar cells. Silicon is the 14th non-metallic element in the periodic table and has the quality to generate electricity by converting captured sunlight into electricity. There are several types of semiconductors, but silicon is still the most widely used, accounting for 95% of the cells manufactured today [24].

A typical solar cell design consists of two layers each doped with either phosphorus, positive doping, or boron, negative doping. The junction of the doped layers generates an electric field that forces the electrons to move, they flow through the solar cell until

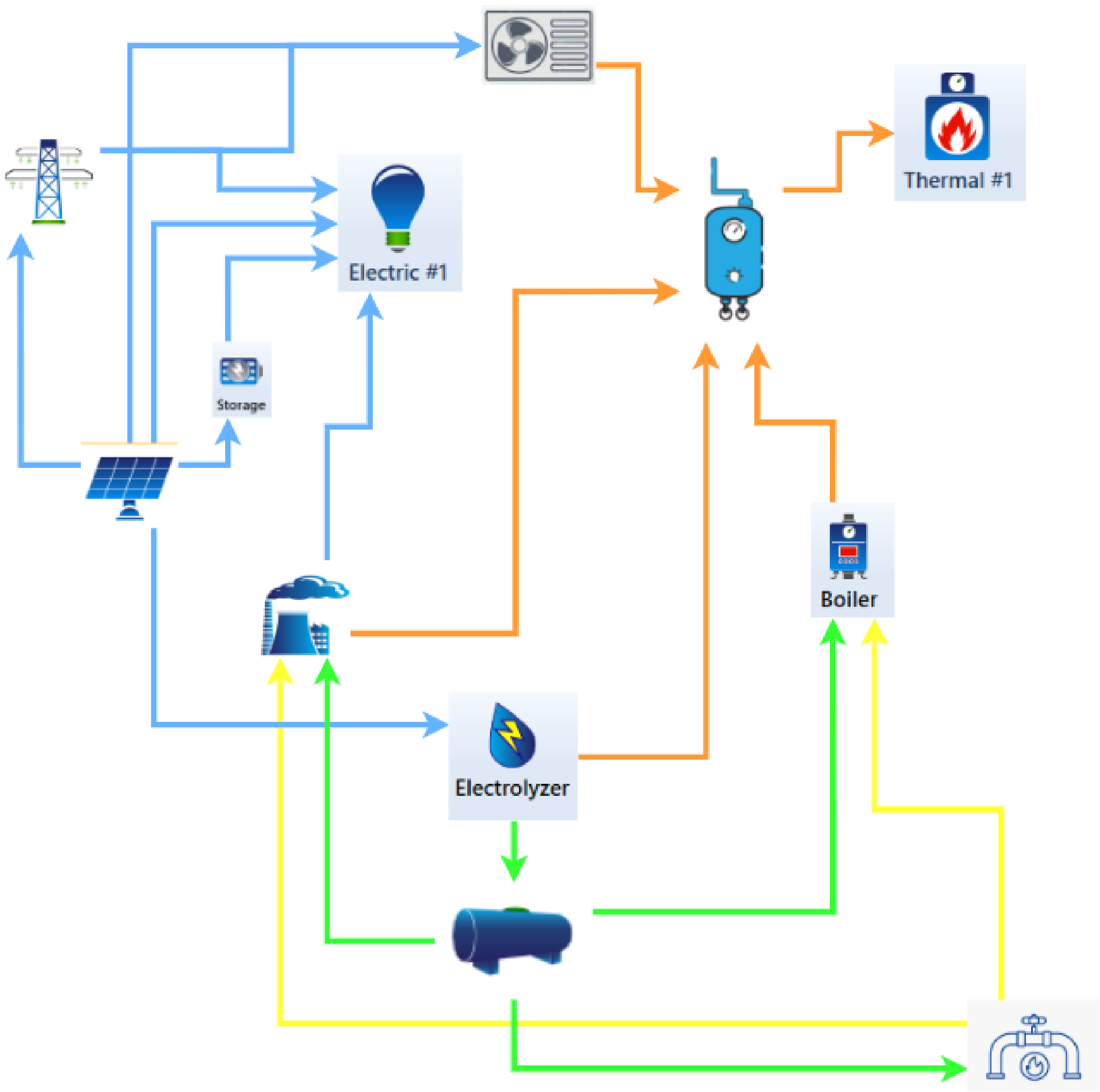


Figure 3.1 System configuration.

they leave the junction generating the electric current. The normal design of solar cells includes metal plates that have the function of capturing the electrons emitted by the cell and guide them to the connecting wires. It is at this point where the energy begins to flow to the inverter (most common design) or any other equipment depending on the configuration of the photovoltaic system.

Although silicon is the most widely used semiconductor for the creation of solar panels, there are other types of semiconductors that have been developed and studied due to their unique characteristics. Among them it can be mention: Multijunction cells; Single-junction gallium arsenide cells; Crystalline silicon cells; Thin-film technologies and Emerging photovoltaics [4]. The research to find more efficient solar cells does not stop, currently the efficiency of solar cells in the laboratory has reached a maximum of 47,1% efficiency for multijunction cells with 4 or more junctions (See Fig. 3.2).

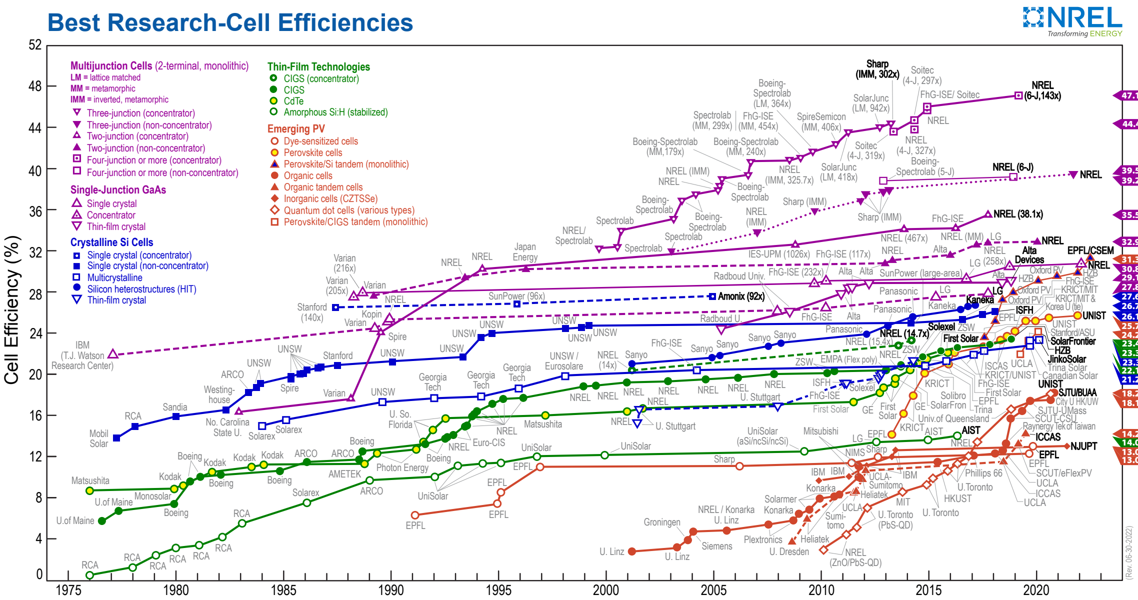


Figure 3.2 Best Research-Cell Efficiencies [4].

Solar cells are the most important part of the solar panel, however not the only one. Solar panels are made up of different elements that give solar cells insulation, greater durability and improve the efficiency of the panels. A solar panel is typically made up of the junction box, backsheet, encapsulant, solar cell array, encapsulant, tempered glass, and an aluminum frame. Each of these is vital to the life and function of the solar panel. For example, tempered glass offers protection and durability; the encapsulant and the backsheet prevents moisture inside the panel and allows better heat dissipation which improves the efficiency of the board.

Silicon cells can be divided into three large groups depending on their formation: monocrystalline, polycrystalline and amorphous silicon cells. Monocrystalline cells are made from a single silicon crystal, which allows a greater mobility of electrons, improving the efficiency of the cell. Monocrystallin cells are the most expensive cells and also the most efficient. Polycrystalline cells are made of silicon fragments, their efficiency is lower than single crystal cells but their cost is lower.Amorphous silicon is used for the manufacture of thin film solar cells, its efficiency is low, however it is useful in certain applications. The efficiency of monocrystalline panels at commercial level is between 15% and 20%, yet SunPower [25] has panels of 21,5%. Polycrystalline silicon panels have lower efficiencies of around 13-14%, however, some commercial polycrystalline panels have been designed with efficiencies of up to 18,3%

For this study, a variable peak power field will be used in order to perform different simulations and generate a wider range of results. The generator configuration will be of the static type on a pitched roof. The panels to be used will be *"TR 78M 555-575 Watt Mono-facial"* from Jinko. These panels have a peak power of "570 W" and are made of crystalline silicon. The data sheet can be found in Appendix A.

3.1.2 Heat Pump (HP)

A HP is a machine that takes heat from one point and moves it to another through an absorption process. It can generate cold or heat depending on the thermal needs of the site to be conditioned. When the process is heating, it takes the heat from the outside and takes it to the interior of the place to be heated. In the case of refrigeration, the process is the opposite, the HP takes the heat from the interior and takes it outside. Typically, the thermal absorption process is carried out by the refrigerant fluid, which circulates through a circuit made up of an evaporator, a compressor, a condenser and an expansion valve [26].

Depending on its configuration there are different types of HP, they can be classified as Air Source HP or Ground Source HP (Fig. 3.3).

Air source heat pump

This type of HP can be subdivided into two categories: Air-Air HP and Air-Water HP, the first are those typically used in air conditioners and their operation is based on collecting heat from the air in one space and depositing it in the air in another place. The Air-Water HP, on the other hand, take the heat from the air in a space and transfer it to a water circuit connected to radiators and/or to the domestic hot water system.

Ground source heat pumps

This category can also be subdivided into two categories, Water-Water HP and Ground-Water HP. The Water-Water HP use underground water from which they extract heat and transfer it to the water circuits of the house. The Ground-Water HP works through pipes buried in the ground from where they extract heat to move it to the water pipes of the houses.

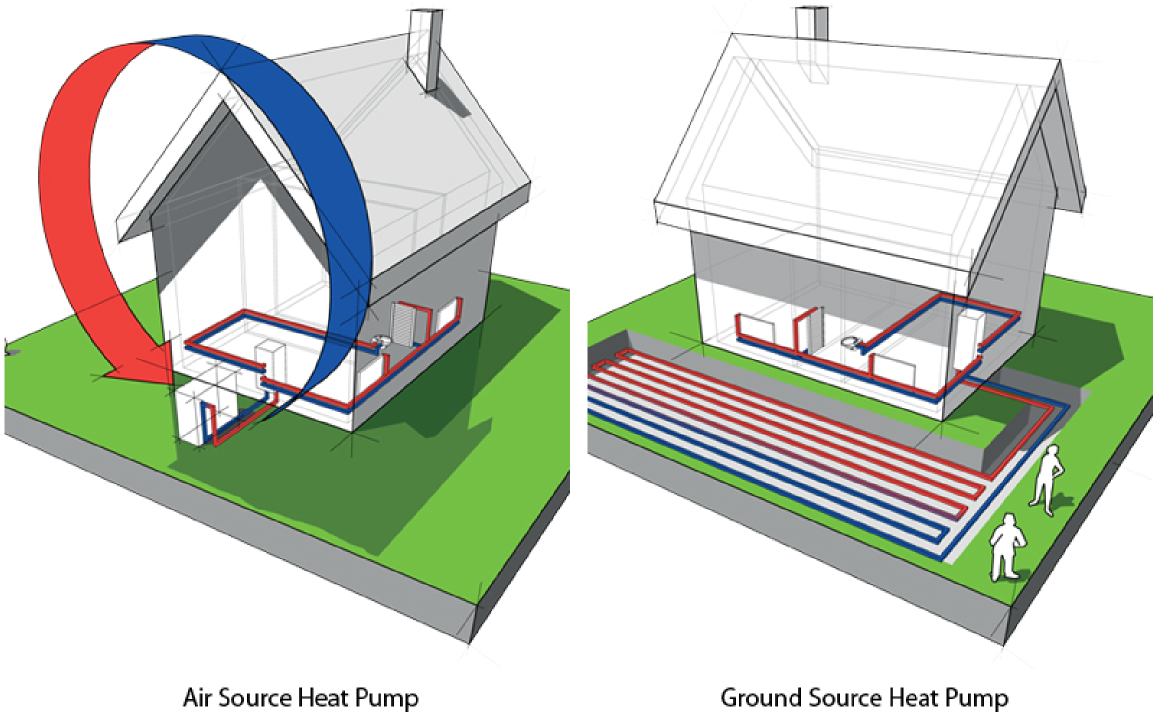


Figure 3.3 Air and ground sourced heat pump [5].

For this project the air source heat pump or also called air-to-water source heat pump will be the main component for heating and cooling and will be feed by the energy generated in the system. This component will allow the generation of cold in the summer months and heat in the winter months. It should be noted that this technology was chosen due to its high efficiency. HP typically has a performance ratio between 3 and 5, this means that by providing 1 kW of electricity for its operation, they can produce between 3 kW and 5 kW of thermal energy. The efficiencies of common conditioning methods do not come close to the efficiency values of HP, electric boilers have an efficiency of 10% and fossil fuels boilers do not exceed 95% efficiency [27].

3.1.3 Combined Heat Power - CHP

CHP, as its name indicates, is a technology that allows the generation of both electricity and heat. The use of heat allows this type of technology to achieve very high combined efficiencies depending on the type of machine. Another important characteristic is the diversity of fuels that it admits, being possible the use of hydrogen in some cases. CHP is a versatile technology capable of providing electricity and heat to different sectors from individual facility to utility resource for multiple end-users [28].

CHP can be used as an emergency equipment in case of power outages, acting uninterruptedly, in addition, it has the possibility of acting jointly with other types of energy such as battery storage and solar panels. Conventional forms of electricity generation have low efficiencies around 50%, however, when including heat as a product of energy generation, the equation changes, delivering efficiencies of the order of 80%. Consequently, the increased efficiency achieved by CHPs brings with it a reduction in carbon emissions [28].

Currently, the leading CHP technologies are 5: reciprocative engines, steam turbines, gas turbines, microturbines and fuel cells. All the mentioned technologies have unique characteristics and key performance indicators, Table 3.1 obtained from NREL [29] shows a comparison between the different technologies and their performance.

Fuel Cell

In this work the study will focus on only one of them, the fuel cell. Fuel cells allow the generation of electricity and water from the hydrogen through an electrochemical process. The type of fuel cell and the temperature of the process are very important as they determine the quality of the heat that can be recovered, the heat is recovered in the form of steam or hot water. The most common types of fuel cells depending on the electrochemical process they involve are: proton exchange membrane (PEMFC), phosphoric acid (PAFC), molten carbonate (MCFC), solid oxide fuel cell (SOFC) and alkaline fuel cell (AFC). Despite a high capital cost, CHP technology remains in high demand due to its important qualities such as power versatility, high efficiency, low carbon emissions, and low noise [30].

The use of a fuel cell as a co-generation unit is particularly interesting because of the favorable ratio of electrical energy to thermal energy. Thus, a design for covering the basic load of the building is possible in the electrical as well as in the heating sector [31].

Proton exchange membrane fuel cells (PEMFC) have emerged as a leading energy conversion technology for stationary, transportation, and portable electronic applications. The wide popularity of PEMFC as an alternative power source is owing to its low temperature operation (<100°C), remarkable efficiency (theoretical efficiency of 83%), quick start-up and shut-down cycle, and near-zero emission of environmentally malign greenhouse gases [32].

A PEMFC will be added to the system to ensure both electrical and thermal supply using hydrogen generated by the system itself as fuel. The efficiency and the heat/electricity ratio used will be extracted form the data available on NREL [29].

Table 3.1 Efficiency for different CHP technologies.

Efficiency	Electrically	Overall
Internal Combustion	34%	79%
Gas Turbine	30%	69%
Microturbine	25%	67%
Fuel Cell	47%	68%
Steam Turbine	23%	80%

3.1.4 Hydrogen Boiler

A gas-fired boiler provides hot water to taps throughout the home and also to radiators in the central heating system. Gas is an extremely efficient fuel and modern condensing boilers have large heat exchangers that collect and use almost all the heat created when the gas burns for heating and hot water, making the boilers 90% or more efficient [33].

To ensure the heat supply in the colder months, a boiler will be used which, like the CHP, will be fueled by hydrogen. Many brands are now offering a mix on gas and hydrogen in the ratio 4/1. It is expected that 100% hydrogen-fired burners will be available by 2025 [34]. The reasons for this slow progress are mainly due to the fact that hydrogen is not yet available to everyone. For this work, it is gonna be assume that the gas boiler could run with 100% hydrogen .

3.1.5 Electrolyzer

The proposed system will be configured in such a way that the electrical energy generated by the photovoltaic field that is not used will be converted into hydrogen through an electrolyzer. The electrolyzer is a device that allows the production of hydrogen through a chemical process (electrolysis) capable of separating the hydrogen and oxygen molecules of which water is composed using electricity. Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte. Different electrolyzers function in different ways, mainly due to the different type of electrolyte material involved and the ionic species it conducts. The three most common technologies today are alkaline water electrolysis (ALK), Proton Exchange Membrane (PEM), and Solid Oxide Electrolyzer cell (SOEC). ALK is the more studied technology with more than a century of research, but PEM are rapidly reaching maturity and are of particular interest for power-to-gas applications, while solid oxide electrolyzers are transitioning from the laboratory to the demonstration phase [35].

PEM

For this work the technology proposed will be PEM. According to IRENA [6], the characteristics of its membranes and electrodes allow it to achieve greater efficiency than other types of electrolyzers. The cost of components used for its manufacture make PEM higher in price comparing to alkaline electrolyzers. PEMs have a compact and simple system designs, a typical PEM design can be seen in Fig. 3.4. The technical information also shows that the heat available form the electrolyzer is the 20%, all this data will be use to carried out the simulation.

Currently, there are some companies in Germany that integrate PEM electrolyzers in the residential sector, some of the most used electrolyzers are the "ME100/350" model from the manufacturer H-TEC with a nominal power of 225 kW and which ensures an efficiency of 74% under standard conditions [36].

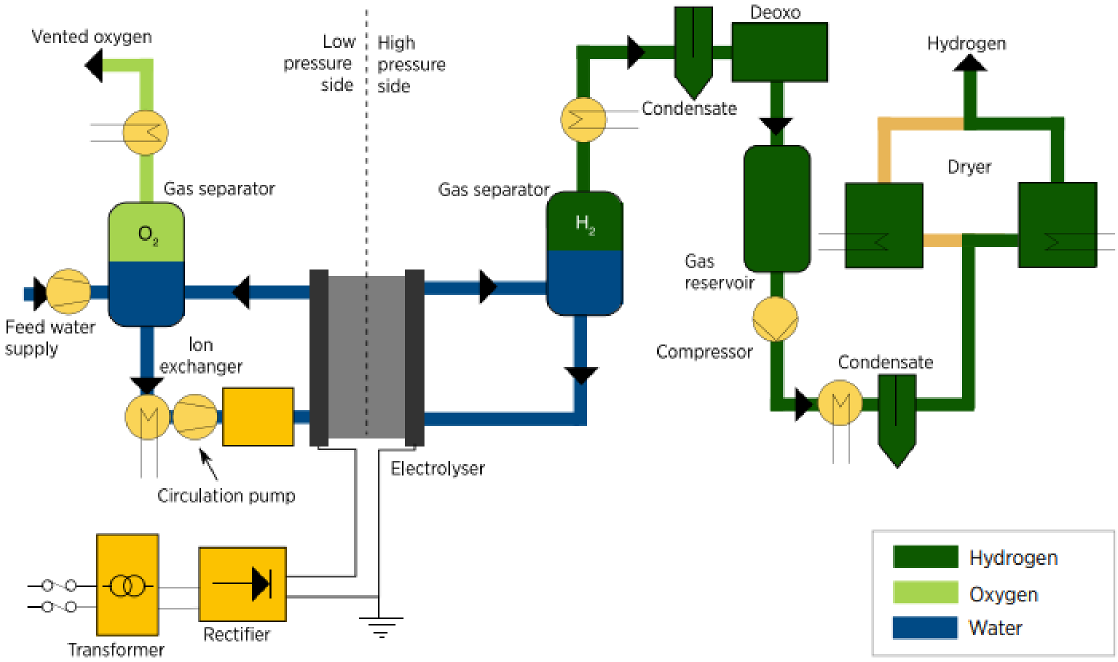


Figure 3.4 Typical design PEM electrolyzer [6].

3.2 Storage System

The system will be composed of 3 different storage systems:

- **Batteries**. To store the electric energy generated by the PV system.
- **Hydrogen Tank**. To store the hydrogen generated by the electrolyzer.
- **Hot Water Tank**. To store hot water.

The three systems mentioned above will be briefly described in the following sections.

3.2.1 Batteries

An electric battery, also called a battery or electric accumulator, is a device composed of electrochemical cells capable of converting the chemical energy inside it into electrical energy. Thus, batteries generate direct current and, in this way, serve to feed different electrical circuits, depending on their size and power. Battery systems have been developed and are present at different levels of electric power such as transmission, distribution and customers level. One way to classify these systems is the definition made by the Energy Storage Association of North America, which divides them in two types: in-front-of-the-meter (FTM) and behind-the-meter (BTM). FTM batteries works on a larger scale and generally provides services to the operators of the electrical system, they are usually connected to the transmission system, distribution and also to generation sources. BTM batteries They are used by end users, they are found inside homes or businesses and their main function is to reduce the electricity bills of consumers.

For this particular job, BTM battery storage systems will be used. BTM battery storage systems, also called small-scale stationary batteries can range between 3 kW to 5 MW. Typically, residential consumer batteries can reach 5 kW /13,5 kWh, while a battery for a commercial or industrial system is typically 2 MW/4 MWh. In Germany, for example, according to IRENA data [37], 40% of the photovoltaic systems are equipped with this type of storage. The constant increase in the use of these systems is mainly due to the fall in their price, they are becoming more economical and accessible to a greater number of electricity users. Electric vehicles as well as the increase in self-consumption have raised the demand for batteries, this fact has resulted in a decrease in their prices. Battery storage systems deployed at the consumer level are typically BTM batteries, because they are placed at a customer's facility. The installation of these battery systems allows to reduce the variability of renewable energies such as solar energy, storing energy when the solar resource is high and consumption is low, and then supplying this energy when it is needed. Connected to the grid, they also allow to play with the price of electricity, storing energy when electricity prices are low and delivering energy when prices rise.

In general, the most commonly used solar batteries are by lead-acid and lithium-ion battery technologies. The difference between both batteries is visible in their name, while lithium-ion batteries are made with lithium, lead-acid batteries are made with lead. Both batteries have been shown to offer good energy storage performance, however, each has its own characteristics .Next, a comparison is made between both technologies [38]:

- **Cost**. Lead-acid batteries are consider cheap while lithium-ion batteries are more expensive.
- **Capacity**. Lithium-ion technology has a higher energy density than lead acid batteries, which means it packs more power and takes up less space.
- **Depth of discharge**. The depth of discharge of a battery is the percentage of energy that can be extracted from it safely and without damaging its proper functioning or affecting its useful life. In lead acid batteries, the depth of discharge is usually low around 50%, this greatly influences the capacity of the battery. Lithium ion batteries, on the other hand, allow depths of discharge greater than 85% without affecting their useful life.
- **Efficiency**.the efficiency of lithium ion batteries is far superior to lead acid batteries, while the former reach efficiencies above 95%, lead acid batteries only reach 85%, the efficiency value is also important in the effective capacity of the batteries.
- **Lifespan**. Lithium batteries again represent a better option in terms of life cycle, they endure a greater number of complete cycles compared to lead acid.

The system simulations will be carried out considering a lithium ion battery system due to its excellent characteristics compared to lead acid batteries. The cost of the battery will not be one of the factors to be studied, so the one with the best performance in terms of efficiency and depth of discharge will be chosen. The size of the battery bank to be used will vary depending on the electricity generator, varying between one and two times its peak power.

3.2.2 H2 Tank

The hydrogen produced by the electrolyzer and not consumed by the CHP unit must to be stored. Nowadays, there are two main ways to store hydrogen, it can be either gas stored or liquid stored. To be stored as gas H2 need to be pressurized, tank pressure normal are between 60 and 700 bar. If H2 is stored as a liquid the process is different because requires a state change, this process involves cryogenic temperatures of −252,8°C to meet the boiling point. Hydrogen can also be stored on the surfaces of solids (by adsorption) or within solids (by absorption) [39].

Hydrogen is an excellent energy carrier with respect to weight. 1 kg of hydrogen contains 33,33 kWh of usable energy, whereas petrol and diesel only hold about 12 kWh/kg. However, in terms of volume, the energy density of the hydrogen is much lower than liquid fuels. At atmospheric conditions, petrol and diesel are around 8,8-10 kWh/liter, while under the same conditions hydrogen contains 0,003 kWh/liter. This condition changes when hydrogen is subjected to different pressures, for example, pressurized hydrogen contains about 0,5 kWh/liter at 200 bar, 1,1 kWh/liter at 500 bar and 1,4 kWh/liter at 700 bar [40].

The best way of transporting hydrogen in terms of energy density is liquid hydrogen, achieving more than 2,3 kWh/liter. However, this process involved a big amount of energy due to the very low temperatures required to condense into its liquid state. State of the art hydrogen liquefaction technology has a power consumption of 10 kWh/kg. This is equivalent to 30% of the usable energy contained in 1 kg of hydrogen [41]. In addition, some amount of stored hydrogen will be lost through evaporation, or "boil off" of liquefied hydrogen, especially when using small tanks with large surface-to-volume ratios.

For the simulations, hydrogen tanks will be used for gas storage, due to the scale of the system. The cryogenic process is more useful for larger storage volumes and its efficiency is low.

Nowadays, companies such as the French company Mahytec [7] are dedicated to commercialize small and medium scale solutions for hydrogen storage, on their website they have storage tank models available including their datasheet. The models on the website are 60 and 500 bar cylinders which are capable of holding 4,2 kg and 9,5 kg of hydrogen. The pressurized hydrogen cylinders can be connected together to hold a larger amount of hydrogen (See Fig. 3.5).

Figure 3.5 500 bar hydrogen tank array by Mahytec [7].

3.2.3 Hot Water Tank

A hot water storage tank is comparable to a closed vessel in which there is a pipe coil that acts as a heating coil. Drinking water flows around the pipe coil, which contains heating water. The pipe coil now functions as a heat exchanger, transferring heat to the service water. The cold water inlet is also heated whenever hot water is withdrawn.

It is important that the hot water tank has very good insulation to minimize heat loss and maintain a temperature of at least 60°C to prevent the formation of legionella bacteria.

Chapter 4

Simulation Results

In this section the system's viability will be evaluated, the idea is to make the buildings totally independent of fossil fuel energy, both electrical and thermal. For this, the following case is presented.

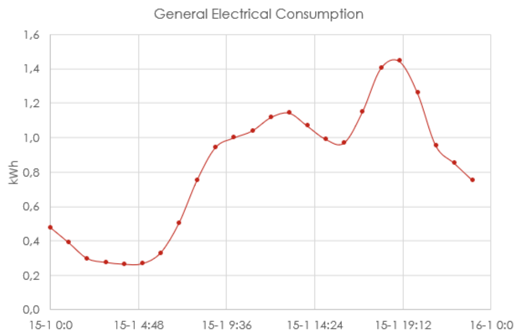
Case of study. A simulation will be performed with electrical and thermal consumption data for a house located in the city of Munich, Germany. The annual amount of electrical and thermal consumption is obtained from the software Polysun [42]. Polysun is a powerful software range for simulation-based planning, design and optimization of holistic energy systems for buildings and neighborhoods.

The simulation will be carried out on Excel software from Microsoft [43].

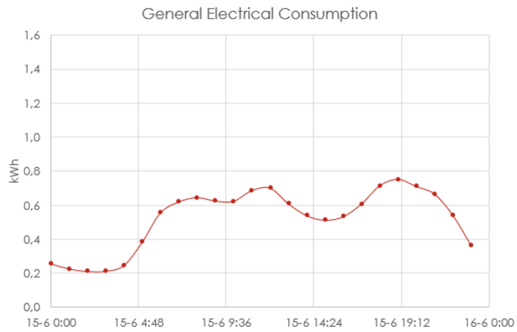
4.1 System Description

The system proposed to perform the simulations is the one shown in Fig. 3.1. In Fig. 3.1 it can be seen as a source of electricity the PV panels and the fuel cell that would act as CHP unit. In the diagram it is also consider the grid as a source of electricity, however, it is included in the system only as an auxiliary element in case of emergency and to be able to commercialize the excess energy that could be generated by the system.

The lines in orange represent the thermal energy flows. In this case, the sources shown on the diagram are the HP (main player on heating), the CHP, the electrolyzer and the hydrogen boiler. The system also shows the electrical and thermal storage systems. The electrical storage system is composed of two parts, the BTM batteries that constitute the short term electrical storage and the hydrogen tank which allows long term electrical storage. A hot water tank will be used for thermal storage. The surplus electricity can be injected into the grid and the surplus hydrogen is considered suitable for injection into the natural gas pipeline network.



(a) Electrical consumption 15-01-2020.



(b) Electrical consumption 15-06-2020.

Figure 4.1 Daily electrical consumption from a residential building.

4.2 Case of Study

As mentioned above, the case of study will be based on a 270 m^2 single-family house located on Munich, for this case Polysun delivers an annual electrical consumption of 20 kWh/m^2, however, the program does not allow downloading the profile associated to this consumption, so the profile available in "Stadtwerke Böhmetal GmbH" will be used [44]. This web has different annual load profiles depending on the type of building, in this case the house holder profile will be choose. On the other hand, the energy consumption for heating is also obtained from Polysun , in this case the program allows the download of the annual profile. The annual heating energy consumption for a 270 m^2 house is 15.651 kWh.

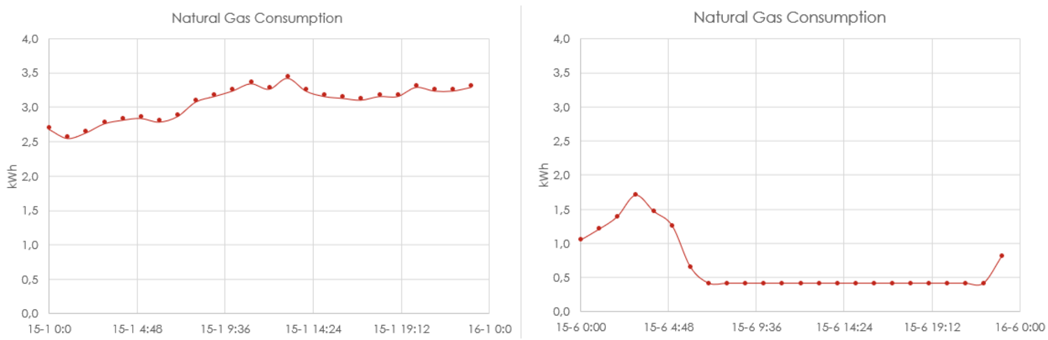
4.2.1 Energy Loads

Electricity Consumption

According to the data provided above, the annual electricity consumption of the house is 5.400 kWh and the daily profile of winter and summer can be seen in Fig. 4.1a and Fig. 4.1b. In Fig. 4.1a, it can be seen the electricity consumption for a residential home on January 15, 2020 and in Fig. 4.1b it can be seen the electricity consumption for a residential home on June 15, 2020. The difference between the daily profile in winter and summer is directly related to the hours of sunlight for each season.

Heating energy consumption

Although there is a transition to the use of electric energy for home air conditioning, the use of fossil fuels, mainly natural gas, is still predominant. In order to homogenize the calculation, the annual consumption of a residential dwelling in kWh will be used to compare it with the rest of the variables necessary for the calculation of the system. The gas consumption for winter and summer can be seen in Fig. 4.2, it can be observed



(a) Natural Gas consumption 15-01-2020. (b) Natural Gas consumption 15-06-2020.

Figure 4.2 Daily natural gas consumption from a residential building.

that in summer the consumption drops to a minimum, leaving only the hot water as a load.

4.2.2 Simulation Parameters

PV Array

The available surface of the house allows the installation of 44 panels with an area of 120 m^2 approx., using the panel mentioned in the previous chapter (570 Wp), this would allow a peak power of 25,08 kWp. The orientation of the panels will be towards the South with an inclination of 30° and the house is located in the city of Munich, Germany. With this data and using the meteorological information from the PVGIS website [45], the annual energy production of the panels is obtained, which totals 22.160 kWh/y.

Battery Storage

The size of the BTM battery bank will be slightly larger than the peak power of the generator, in this case a battery bank of 1,2 times the peak power of the generator will be used. Thus, the size of the battery bank will be 30 kWh. For the simulation, it is considered a lithium ion battery bank with a round trip efficiency of 98% and the state of charge (Soc) of the batteries should not be less than 10%.

Electrolyzer

The size of the electrolyzer is directly related to the maximum power of the photovoltaic field, this is proposed so that when there is no consumption and there is maximum irradiation, the electrolyzer is able to take advantage of all the energy coming from the panels. For this reason, the power of the electrolyzer is set at 25 kW . The efficiency of the electrolyzer is defined as 74% and the conversion factor between electrical energy and usable heat is 20%. With this it can be said that the thermal capacity of the electrolyzer is 5,02 kW.

H2 Tank

In order to meet self-sufficiency requirements, long-term storage is needed, and this is where hydrogen plays a key role. It is decided to store hydrogen as gas at 500 bar. According to the simulations, 180 kg of hydrogen of capacity would be needed, which is equivalent to 5.999 kWh and would occupy a volume of 5.454 Lt. It is determined that the initial level of the tank is 55% and the efficiency of this storage system is set on 85%.

Fuel Cell

The fuel cell will allow the system to be supplied with energy when the batteries are discharged and there is insufficient electricity supply from the photovoltaic panels. This is why the power of this equipment is determined according to the maximum electrical consumption resulting from the sum of the heat pump consumption and the electrical consumption of the house. With this, it is determined that the fuel cell should be 10 kW. As mentioned above, the electrical efficiency of the fuel cell is around 47%, while the combined cycle efficiency is 68%, with this data it can be calculated a ratio of 0,45 between heat and electricity production. Thus the heat that the fuel cell could contribute to the system is 4,5 kW.

Heat Pump

The size of the heat pump is determined by the maximum thermal demand generated in the house. In this case, an 8 kW heat pump would meet the needs of this building. The heat pump is simulated with an efficiency of 350%.

Boiler

The system will also include a hydrogen-fueled boiler with a capacity of 1 kW, which will be included in the system as a redundant system in case of heat pump failure or power failure. An efficiency of 97% is estimated for this equipment.

Hot Water Tank

The hot water tank will be designed with a capacity of 2 m^3. Assuming a temperature difference of 10°C, the total energy supplied will be 23,2 kWh. The hot water tank will be the heat regulator of the system, i.e. from here the thresholds will be set with which the operation of the heat pump and boiler will be controlled. For this simulation, a value of 10 kWh is set for the heat pump and 0,1 kWh for the boiler, if the available energy in the tank reaches levels below those mentioned, these systems will be activated.

Table 4.1 Thermal energy generated from the system.

Thermal Results		
Equipment	Annual Energy kWh	% from Total Demand
Heat Pump	13.070	81%
Fuel Cell	1.156	13%
Electrolyzer	1.847	7%
Boiler	10	0%
Total	16.084	102,76%

Table 4.2 Electricity generation from the system.

Electrical Results	
Equipment	Annual Energy kWh
PV	22.160
Fuel Cell	2.560
Total	24.720

4.2.3 Simulation Results

According to the data provided above, the simulation of the system is carried out, obtaining the results shown in Tables 4.1, 4.2, 4.3 and 4.4.

At the Table 4.1, it can be seen that the thermal contribution is mainly due to the heat pump with an annual total of 13.070 kWh, the electrolyzer has a heat contribution of 1.847 kWh and the fuel cell generate 1.156 kWh. The thermal contribution of the boiler is 10 kWh, this element can therefore be disregarded.

Electric power generation is dominated by the PV field with an annual total of 22.160 kWh as per Table 4.2 and the hydrogen fuel cell achieves an output of 2.560 kWh. The energy imported from the grid is practically zero with 2 kWh for the whole year. The surplus energy is 6.238 kWh, this electricity can be delivered to the grid.

On the hydrogen side, Table 4.3 shows how the electrolyzer generates a total of 6.926 kWh per year of hydrogen, this allows the final hydrogen reserves in the tank to be 3.689 kWh. In summary, the amount of energy in terms of fuel and electricity required from the grid is almost zero and would open up a total exportable energy of 6.244 kWh (Table 4.4). All the parameters used for the simulation can be check in more detail at Appendix B.1.

Figure 4.3 shows the heat balance of the system throughout the year, in this graph it can be seen the contributions of each element as well as the demand in red and the state of the water tank in light blue. In blue you can see the heat input of the heat pump, it can be seen that during the summer months this decreases which is

Table 4.3 Energy balance from hydrogen system.

H2	
	Fuel kWh
Electrolyzer Generation	6.926
Tank Level (EOY)	3.689

Table 4.4 Energy imported and exported from the grid.

Energy Balance			
	Electricity kWh	Fuel kWh	**Total kWh**
Imported	1	0	**1**
Exported	6.244	0	**6.244**

due to the lower need for heating and therefore to an adjustment of parameters that was made to that equipment. While the months of January, February, March, October, November and December the heat pump operates at 100%, the months of April and September it operates at 50% and the months of May through August it operates only at 10% of the total capacity of the heat pump. In green it can be seen the heat contribution of the fuel cell, the graph shows that its performance is limited to the winter months (November to February), this is due to two things: the first is a higher demand for heating and the second is the lack of solar resource and therefore the lack of electricity to feed the heat pump. In these months the hydrogen reserve plays a key role in supplying the lack of electrical energy as it is used as fuel for the fuel cell. Finally, in yellow it can be see the heat input generated by the electrolyzer. The figure shows how it is only present during the beginning of the summer (April to June), this is due to the presence of a greater solar resource during these months and to the level of the hydrogen tank which lowered its reserves to the minimum during the winter months and needs to be recharged. The presence of the heat coming from the electrolyzer coincides with an almost null contribution of the heat pump, it should be remembered that for these months the heating needs decrease and can be covered almost entirely by the heat generated by the electrolyzer. The contribution of the electrolyzer ends drastically in the month of July, this fact is due to the fact that the hydrogen reserve tank is full and therefore the electrolyzer is not required to operate.

Figure 4.4 shows the daily thermal behavior of the house for a winter day (4.4a) and a summer day (4.4b). As mentioned above, in winter the heating needs are higher, which is clearly shown by the red lines in both graphs; in summer there is only a peak in the morning, presumably attributed to the showers. This higher thermal demand in winter causes the hot water tank to discharge faster and thus the heat pump to start up. The behavior of the heat pump is oscillating during the winter days since it is the main responsible for supplying the thermal needs of the house. In summer its contribution is very low and it is only used to cover the morning peak. In winter, the lack of electrical energy causes the fuel cell to start operating, this fact also contributes heat to the system, increasing the load of the hp. In summer the fuel cell is not used. The electrolyzer is not in operation in winter, mainly due to the lack of solar resource, however in summer it has a considerable performance providing heat to the system and at the same time relaxing the load of the HP.

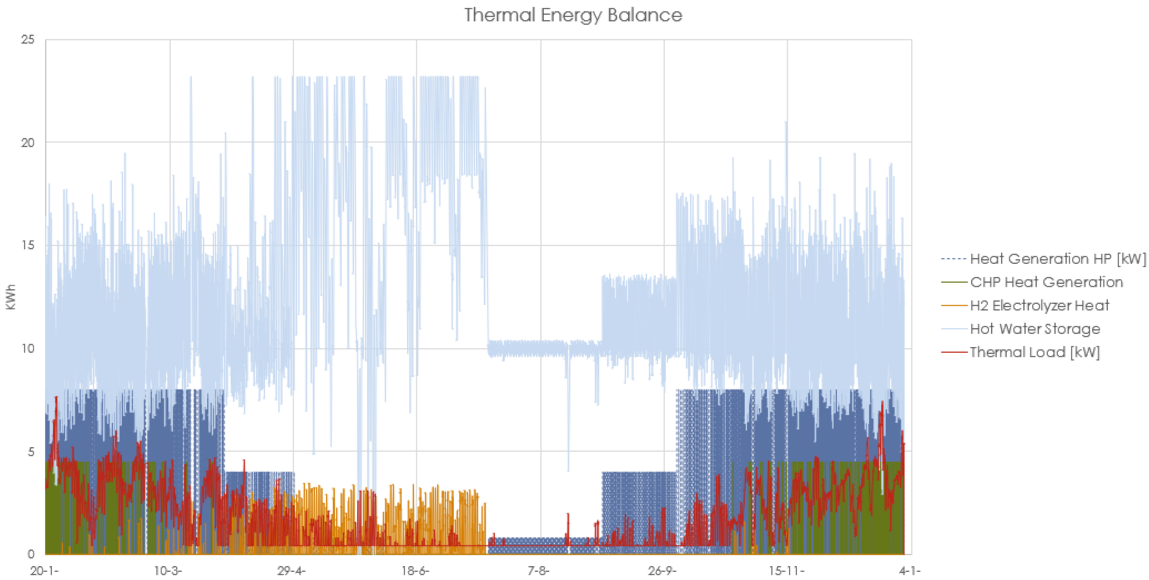
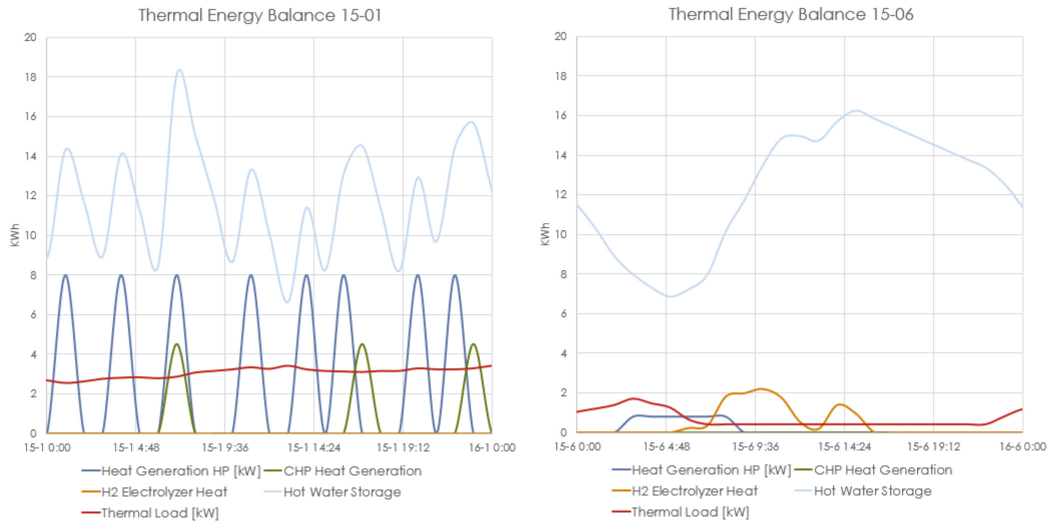


Figure 4.3 Thermal energy generation along the year.

Figure 4.5 shows the behavior of the hydrogen tank, it is observed that the initial state is 3.300 kWh and has a significant decrease during the winter months, the lowest month is March with 500 kWh, however, the amount of hydrogen in the summer months increases considerably reaching the maximum of the tank, after the tank is full the electrolyzer stops and the electricity surplus is injected into the grid. By the end of the year the tank maintains an available energy of 3.689 kWh.

Figure 4.6 shows the electricity balance of the system, in green it can be seen the electrical load of the house including the consumption generated by the heat pump, the graphic shows how in the winter months this consumption is higher than in the summer months due to the greater need for heating. The main generation of energy is due to the solar panels that in the graph are represented by the lines in red, here it can be seen a considerable increase in the generation of energy in the summer months due to the increase of the solar resource. The power generation from the fuel cell follows the same pattern as explained in Fig. 4.3, where its presence is limited to the winter



(a) Thermal energy generation 15-01. (b) Thermal energy generation 15-06.

Figure 4.4 Daily thermal balance.

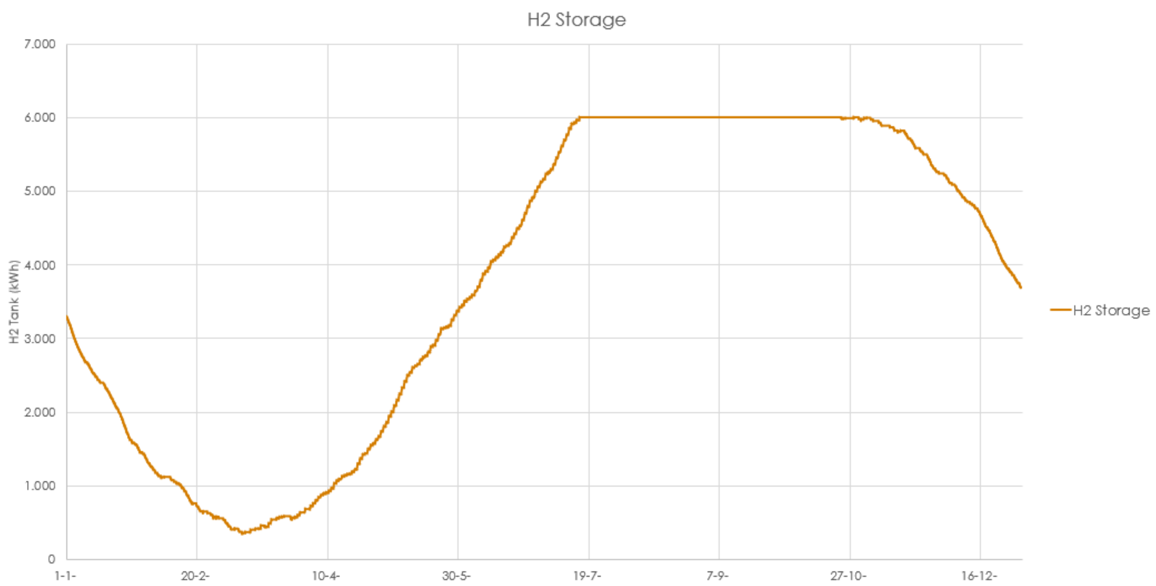


Figure 4.5 H2 tank storage energy along the year.

months. In violet it can be seen the state of charge of the batteries, graph shows that in winter there are pronounced discharges, however in summer maintain a charge status greater than 70% throughout the hole season. The graph also represents the surplus energy, in this case it is illustrated on the negative axis indicating that it is energy that is returned to the grid, this coincides with the period in which the hydrogen tank is full.

Figure 4.7 shows the daily detail of electricity generation and consumption. Figure 4.7a represents January 15 (winter) and Figure 4.7b shows June 15 (summer). In these images, it can be seen in more detail what was previously mentioned, the system load is much higher in winter mainly due to the operation of the HP. In winter, the PV system has very little contribution due to the lack of solar resource, however, in the middle of summer its contribution is considerable. The charge of the batteries remains low during the winter, the system needs all possible sources to obtain electricity, in summer the batteries are kept charged almost all the time. In winter, the fuel cell comes into action when the batteries reach a discharge of 10% in order to provide electricity to the system, on the contrary, in summer its action is null. In both days there is no surplus of energy, in winter this condition is normal due to the low solar resource, however in summer this is because the surplus energy is used in the generation of hydrogen, until this day the hydrogen tank is not full yet.

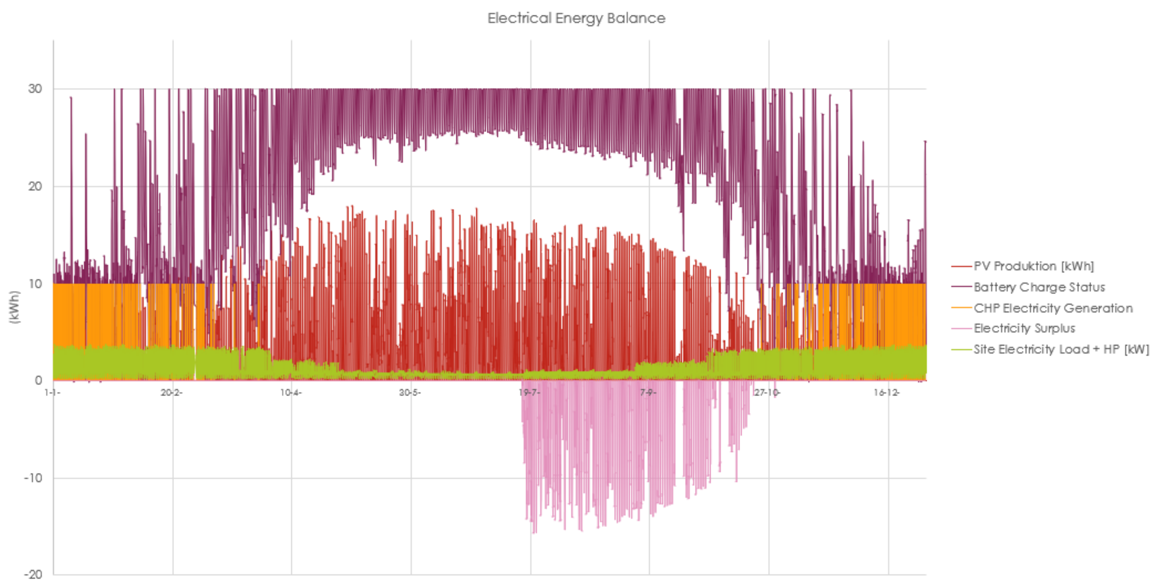
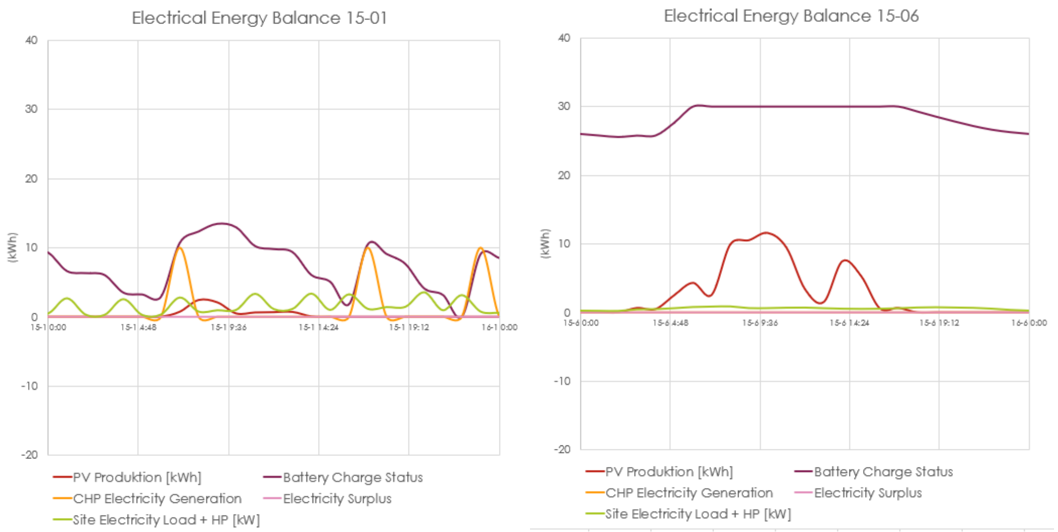


Figure 4.6 Electricity balance along the year.



(a) Electricity balance 15-01.

(b) Electricity balance 15-06.

Figure 4.7 Daily electrical balance.

Chapter 5

Conclusions

The house used for the simulations meets the expectations of self-sufficiency and even allows economic benefit by having the possibility of injecting the surplus energy to the grid.

The initial plan of using batteries as short-term electrical storage system and hydrogen as long-term storage is fulfilled and can be clearly seen in Figure 4.5.

The inclusion of the boiler as an additional heating system can be dispensed with as its contribution is almost zero.

The system needs excessive hydrogen storage to achieve energy self-sufficiency, according to the design characteristics the tank would occupy a volume of almost 5,4 m^3.

Economic analysis is not performed in part because regulations do not yet exist and the hydrogen market for small consumers is still in its initial states. There is insufficient information providing costs and characteristics for small scale equipment which limits any economic study.

The work done is considered beneficial for the integration of hydrogen in the residential sector and serves as a precedent for design software to implement in their solutions systems like the one just proposed. In the search of bibliography and material for this work was not found any software that would allow the integration of electricity and heating with the detail achieved in this document.

The system presented in this report contributes directly to decarbonization and independence from fossil fuels, the high prices of natural resources could make this type of integrations competitive solutions not only technically but also economically.

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Appendix A

Data Sheet

PV Panels

www.jinkosolar.com

JinKO Solar
Building Your Trust in Solar

TR 78M
555-575 Watt
Mono-facial

Tiling Ribbon (TR) Technology

Positive power tolerance of 0~+3%

Tiger Pro

PV CYCLE
CE
POSITIVE QUALITY
CLEAN ENERGY COUNCIL MEMBER

ISO9001:2015, ISO14001:2015, ISO45001:2018 certified factory

IEC61215(2016), IEC61730(2016) certified product

KEY FEATURES

TR technology + Half Cell
TR technology with Half cell aims to eliminate the cell gap to increase module efficiency (mono-facial up to 21.40%)

MBB instead of 5BB
MBB technology decreases the distance between bus bars and finger grid line which is benefit to power increase.

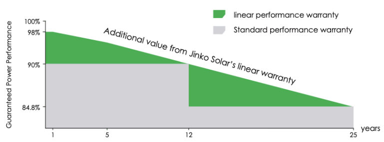
Higher lifetime Power Yield
2% first year degradation,
0.55% linear degradation

Best Warranty
12 year product warranty,
25 year linear power warranty

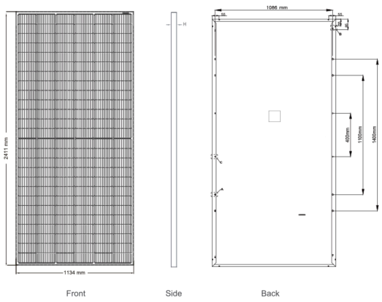
Strengthened Mechanical Support
5400 Pa snow load, 2400 Pa wind load

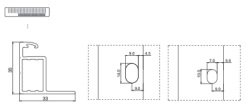
LINEAR PERFORMANCE WARRANTY

12 Year Product Warranty • 25 Year Linear Power Warranty
0.55% Annual Degradation Over 25 years



Engineering Drawings





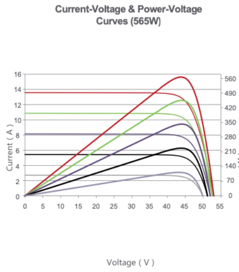
Length: ±2mm
Width: ±2mm
Height: ±1mm
Row Pitch: ±2mm

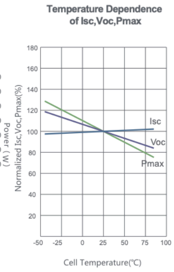
Packaging Configuration

(Two pallets = One stack)

31pcs/pallets, 62pcs/stack, 496pcs/ 40'HQ Container

Electrical Performance & Temperature Dependence





Mechanical Characteristics

Cell Type	P type Mono-crystalline
No.of cells	156 (2×78)
Dimensions	2411×1134×35mm (94.92×44.65×1.38 inch)
Weight	30.6 kg (67.5 lbs)
Front Glass	3.2mm,Anti-Reflection Coating, High Transmission, Low Iron, Tempered Glass
Frame	Anodized Aluminium Alloy
Junction Box	IP68 Rated
Output Cables	TUV 1×4.0mm² (+): 290mm , (-): 145 mm or Customized Length

SPECIFICATIONS

Module Type	JKM555M-7RL4-V		JKM560M-7RL4-V		JKM565M-7RL4-V		JKM570M-7RL4-V		JKM575M-7RL4-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	555Wp	413Wp	560Wp	417Wp	565Wp	420Wp	570Wp	424Wp	575Wp	428Wp
Maximum Power Voltage (Vmp)	43.95V	40.96V	44.06V	41.05V	44.18V	41.13V	44.29V	41.25V	44.40V	41.33V
Maximum Power Current (Imp)	12.63A	10.08A	12.71A	10.15A	12.79A	10.22A	12.87A	10.28A	12.95A	10.35A
Open-circuit Voltage (Voc)	53.44V	50.44V	53.54V	50.54V	53.64V	50.63V	53.74V	50.72V	53.84V	50.82V
Short-circuit Current (Isc)	13.26A	10.71A	13.35A	10.78A	13.44A	10.86A	13.52A	10.92A	13.61A	10.99A
Module Efficiency STC (%)	20.30%		20.48%		20.67%		20.85%		21.03%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1500VDC (IEC)									
Maximum series fuse rating	25A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.35%/℃									
Temperature coefficients of Voc	-0.28%/℃									
Temperature coefficients of Isc	0.048%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

*STC: Irradiance 1000W/m² Cell Temperature 25°C AM=1.5

NOCT: Irradiance 800W/m² Ambient Temperature 20°C AM=1.5 Wind Speed 1m/s

Appendix B

Simulation Parameters

B.1 Case of study

Electricity Load Profile and Consumption - Thermal Load				
Load Profile	Anual Elect Consumption kWh/a	Total Thermal Load [kWh/y]	Covered Thermal Load [kWh/y]	
Haushalt H0	5.400	15.651	15.651	
Area [m2]	Anual Electricy per Area [kWh/m2]			
270	20			

PV and Batteries				
PV Size [kWp]	25,1			
Battery Storage [kWh]	30		Round Trip Efficiency	0,98

Electrolyser				
Technology	Efficiency	Capacity [kW]	Heat Ratio	Heat [kW]
PEM ME450/1400	75%	25,0	0,2	5

H2 Tank		33,33 kWh/kg		
Efficiency	Tank Size [kg]	Tank Size [kWh]	Type	Volume (L)
85%	180	5.999	Gas 500bar	5.454
Tank Inicial Charge %	Tank Inicial Charge [kWh]	kWh_elect		Volume (m3)
55%	3299,67	2371		5,454

CHP				
Technology	Electrical Efficiency	Overall Efficiency	Nominal Electricity generation [kW]	Wäme/Strom
Fuel Cell	47%	68%	10	0,45

Month	Soc Battery Storage
1	10%
2	10%
3	10%
4	10%
5	10%
6	10%
7	10%
8	10%
9	10%
10	10%
11	10%
12	10%

*Working schedule of CHP depends on the Soc of battery storage. CHP starts when batteries are under the Soc of the table.

**It is considered that CHP could run with H2 and other fuels.

Analysis overview			
Heat			
Electrolyzer	1.847	kWh/a	11%
Heat Pump	13.070	kWh/a	81%
CHP	1.156	kWh/a	7%
Boiler	10	kWh/a	0%
Total	**16.084**	**kWh/a**	**102,76%**
Electricity			
Grid Imported Electricity	1	kWh/a	
CHP	2.560	kWh/a	
PV	22.160	kWh/a	
Surplus	6.238	kWh/a	
Total System Generation	18.369	kWh/a	
H2			
Electrolyzer Generation	6.926	kWh/a	
H2 Surplus	6	kWh/a	
H2 Tank Level (EOY)	3689	kWh	
Other Fuel Consumption	-	kWh/a	
Total Energy imported	**1**	**kWh/a**	
Total Energy Exported	**6.244**	**kWh/a**	

Heat Pump

Name	Q0 [kW]	P0 [kW]	QH [kW]	P0_Factor
HP_test1	0	2,3	8	3,50

Monat	Anteil WP	kW th
1	1	8
2	1	8
3	1	8
4	0,5	4
5	0,1	1
6	0,1	1
7	0,1	1
8	0,1	1
9	0,5	4
10	1	8
11	1	8
12	1	8

*Heat Pump Thermal Power could be adjusted for each month.

Hot Water Tank 1,16 kwh/(m3K)

Temperature Diference	Tank Size [m3]	Tank Size [kWh]	Tank Threshold [kWh] HP	Tank Threshold Boiler [kWh]
10	2	23,2	10	0,1

Boiler

Nominal Thermal Power [kW]	Efficiency
1	97%

*It is considered that Boiler could run with H2 and other fuels.

Percentage of the desired thermal Load covered by the system

Monat	
1	100%
2	100%
3	100%
4	100%
5	100%
6	100%
7	100%
8	100%
9	100%
10	100%
11	100%
12	100%