Simulation of a Hybrid Short-Term & Long-Term Energy Storage System in Energy Communities

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Executive Summary

The Paris agreement has set European countries on a path towards decarbonization of the energy market, with policies such as reducing 55% of carbon dioxide emissions of the energy sector by 2030 compared to the levels in 1990, and having a share of 40% renewable energy sources by 2030. Due to the high dependence of natural gas in the Netherlands, various challenges will be faced when facing out fossil fuels. The major drawback of RES is that they are non-dispatchable, meaning their output generation fluctuates over time with respect to weather conditions, resulting in a temporal mismatch of supply and demand.

In order to allow shifting of non-dispatchable loads, energy storage is required. Energy storage refers to storage of electricity or heat in a storage medium and the later extraction from that medium. A division between short-term and long-term storage represents the standard solution. Shifting demand over longer periods of time is important, as there is often a day-to-night mismatch of renewable energy production and demand as well as a seasonal mismatch; as RES are more plentiful in summer months, while energy demand of buildings is higher in winter months. However, the integration and optimization of a hybrid short-term and long-term energy storage in a decentralized energy system has not been widely studied. Therefore, the research question used to structure the research is the following:

> ***How can the short-term and long-term storage capacity in a decentralized renewable energy system be optimized to guarantee security of supply?***

Firstly, a literature research is developed to determine the most feasible short-term and long-term energy storage technologies in decentralized energy systems. The short-term energy storage technologies analyzed were batteries, supercapacitors, superconducting magnetic energy storage and flywheels. It was concluded that batteries (Li-ion batteries) are the most feasible short-term energy storage technology, due to the high efficiency, low costs, high charge and discharge rate, high energy and power densities, among other factors. Moreover, compressed air energy storage and hydrogen were analyzed for long-term energy storage, where it was concluded that hydrogen is the most feasible solution. However, the implementation of a hydrogen system, including an electrolyzer, compressor, hydrogen tank, and fuel cell, is associated with very high costs.

When designing a system with solar generation, a battery, and a hydrogen system, the capacity of the components highly depend on the demand patterns of the community. Therefore, to derive the optimal sizing of the components with the goal to minimize the total costs of the system, a simulation of the energy system is developed in MATLAB. For this simulation, the hourly generation and demand data of the years 2010-2020 were used, among with the technical and economic parameters of the components. This simulation displays the energy flow through the system at any hour of the year, and derives the total costs of the system, the electricity costs of the community, and the levelized costs of energy, to determine the techno-economic feasibility of the system.

The simulation shows that the minimization of the system costs is obtained by maximizing the capacity of PV generation while minimizing the capacity of the hydrogen system. This is due to the very high costs associated with the components of the hydrogen system. The system has an efficiency of 60.66% when dumped energy is not considered, and 16.82% when dumped energy is considering, highlighting the fact that the system throws away a considerable amount of energy. The total system costs for the year 2020 are found to be €61,746, the electricity costs for the community in 2020 are €61,721, and the levelized costs of energy is €0.8917/kWh. Furthermore, the electricity prices of the three sources are €0.126/kWh, €0.992/kWh and €1.975/kWh for the PV, battery and hydrogen electricity, respectively.

Lastly, the institutional and social factors affecting the development of decentralized energy systems and hydrogen are analyzed to derive policy recommendations. Institutional tools that can help with the successful implementation of hydrogen are subsidize schemes for green hydrogen production, which nowadays are being studied and implemented by several members of state, and CO2 pricing to help reduce the attractiveness of traditional sources. Social factors affecting the development of decentralized energy systems involve willingness of the participating household, household engagement, and trust among actors. By tackling these factors, the implementation of decentralized energy systems can be done more successfully.

This research shows that the implementation of renewable energy sources, coupled with batteries for short-term energy storage and hydrogen with long-term energy storage is a potential solution to tackle the high intermittency of renewable sources. However, the very high costs involved with this system and the low efficiencies associated with the hydrogen technologies make it impossible to compete with traditional fossil fuel sources.

Contents

List of Abbreviations

DES Decentralized Energy Systems

LCOE Levelized Costs of Energy

O&M Operating and Maintenance

PV Photovoltaic

PEM Polymer Electrolyte Membrane

RES Renewable Energy Sources

SOC State of Charge

SOH State of Hydrogen

TGV The Green Village

List of Figures

List of Tables

Chapter 1

Introduction

Energy sustainability is one of the most widely debated topics of the past decades. The recently concluded Paris agreement has set European countries on a long path towards decarbonization of the energy market. In December 2019, the European Green Deal proposed the transformation of the EU economy and society to meet climate ambitions, with objectives such as reducing 55% of carbon dioxide emissions of the energy sector by 2030 compared to the levels in 1990, and having a share of 40% renewable energy sources (RES) for electricity generation (EC, 2021). However, the energy consumption of households in the Netherlands in 2018 relied 79% on natural gas and 21% on electricity generated mainly in centralized coal and natural gas plants, making natural gas covered almost 90% of residential heating (van den Ende, 2017). The Netherlands' dependency on fossil fuels is illustrated in Figure 1.1, where it is evident that natural gas and oil cover the majority of the energy supply. The decarbonization of the electricity market is achieved through a rapid increase in share of renewable sources. Although it is logical to assume the impact of renewable technologies is entirely positive, research and experience indicate that the intermittency of renewable energies and grid congestion highly affects security of supply (Liebensteiner & Wrienz, 2019).

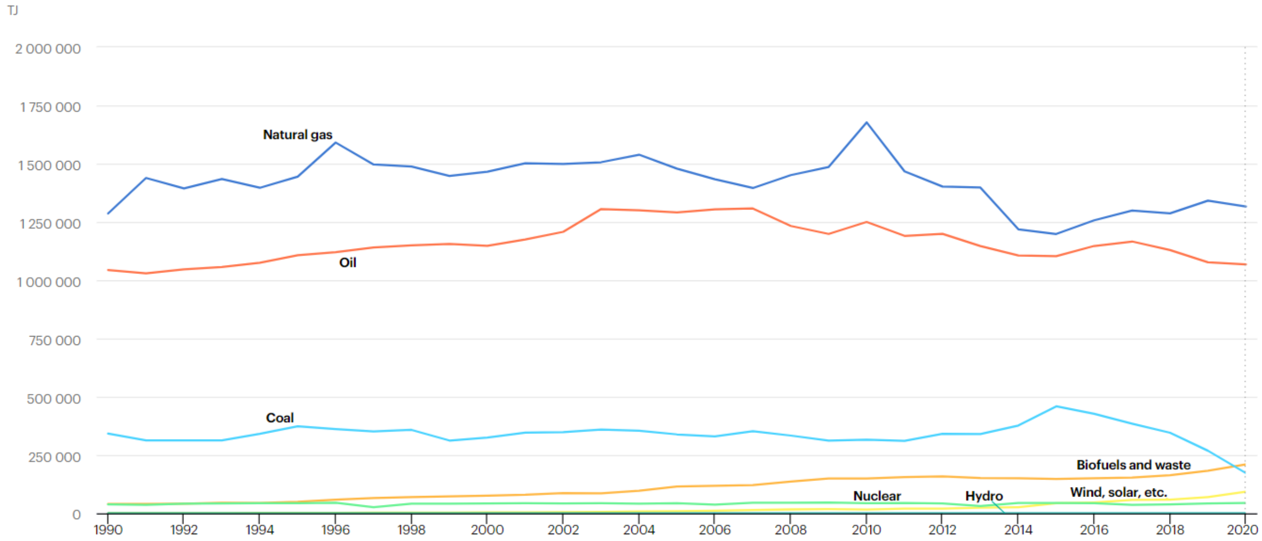

Figure 1.1: Total Energy Supply by Source in the Netherlands (1990-2020). Retrieved from IEA (2021)

A real-life example of negative impacts when increasing the renewable energy share is represented in Germany's situation following their nuclear phase-out decision. Germany had the objective to rapidly increase their share of renewable energy sources; and in 2011, the government decided to decommission all nuclear plants by 2022, with the goal to replace this share with renewable energy sources. However, after the decommission of nuclear power plants, their greenhouse gas (GHG) emissions began increasing with the increase of their share of renewable sources (Knopf et al., 2014). This was due to their increasing reliance on fossil fuels when renewable sources and other sources that do not emit GHG (such as nuclear), were not available in their energy share. (Carpenter, 2020).

The major drawback of RES is that they are non-dispatchable, meaning that their output generation fluctuates over time with respect to weather conditions (i.e., solar radiation or wind velocities), resulting in a temporal mismatch of supply and demand (Murray et al., 2018a). As seen in Germany over the past decade, this temporal mismatch becomes more severe as the share of RES increases. In order to allow shifting of non-dispatchable loads, energy storage is required (Frate et al., 2021). Energy storage refers to storage of electricity or heat in a storage medium and the later extraction from that medium (Sanajaoba, 2019). The most distinguished energy storage technologies are batteries, pumped-hydro storage, and thermal energy storage (Avril et al., 2010). A division between short-term and long-term storage represents the standard solution (Rana et al., 2022). Shifting demand over longer periods of time is important, as there is often a day-to-night mismatch of renewable energy production and demand as well as a seasonal mismatch; as RES are more plentiful in summer months, while energy demand of buildings is higher in winter months.

In order to support energy self-sufficiency within countries, decrease GHG emissions, and reduce dependence of fossil fuel sources, the replacement of centralized plants with decentralized renewable energy systems is in the scope of future research (Murray et al., 2018a). The future energy market may rely on partial shifts from centralized energy generation to distributed energy generation that is based around neighbourhoods of prosumers in Decentralized Energy Systems (DES) (Murray et al., 2018a). With the current issues of intermittency of renewable sources and the need to set a sustainable path towards decarbonization, it is critical to understand how decentralized renewable energy systems could operate in the near future, and the institutional and social factors that model this transition.

The Green Village (TGV), a field lab to test innovative technologies in the built environment, has set itself the target of making its site fully local by 2025. The objective of TGV is to accelerate innovations in the energy transition by understanding how a fully energy-local system can run, what barriers are faced, and what possibilities are available to provide locally produced renewable energy and storage without external energy sources (TGV, 2022). The electricity, heat and hydrogen generation, along with short-term and long-term storage technologies, are elements that must be analyzed and optimized for an efficient use of the system.

1.1 Literature Overview

Using energy storage in renewable energy systems is a topic recently discussed in literature. Existing research focuses on the techno-economic analysis of a stand-alone photovoltaic (and/or wind) system where hydrogen storage is present to mitigate the variability of renewable sources. The aim of these studies is to optimize the capacity of the system elements chain. These studies consider solar and/or wind generation as forms of electricity production and they only develop the techno-economic analysis for the hydrogen storage system and energy generation. Furthermore, the institutional, environmental and social landscape of these local energy systems is only considered and analyzed by Rivera-Niquepa et al. (2020).

Additionally, several studies have been developed within The Green Village to generate insights into viable solutions for integrating energy generation and storage technologies for a local TGV. A hybrid generation system with electricity production from solar photovoltaic (PV) panels, heat production from PV-T panels, ground source heat pumps and fuel cells, and batteries and hydrogen as sources for short-term and long-term storage, respectively, has been proposed. However, it is found that a detailed optimization of various subsystems is still required before TGV becomes fully-local by 2025. More specifically, the storage subsystem, with respect to batteries and hydrogen, requires a thorough analysis. The balancing of short-term and long-term storage capacity is not yet optimized, which could increase the technical and economical feasibility of the system. With current technologies, long-term storage gives rise to challenges such as low electric efficiencies and high costs, which calls for a detailed optimization of capacity. The fuel cell, which is the device that generates electricity through an electrochemical reaction with hydrogen as input material, releases half of the energy stored in the form of heat. Therefore, the effective recovery of this heat can decrease energy losses within the system.

In short, the main knowledge gap found in both scientific literature and TGV studies is that an optimization model where both short-term and long-term storage technologies are integrated for a techno-economical analysis is not yet present. According to C. Chen et al. (2021), hybrid renewable energy systems must be considered, using batteries to address the short-term (such as diurnal pattern) variation and hydrogen to address the long-term (such as seasonal pattern) variation. However, the combination of these two as energy buffer in the built environment has not been sufficiently studied. Lastly, an institutional analysis must also be drawn to arrive at policy recommendations for hydrogen in the built environment, which nowadays has not been developed in an autonomous renewable-powered system.

After having established the knowledge gaps, the main research question will follow accordingly:

> *How can the short-term and long-term storage capacity in a decentralized renewable energy system be optimized to guarantee security of supply?*

1.2 Research Approach

To answer the main research question, the potential energy storage technologies, short-term and long-term, their implementation, and the consequences of the proposed system in terms of its technical, economical, institutional and social aspects need to be identified. The technical and economical evaluation of a hybrid storage system with batteries and hydrogen has not been widely studied, along with the institutional and social factors affecting the development of such systems (Avril et al., 2010). The distribution subsystem will not be designed in this project, but will be considered in the scope, and possible recommendations for an optimized TGV will be given.

To conduct this design, various methods will be applied to arrive at a conclusion and give recommendations for an optimized TGV. First, a literature review will be performed, which will uncover the available options within the design space. The search for relevant literature is performed via the databases Scopus and Google Scholar. Within the design space, specific technical questions and requirements will need to be formulated and answered, by which interviews will be performed with the external advisor to obtain specific information, as well as understanding of their interests. Nevertheless, the core of this MSc thesis project will be the development of an optimization model to optimize the capacity of the short-term and long-term storage system at TGV, with the goal to minimize the total system costs and costs of energy for the end consumer. This model will be performed in MATLAB, and will provide guidance to TGV on how the next steps will look like for an optimized storage system. Lastly, the institutional and social landscape of the proposed system will be analyzed to arrive at policy recommendations and enhance the development of hydrogen in the built environment.

1.3 Research Questions

After having defined this study's primary research question (See Section 1.1), along with the research approach, the following research sub-questions are derived:

> *Sub question 1: What are potential technologies to be implemented in decentralized energy systems for short-term and long-term storage?*
>
> *Sub question 2: How can the capacity of the different components of the short-term and long-term energy storage system at TGV be optimized to achieve the minimum costs of the system?*
>
> *Sub question 3: What recommendations can be given based on institutional and social factors that affect the development and implementation of decentralized energy systems in the Netherlands?*

These questions will be answered during the course of the research to gain the required knowledge to steer research and achieve the final objective.

1.4 Research Methods

To answer each research sub-question, quantitative and qualitative methods are utilized to gather and analyze data. In this section, each sub-question is delineated to present the main research methods utilized for data gathering, as well as data analysis tools utilized to analyze the obtained data.

Sub-question 1: What are potential technologies to be implemented at TGV for short-term and long-term storage?

For the analysis of different storage technologies, two research methods are utilized to gather data: desk research and empirical data gathering methods. More specifically, a literature review is performed, where data on different options for storage technologies, the characteristics and efficiencies of each technology, and an overview of a decentralized renewable energy system, is gathered. A simple summary where all the information gathered during the literature review is present as data analysis tools, so it eases the analysis and understanding of the data.

Sub-question 2: How can the capacity of the different components of the short-term and long-term energy storage system at TGV be optimized based on daily and seasonal variation?

The main data input in this section coming from sub question 1 will be focused on the selection of a specific short-term and long-term energy storage for this specific case. Secondly, data of the generation and demand by TGV will be given by the external advisor, Joep van der Weijden, which will be used to model the load and discharge of both storage options at any specific moment in time.

Lastly, an optimization model is developed, representing a real-world situation. As previously-mentioned, the data analysis tool that is utilized is an optimization model which will be performed in MATLAB. The purpose of this model is to minimize the total system costs and costs of energy for the end consumer. The goal is to achieve the lowest possible costs of electricity while also ensuring 100% energy availability. This will be done by efficiently balancing the load and discharge of both batteries and hydrogen based on demand requirements.

Sub-question 3: What recommendations can be given based on institutional and social factors that affect the development and implementation of decentralized energy systems in the Netherlands?

The main data input for the analysis of the institutional and social factors affecting the development of decentralized renewable energy systems in the Netherlands will come from sub research question 1 and 2, as well as further literature research to obtain all the required data for the analysis. The main data gathered to answer this question is related to institutional and social conditions, characteristics, as well as consequences of implementing hydrogen in the built environment. Lastly, a table where all the information gathered during the analysis is present as data analysis tool, similar to research sub question 1.

1.5 Structure

The remainder of this paper is organized as follows: Chapter 2 provides an overview of the different technologies associated with decentralized energy system, including electricity generation technologies and energy storage technologies. With an in-depth literature research, the most feasible technologies for decentralized energy systems are concluded. In Chapter 3, the designed energy system is described, as well as the data required for this system. Chapter 4 describes the simulation performed in this research, where the designed system in Chapter 3 is modelled. Chapter 5 presents the results from this simulation. An institutional and social analysis of DES and hydrogen technologies is performed in Chapter 6. Then, a discussion of the results and the main assumptions and limitations of this research are explained in Chapter 7. Lastly, the research findings and recommendations are concluded in Chapter 8.

Chapter 2

Socio-Technical Review of Decentralized Energy Systems

For countries to obtain energy self-sufficiency, decrease greenhouse gas emissions, and reduce the dependence on fossil fuel sources, RES are set to replace traditional energy supply by 2050 (Murray et al., 2018b). By shifting from centralized energy sources to decentralized renewable energy, with sources such as PV panels or wind turbines, the energy market may depend on partial shifts from centralized energy generation to distributed energy generation established around neighborhoods of prosumers in DES (Murray et al., 2018b). However, the major disadvantage of RES is that they are non-dispatchable, meaning their energy output fluctuates stochastically over time with associated weather conditions, resulting in a temporal mismatch of supply and demand (Murray et al., 2018b). Nowadays, this mismatch is handled by exporting excess production to the grid or by importing electricity from the grid when demand is not met by renewable production. Nonetheless, as the share of renewable sources in electricity production increases, the temporal mismatch becomes more severe.

To allow shifting of non-dispatchable loads, energy storage is required (Frate et al., 2021). As previously-explained, a common classification of energy storage technologies is done by differentiating short-term storage and long-term storage. Moving demand over lengthy periods of time is relevant, as not only a daily mismatch (day-to-night) of renewable energy and demand is present, also seasonal mismatch as RES are more plentiful in summer while demand tends to be higher in winter. One of the most widely studied technologies for energy storage are electrochemical batteries, which have been widely applied in renewable systems. Due to the fast response on battery charging and discharging, batteries are largely applied for short-term storage devices. On the other hand, hydrogen energy storage, with a belonging characteristic of high energy density, is commonly studied for long-term storage, which can stabilize the power grid from a seasonal perspective. To understand how energy storage can be implemented in a decentralized energy system, it must be clear first what a decentralized energy system is.

DES are characterized by placing energy production technologies closer to the site of consumption, which allows for more optimal use of renewable energy, decreases consumption of fossil fuel sources and increases eco-efficiency (Unescap, n.d.). Traditionally, centralized power generation and large-distance transmission of power to consumers have been the approach of the energy market. Contrariwise, DES offer to install power generation sources closer to consumers. By implementing generation in a decentralized manner, issues such as transmission and distribution inefficiencies and economic and environmental costs can be decreased (Unescap, n.d.). A rudimentary design of a DES is presented below in Figure 2.1, where the different elements of the system are displayed: the electricity generation from solar panels or wind turbines, a short-term electricity storage medium, and a long-term energy storage system for seasonal electricity storage.

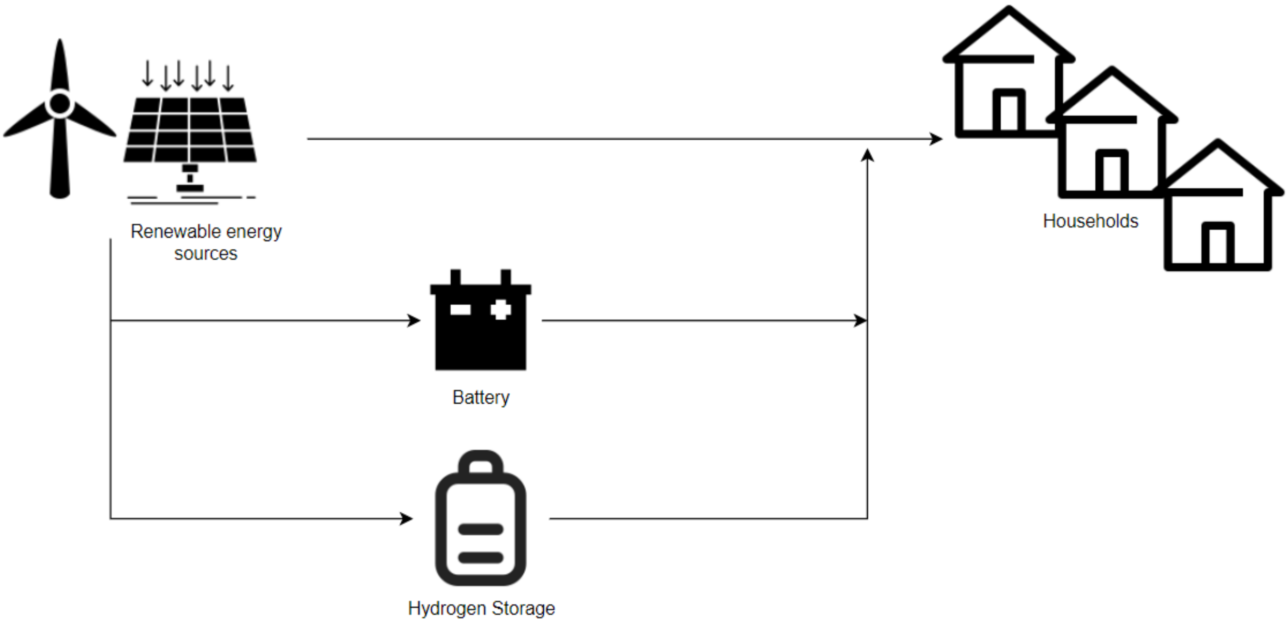

Figure 2.1: Rudimentary design of a decentralized renewable energy system

In this chapter, the different elements of a decentralized energy system are reviewed and discussed. First, the electricity and heat generation elements are introduced, focusing mainly on the most widely studied and implemented sources for electricity generation in DES. Secondly, storage technologies are presented and divided in five categories, electrochemical, electrical, mechanical, chemical, and thermal storage, so a clear classification of the different technologies is present. Subsequently, the main actors involved in DES are introduced. The chapter will finish with some concluding remarks about DES.

2.1 Generation in Decentralized Energy System

Europe is beginning a transition towards a greater active participation of end-consumers by becoming producers themselves (Altmann et al., 2010). In a decentralized energy system, energy production is done on-site, and energy storage is present to shift the energy surplus to a later time of energy deficit. Demand of households comes in two forms; electricity and heat. This section will present the different sources for electricity and heat generation in decentralized energy systems with the aim to understand the technologies, the enhancers and challenges they suppose.

2.1.1 Electricity Generation

PV Generation

The solar photovoltaic (PV) market for electricity generation has considerably increased in recent years. Only in 2018, 102.4 GW of PV panels were installed globally, while the total PV capacity available in the world in 2012 was 100.9 GW. In 2018, the total global solar power capacity reached over 500 GW, and China, United Stated, India and Japan are the main producers of solar energy (Muteri et al., 2020). In Europe, PV panels are a mature technology, as 80% of the world's installed PV capacity in 2008 was in the EU (Altmann et al., 2010). Furthermore, due to the new 40% renewable sources target in 2030, the European members of state aim to increase the total installed capacity of PV in the next several years.

A lot of effort has been made to improve PV performances from a technical, economical and also environmental perspectives. Due to recent technological developments and increased governmental support, driven by European policies such as the already-mentioned Paris agreement, the costs of PV have been reduced, increasing the economic feasibility of solar panels (Mughal et al., 2022). PV panels are dependent on solar radiation and therefore only generate electricity when the sun is shining. This makes solar energy during sundown and very cloudy weather not possible. Solar PV panels can be used in all different scales; for the micro scale, PV panels can be placed on the roof of the house and directly connected to the grid within the building, while for district-scale there are so-called solar farms.

Solar energy is transformed into electricity by solar PV cells, which are devices that produce electricity and can vary in semiconductor materials, sizes and shapes (Muteri et al., 2020). Solar cells can be connected to each other and attached on a frame to form a PV module. Moreover, when numerous PV modules are wired together, they form an array. PV modules and arrays produce electricity, and they account only for one part of the different elements of a PV system. The other components that form a PV system are:

> Mounting structure: a durable structure that supports PV modules and faces the panels toward the sun. This structure serves as protection of external influences such as wind, rain and moisture, as well as prevents corrosion over decades.
>
> Inverter: a component that converts the DC electricity produced by modules into alternating current (AC) electricity, which is used for local transmission of energy.
>
> Storage system: in a decentralized energy system, storage is necessary for the storage of energy, since a DES may not be connected to the electric grid. As outlined previously, the author only considers not-connected systems to the grid.
>
> Other components: components to connect all the parts together safely and securely, such as cables, connectors, and supports.

Wind Generation

Just as solar PV panels, wind turbines are weather dependent and deliver high intermittency in generation. At the end of 2009, wind energy generated about 1.8% of the global demand for electricity with almost 160 GW of installed capacity (IPCC, 2011). This equals about 0.2% of the total global primary energy demand. Wind energy capacity is currently growing at a high rate, with global installed capacity roughly doubling every three years (WWEA, 2010). The IPCC even estimates that wind energy could potentially provide over 20% of the global electricity demand by 2050 (IPCC, 2011), while other more moderate estimations foresee a smaller contribution (Davidsson Kurland et al., 2012). In 2017, 336 TWh were generated by wind power, supplying 11.6% of the European's energy demand, with a total installed capacity of 169 GW (WindEurope, 2018). Nowadays, Europe's installed wind capacity is 205 GW, which accounts for 15% of the total electricity consumed in 2019 (WindEurope, 2020).

Wind generation offers many advantages, such as technological maturity, good infrastructure and relative cost competitiveness (He & Chen, 2009). Wind energy is expected to play a critical role in the future energy market (Murray et al., 2018b). At sites with high wind velocities, it is already competitive with that of traditional fossil fuel generation technologies. However, wind turbines must become more efficient, more robust and less costly than current turbines (Islam et al., 2013). In a DES, wind turbines could be placed on-site. Depending on the scale of the system, wind energy can potentially be the most efficient and the cheapest solution. However, in a small-community scale, the economic feasibility of a wind turbine is poor. This adversity, as well as challenges such as required space and lack of social acceptance when a wind turbine is placed near someone's home (Petrova, 2016), seem to encounter the implementation of wind turbines in the built-environment.

2.1.2 Heat Generation

Heat demand must also be fulfilled in decentralized energy systems. Traditionally, the Netherlands has been heavily dependent on fossil fuel sources, specially natural gas (van den Ende, 2017). However, various sustainable sources are emerging recently for heat generation.

Heat Pumps
Heat pumps are a technology often utilized in DES to reduce fossil fuel usage for water and space heating. A heat pump uses a heat exchanging mechanism, where heat from a low temperature source is pumped to a source with higher temperatures (Sarbu & Sebarchievici, 2014). During summer times, the heat pump can provide the necessary cooling, and will provide the necessary heating during winter times. Heat pumps can extract heat from the air (air-source heat pump), from the ground (ground-source heat pumps) and from water (water-source heat pumps).

Additionally, photovoltaic thermal collectors (PV-T) are a mature technology to fulfill the heat demand. PV-T panels combine PV cells to convert solar radiation into usable electrical energy, as well as solar thermal collector to convert the otherwise unused waste heat into usable thermal energy. In the same way as PV panels, PV-T panels can be placed on the roof of a household, and can be used in both community scale and district scale (Iqbal & Rahaman, 2019; de Uribarri et al., 2017; Huang et al., 2019)

Boilers
An already existing technology for central heating is a boiler, which utilizes an energy source to heat a tank with water (Martinopoulos et al., 2018). Nowadays, natural gas is mostly used as energy sources for boilers in the Dutch built environment. An electric boiler is a sustainable solution to implement in a decentralized renewable energy system, as it uses electricity as a source to heat up the water in the tank. Relevant advantages of electric boilers is that they can use the power generated from PV panels or wind turbines (meaning heating is done in a completely sustainable way), and that they can be applied to a single-household scale as well as district-scale (Sinha et al., 2019).

A second alternative is to replace natural gas with hydrogen gas in conventional boilers. With the use of direct combustion, the hydrogen gas is incinerated in a similar was as natural gas would be incinerated on a traditional boiler (Dodds et al., 2015). Similarly to electric boilers, a hydrogen boiler can be applied to different system scales, such as single household or a whole community (Ozturk & Dincer, 2021). However, hydrogen boilers are not commercially available at the moment, unlike electric boilers (Ozturk & Dincer, 2021).

2.2 Energy Storage

Energy storage technologies are rapidly increasing as a key part of the solution to increase access to electricity in DES, as well as providing stability and flexibility in these systems, improvement in power quality, and increasing the potential of achieving 100% renewable energy share (IRENA, 2017). DES include the connection of storage with residential renewable production to increase self-consumption of renewable energy and/or to avoid peak demand charges by leveling load (Sanajaoba, 2019). In the previous few years in Germany approximately 40% of small-scale solar PV systems are coupled with battery storage due to financial support from the government. Moreover, electricity storage capacity is set to triple by 2030, if countries proceed to double the share of renewable sources in the world's energy system (IRENA, 2017).

In this section, the main energy storage technologies are presented and analyzed based on their application and integration in decentralized energy systems. Energy storage is categorized into five broad categories: electrochemical, mechanical, electrical, thermal, and hydrogen storage technologies.

2.2.1 Electrochemical Storage

Batteries

Batteries are one of the most widely used storage technologies in the market, with high energy densities and high voltages (Koohi-Fayegh & Rosen, 2020). The energy in batteries is stored in the form of electrochemical energy, in a set of multiple interconnected cells. Each cell consists of two conductor electrodes and an electrolyte, placed together inside a container, and connected to an external source (see Figure 2.2) (Díaz-González et al., 2012). The electrolyte enables the exchange of ions between the two electrodes; while the electrons flow through the external circuit.

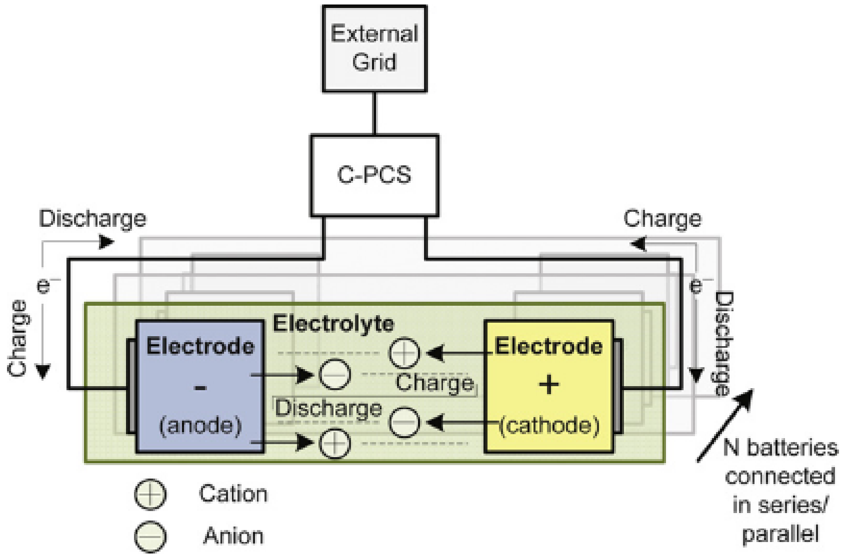

Figure 2.2: Key components of a battery. Retrieved from Díaz-González et al. (2012)

Various types of battery storage technologies are now in a mature phase. Lithium-ion (Li-ion), sodium-sulphur (NaS), nickel-cadmium (NiCd) and lead acid (Pb-acid) are some of the most used batteries nowadays. Pb-acid batteries have been used for more than 130 years in various applications, and are still the most widely used small-medium scale storage technology (Beaudin et al., 2010). In China, Pb-acid batteries are used in approximately 75% of new solar PV systems (Beaudin et al., 2010). Some advantages of Pb-acid batteries are the low costs (300 €/kW), high reliability, high efficiency (65-80%), and are good for continuous power supply and power quality (H. Chen et al., 2009). However, they have short life cycles (500-1000 cycles), require regular maintenance, have low energy density, emit hazardous gasses and fumes, and require a thermal management system due to low performance in cold temperatures. Due to the low cycle life, Pb-acid batteries are mainly utilized for back-up power supply (H. Chen et al., 2009).

Li-ion batteries are playing an increasingly critical role in electrical energy storage. Initially introduced in 1991, the demand for these batteries has grown exponentially since then. This is attributed to the high efficiency (over 95%), long life cycle (3000 cycles), zero maintenance requirements, high charge and discharge rate, and high energy and power density (Palizban & Kauhaniemi, 2016). Furthermore, the capital cost of Li-ion batteries has significantly decreased in the past decade (from 1200 $/kW in 2009 to 400-600 $/kW in 2022) (Koohi-Fayegh & Rosen, 2020; Luo et al., 2015). These attributes make Li-ion batteries the most outstanding choice for self consumption and off-grid applications. Most specifically, a relatively new technology is the Lithium Iron Phosphate (LiFePo4) battery, which allows the greatest number of charge/discharge cycles (Systems, 2022). For these reasons, the Li-ion batteries main application is stationary energy storage systems for applications requiring long life, rather than emergency back-up power (Systems, 2022).

Ni-Cd and NaS batteries are other highly used technologies in the market. Ni-Cd batteries have been studied and developed since 1950, making them a well-established technology in the market. Ni-Cd batteries have competed with Pb-acid batteries since their launch, as they offer longer cycle life (over 3500 cycles), higher energy density (50-75 Wh/kg) and low maintenance requirements. However, its commercial success has been limited due to its costs, previously being at more than 10 times of Pb-acid (Dell & Rand, 2001). One of the most critical drawbacks of this technology is the toxicity of cadmium and nickel. For this reason, the European Commission drew up a proposal in 2003 including recycling targets of 75% for this type of battery; since then, the utilization of the battery has been on a continuous decline (Beaudin et al., 2010).

On the other hand, NaS batteries are a promising technology with high energy density (Díaz-González et al., 2012). Important features of NaS batteries are no self-discharge, low maintenance and long cycle life (4500 cycles), which make this battery a highly promising option for applications in DES (Beaudin et al., 2010). NaS batteries are environmentally-friendly, as only sodium must be handled as a hazardous material, and 99% of the weight of the battery can be recycled (Beaudin et al., 2010). However, one special characteristic of these batteries is that they have to operate at a temperature of around 350ºC, and are subject to high capital costs ($700-900/kWh). These attributes make NaS to find their main application in stationary power reserve.

Table 2.1 displays a clear comparison between the four previously-discussed batteries. The energy densities, efficiencies, costs, lifetime cycles, and most relevant applications of each battery type are presented.

Table 2.1: Battery technologies comparison

Types	**Energy density**	**Efficiency**	**Costs**	**Lifetime-cycles**	**Applications**
Lithium-ion batteries	75-200 Wh/kg	>90%	$600/kWh	10,000 cycles	Transportation, buildings and grid-connected micro-turbines.
Lead acid batteries	30-50 Wh/kg	65-80%	$300-600/kWh	500-1000 cycles	Power quality, uninterruptible power supply and spinning reserve.
Nickel-Cadmium batteries	50-75 Wh/kg	80-95%	$1000/kWh	2000-2500 cycles	Power tools, portable devices, emergency lighting.
Sodium sulfur batteries	150-240 Wh/kg	75-90%	$700-900/kWh	4500 cycles	Stationary power reserve in grid applications.

Supercapacitors

Supercapacitors, also known as double-layer capacitors or ultracapacitors, are a form of energy storage based on two conductor electrodes, an electrolyte, and a porous membrane where an ion is transported from one electrode to another (Díaz-González et al., 2012). Batteries and supercapacitors are usually compared to each other. Nonetheless, no transfer of electrons occur in supercapacitors as the operating voltage is lower. The main differences between the two storage technologies is that batteries are able to store up to 30 times more charge than supercapacitors per unit of mass, but supercapacitors can deliver up to thousands of times the power of a battery of the same mass (Koohi-Fayegh & Rosen, 2020). Due to the low-cell voltage of supercapacitors (about 3 V), the desired voltage and capacity are achieved by the series and parallel connection of a set of cells (MacKay & Winser, 2011). An overview of the components on a supercapacitor is shown in Figure 2.3.

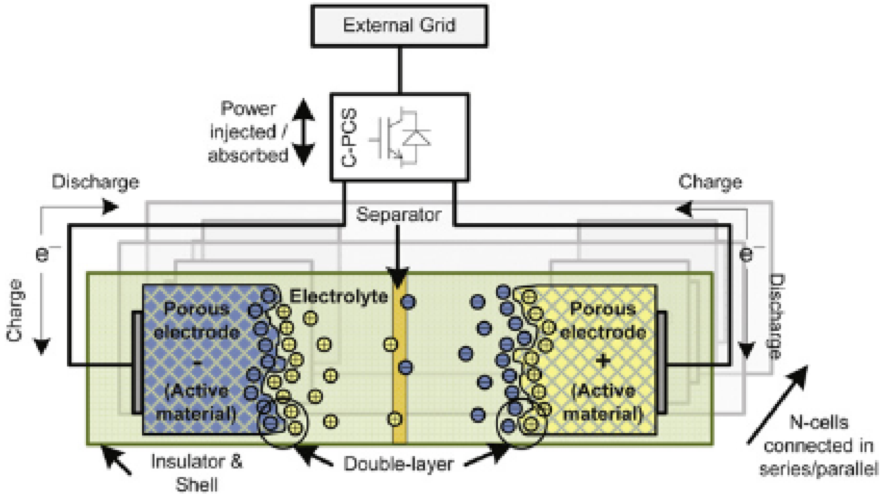

Figure 2.3: Key components of supercapacitor storage system. Retrieved from Díaz-González et al. (2012)

Supercapacitors possess power densities up to 10 times higher than batteries (Koohi-Fayegh & Rosen, 2020). The high self-discharge of the system (up to 40% of its maximum capacity per day (Beaudin et al., 2010), characterize this technology for short term applications with short time responses. Important advantages of this storage technology are their long life cycles (10,000-100,000 cycles, and lifetime of 8-10 years), essentially no maintenance, high energy efficiencies of approximately 75-80% and charge and discharge cycle times of 30 seconds (Helwig & Ahfock, 2009). However, its energy density is very low (2-5 Wh/kg), as well as the most important drawback for this storage technology, which is the high costs, estimated in 10,000-20,000 $/kW (Koohi-Fayegh & Rosen, 2020)(Beaudin et al., 2010). The main applications of supercapacitors, shaped by the short duration and high energy dissipation, are power factor correction and power quality control (Beaudin et al., 2010).

2.2.2 Electrical Storage

Superconducting magnetic energy storage

Superconducting magnetic energy storage (SMES) is a relatively new technology, introduced in 1970, which operates by utilizing a large superconducting coil, which has near zero electrical resistance and near zero temperature, capable of storing electrical energy in the magnetic field generated by DC current flowing through it at cryogenic temperature (Koohi-Fayegh & Rosen, 2020). No energy losses are present in the coil as superconductors offer no resistance to electron flow (Díaz-González et al., 2012). Furthermore, SMES coils can discharge large amounts of power almost instantaneously, and can undergo an unlimited number of charging and discharging cycles at high efficiency. However, SMES units can only generate electricity at rated capacity for a few seconds, have strong magnetic fields, and are highly expensive ($1000–10,000/kW) due to the need for cryogenic temperature to maintain superconductivity.

SMES devices in the range of 1-10 MW are commercially available, and larger-scale devices of approximately 50MW capacity are installed in the United Stated. The main applications of SMES systems are for system stability, voltage stability, power quality improvement, and uninterruptible power supply (Koohi-Fayegh & Rosen, 2020). Studies have been performed for the implementation of SMES systems in renewable energy system. However, the high costs indicate that SMES are not suitable for these applications. Ngamroo et al. (2009), indicate that batteries, supercapacitors and flywheels are more fitted technologies for implementation in renewable energy systems.

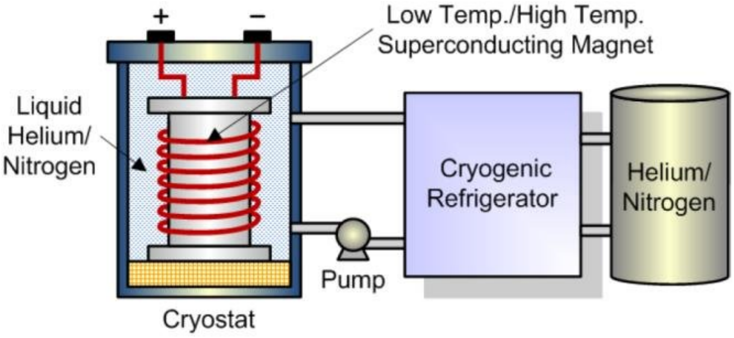

Figure 2.4: Key components of a superconducting magnetic energy storage system. Retrieved from Díaz-González et al. (2012)

2.2.3 Mechanical Storage

Flywheels

Flywheels have been used for thousands of years, making them the oldest form of energy storage (Zhou, 2022). Energy is stored in the angular momentum of a spinning mass. The storage is powered up by a motor, and the same motor is used during discharge as a generator to produce energy from the kinetic energy of the flywheel (Zhou, 2022). The flywheel capacity is subject to the size and speed of the rotor, deriving in two types of flywheel systems: low speed (under 10,000 rpm, which are the most attractive flywheel systems in industry), and high speed (above 10,000 rpm) (Rana et al., 2022). Flywheel storage systems have interesting properties such as long life cycles (up to 1 million, and 25 years of lifetime), efficiencies up to 90%, no capacity degradation, no greenhouse gasses emissions, no hazardous components, and very high response (Palizban & Kauhaniemi, 2016; IRENA, 2017). However, they suffer from an approximate 20% self-discharge rate per hour, low storage capacity, high costs (2000-6000 \$/kWh) and noise pollution, making flywheel energy storage systems poorly feasible for implementation in decentralized energy systems. The main applications of flywheels are uninterruptible power supply and power quality improvement (Amiryar & Pullen, 2017). An overview of a flywheel is presented below (see Figure 2.5), where the different components of the system are displayed.

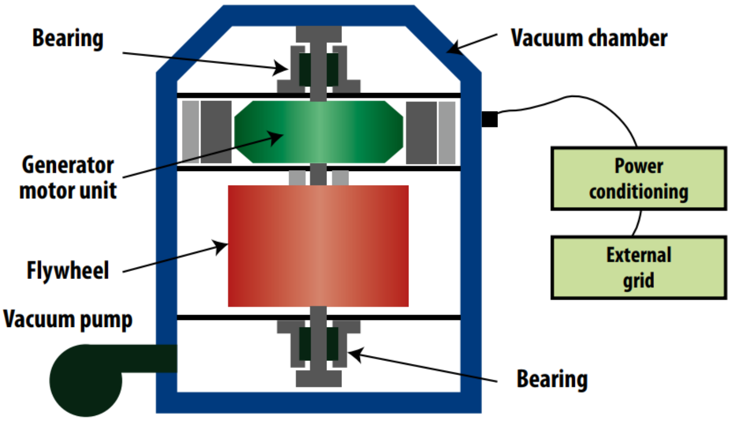

Figure 2.5: Key components of a flywheel energy storage system. Retrieved from Díaz-González et al. (2012)

Compressed Air

In a compressed air energy storage (CAES) system, electrical energy is stored in the form of compressed air in a reservoir (Rana et al., 2022). When energy generation is high, the excess energy is utilized to compress air, while when energy demand is high, the air can be delivered to a turbine where the air is heated and expanded to generate electricity (Parra et al., 2017). Reservoirs used to store the compressed air include aquifers, salt caverns, and hard rock caverns. Such geological formations might not be available everywhere and large underground steel tanks able to withstand high pressures can be installed underground at a considerably higher system cost (Palizban & Kauhaniemi, 2016).

Nowadays, CAES systems are not widespread mainly due to geological constraints. CAES systems are utilized in large-scale approaches (50-300 MW) for long periods of storage time (typically for more than a year) due to very low losses (Rana et al., 2022). Only two plants have been constructed in the world so far; one in Germany (290 MW) and the other in the USA (110 MW) (Ibrahim et al., 2008). Although only two CAES plants are installed, they have demonstrated high reliability and economic feasibility, and are attracting high interest to mitigate the intermittency of renewable sources. CAES systems have many attractive qualities such as high power capacity (up to 300 MW), quick start-up time (10 min normal operation), long storage period (over a year) and relatively high efficiency (60-80%) (H. Chen et al., 2009). However, the geographical dependence, the requirement for large-scale power storage to make the system feasible, and low energy densities (12 kWh/m3), are some of the disadvantages of these systems (H. Chen et al., 2009; Ibrahim et al., 2008). These characteristics limit the implementation of CAES systems in small-scale energy systems.

In Figure 2.6, a schematic diagram of a CAES system is presented. It consists of five major components: an energy generator that provides energy to the compressor or turbine trains, an air compressor, a turbine train, containing both high- and low-pressure turbines, a container for storing compressed air, and equipment control such as fuel storage and heat exchanger units.

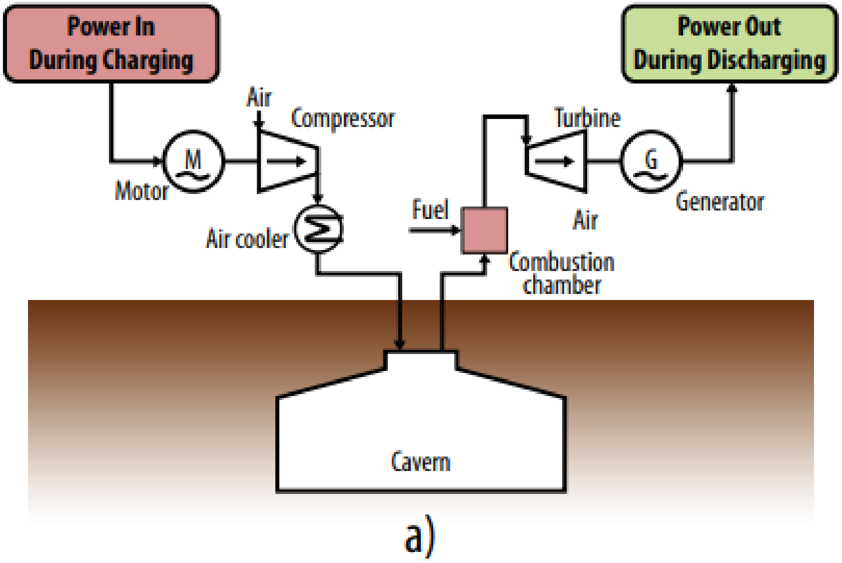

Figure 2.6: Schematic diagram of a CAES system. Retrieved from Díaz-González et al. (2012)

2.2.4 Chemical Storage: Hydrogen

Hydrogen
Hydrogen storage systems, unlike the other forms of energy storage, separates processes for hydrogen production, storage, and use (Beaudin et al., 2010). First, hydrogen is produced via direct or electrolytic methods, stored for a period of time, and then chemically reacted to produce electricity. The most common method for hydrogen production is by splitting water (electrolysis) (Koohi-Fayegh & Rosen, 2020). The energy required to run this process can be obtained from renewable energy sources, gasifying biomass, or from fossil fuels, which is the most utilized source nowadays (Díaz-González et al., 2012). Hydrogen storage offers high calorific, high energy density and non-toxic sources of energy storage. Furthermore, due to having practically zero self-discharge, this storage system allows the storage of energy for long periods of time. The three components of a hydrogen storage system are an electrolyzer, a hydrogen tank, and a fuel cell, as represented in Figure 2.7

Electrolyzers are a key part of hydrogen storage systems. With these devices, water is electrolytically reduced to hydrogen and water (Díaz-González et al., 2012). There are various kinds of electrolyzers, ranging from the most used Alkaline electrolyzers, to the more current Polymer Electrolyte Membrane (PEM) electrolyzer, and to high temperature solid oxide electrolyzer (Díaz-González et al., 2012). Alkaline electrolysis are the most common electrolyzer technologies due to their technology maturity and lower costs (600 \$/kWh)(Parra et al., 2017). PEM electrolysis offers a higher quality product, with higher power densities and more flexibility to partial loading (Bessarabov et al., 2016); however, the costs of this technology elevates to 1000-2000 \$/kWh (Breyer et al., 2015). These two forms of electrolyzers operate at low-temperature electrolysis (50-80ºC), with efficiencies of approximately 50% (Bhandari et al., 2014). Moreover, solid oxide electrolysis is still in early stages of research and development given some challenges such as corrosion, seals, and thermal cycling. However, it is gaining interest as its efficiency ranges from 81% to 86% (Cai et al., 2014). Electrolyzers are categorized based on liquid or solid electrolyte. The usage of solid electrolytes enables PEM electrolyzers to produce hydrogen at suitable pressures (13-400 bar) to store hydrogen in tanks or metal hydrides (Parra et al., 2017).

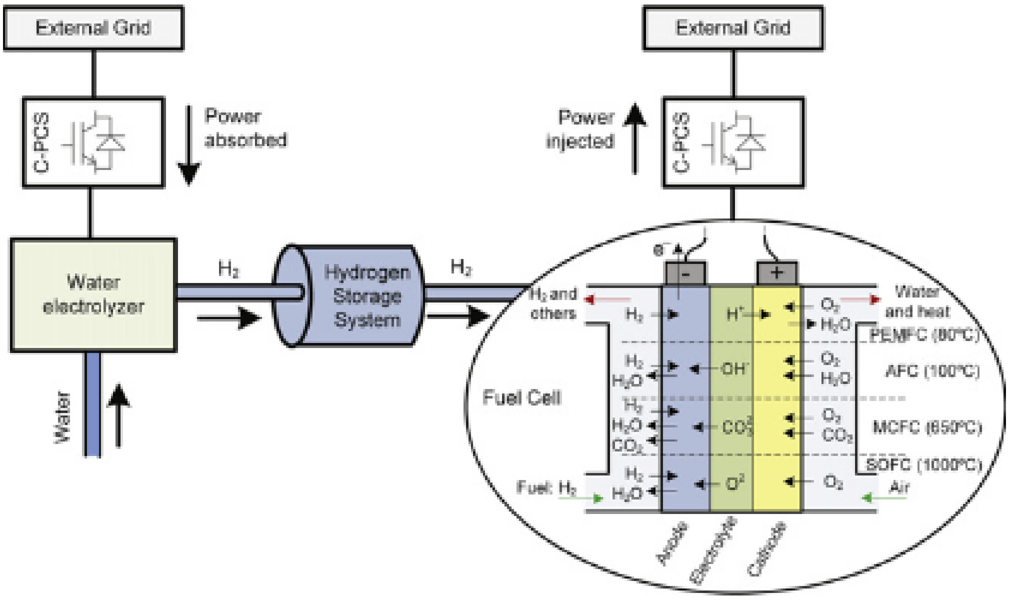

Figure 2.7: Schematic diagram of a hydrogen storage system. Retrieved from Díaz-González et al. (2012)

After hydrogen has been produced, it is stored in the form of gas, liquid, or metal hydride (Parra et al., 2017). High-pressure storage of hydrogen is done in high-pressure tanks (350-700 bar), while the less-studied liquified hydrogen storage is done at the cryogenic temperature of -260ºC. However, these forms of hydrogen storage do not offer the potential to meet the space targets for on-board transport applications, which are the main drivers for metal hydrides storage (Walker, 2008). The main barriers faced nowadays with hydrogen storage is the current costs of equipment and the constraints in weight and space (Bhandari et al., 2014).

To convert hydrogen into electricity, fuel cells are utilized. Fuel cells are a low power-density technology that convert chemical energy from water and hydrogen into electricity, with efficiencies from 40-60% (Koohi-Fayegh & Rosen, 2020)(Parra et al., 2017). There are several types of fuel cells, varying from polymer electrolyte membrane (PEM), Alkaline, Phosphoric acid (PAFC), molten carbonate (MCFC) to solid oxide (SOFC). PEM fuel cells and SOFC are the most widely used technologies. The main operating difference is the temperature (50-100ºC for PEM fuel cells and 600-800 ºC for SOFC). PEM fuel cells have the advantage of low maintenance and corrosion, while SOFC offer higher efficiencies (60%). However, since the catalytic material for PEM fuel cells is platinum, the cost of this fuel cell highly increases (approximately 800$/kW and 500 $/kW for SOFC).

From an application perspective of hydrogen storage, studies have been performed on decentralized energy systems. It has been concluded that, even with low round-trip efficiencies (25-40 %), the implementation of hydrogen system allows the integration of RES and allows a higher flexibility than batteries for larger systems. A hybrid storage system including Li-ion batteries and compressed hydrogen storage was proposed as daily and long-term storage, respectively (Parra et al., 2014). Hydrogen was suggested since battery storage could not deal with the seasonal mismatch. It was found that such a system is able to increase the self-consumption of PV energy and to reduce the electricity imported from the grid to practically 0% (Parra et al., 2014).

2.2.5 Thermal Storage

Thermal energy storage (TES) refers to the storage of thermal energy when there is a surplus of production from a heat source (Rana et al., 2022). TES stores heat or “cold” and consists of a storage medium for heat injection and extraction from the medium (Rana et al., 2022). Heat storage mediums can be naturally available (underground), or they can be artificially made using a container that prevents heat loss or gain from the surroundings (Rana et al., 2022). The main TES modes are sensible and latent heat. The most widely used TES mode is sensible heat, including hot water storage (traditionally the most used), underground TES (aquifer, cavern, etc.), and rock filled storage (Rana et al., 2022). On the other hand, latent heat is a recent technology that involves the change of phase of a storage material, often solid and liquid phases (Parra et al., 2017). Latent heat has been the focus of recent research due to having improved characteristics compared to sensible heat storage, mainly due to the isothermal nature of the process, the higher energy density and improved thermal properties (Parra et al., 2017).

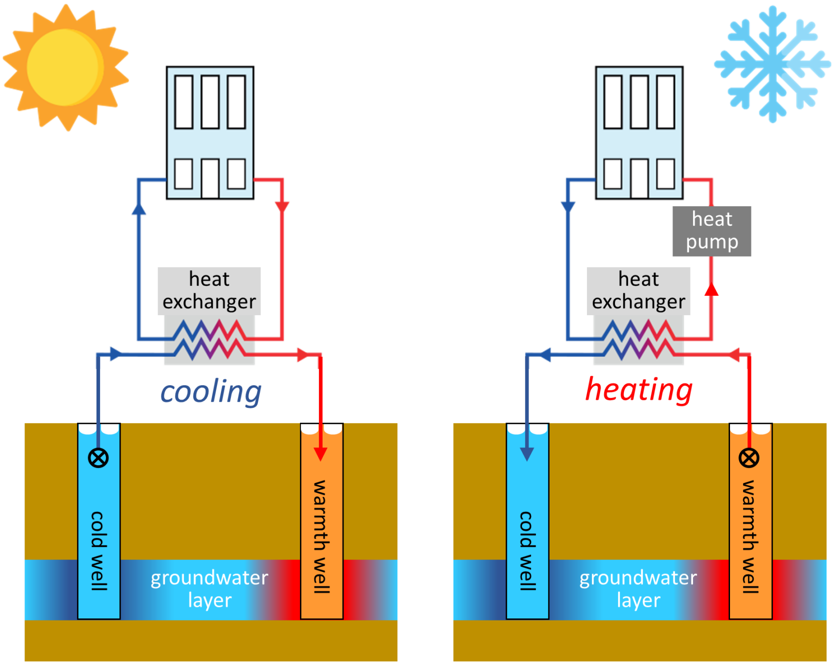

Figure 2.8: Schematic diagram of a Thermal energy storage system. Retrieved from Díaz-González et al. (2012)

Heat storage, similarly to electricity storage, can be delivered in seasonal or short time periods. For seasonal storage, the main technology used is based on underground thermal storage, where a large system is required that is capable of storing heat for its use several months later (Parra et al., 2017). For example, a ground heat storage system can be coupled to a community to store the surplus heat in the summer and use it in the winter when heat demand increases. However, the main disadvantages of seasonal heat storage are the large space required and the costs of the containers and implementation (Parra et al., 2017). The most frequently implemented technology in northern European buildings is borehole TES in combination with a heat pump (Hesaraki et al., 2015). In the Netherlands, the aquifer thermal storage, an underground storage medium, is the most widely implemented technology, with over 2,000 installations (Kaldellis et al., 2009). This technology is able to deliver higher energy densities and lower costs; however, geological conditions are required for this technology to be applied (Hadjipaschalis et al., 2009). Nowadays, the main barriers faced by thermal storage technologies are the lack of technical feasibility, the lack of knowledge in the technology, the high investment costs, and lack of policies and legislation (Tatsidjodoung et al., 2013).

2.3 Actors Involved

Since the development of centralized electric power systems, the structure has been organized into generation, transmission, and distribution, placing customers at the end of the supply chain (IRENA, 2019). However, with the increasing need for decentralized energy systems and the emergence of new players, such as prosumers, the energy market will be remodelled and new roles will emerge for current actors. The actors presented in this section include centralized energy producers, the transmission system operator (TSO), the distribution system operator (DSO), and prosumers.

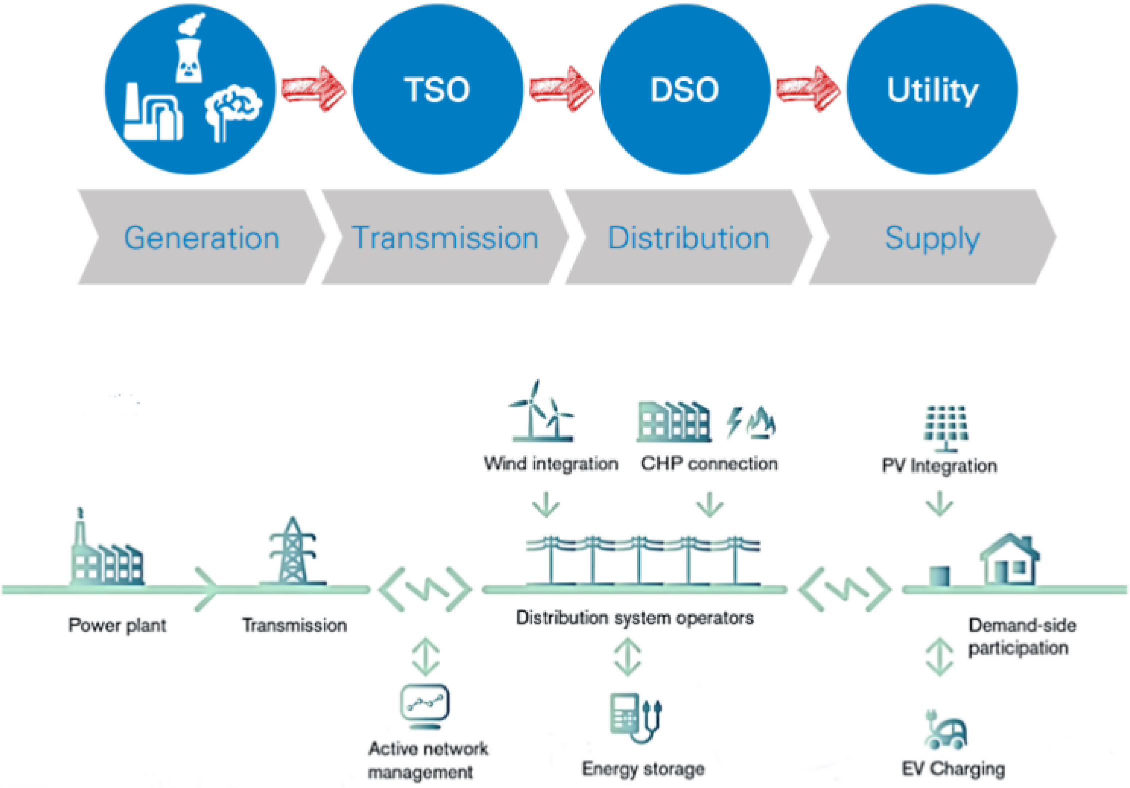

Figure 2.9: Energy market actor structure: traditional and future structure. Retrieved from EDSO (2022)

2.3.1 Energy Producer

In the future energy market, centralized plants will continue to be the main producers of electricity (Zhou, 2022). With the recently concluded decarbonization policies, it is observable in today's energy market that companies that prioritized the purchase of clean power plants, such as Enel, Iberdrola, NextEra Energy and Orsted, are leading the race to electrify the global economy (Meister et al., 2018). These clean energy supermajors' market cap have surpassed those of oil companies (see Figure 2.10), and are expected to have a continuous growth as the development and implementation of sustainable technologies becomes greater (Meister et al., 2018). Energy and Oil companies will continue to increase their share of renewable sources.

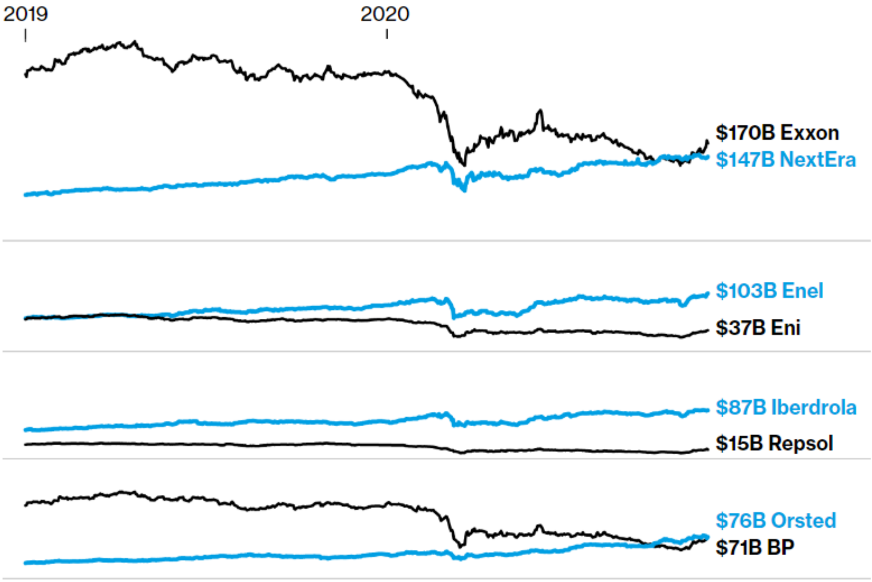

Figure 2.10: Energy market supermajors. Retrieved from Meister et al. (2018)

2.3.2 TSO

The transmission system operator (TSO) is responsible for controlling and operating the transmission grid, which includes monitoring and controlling the grid topology and voltage in all parts of the transmission grid (Koch, 2015). While the electricity system will maintain a central transmission backbone network, the development of renewable sources, decentralized generation and smart-communities could lead to a decline in dependence on the transmission network. For TSOs, this increases the risk of obsolete assets and related regulated revenues (Baes & Carlot, 2018). TSOs have the opportunity to develop their position within the value chain by influencing and supporting innovative systems and technologies. Some examples of how TSOs can develop their traditional role in the future energy systems, based on Baes & Carlot (2018) are:

> Implementation of state-of-the-art technologies in pilot cases: e.g., Terna and RTE invest in batteries in a range of applications for congested and imbalanced grid assets.
>
> National Grid has developed a blockchain energy-trading platform and incentives electric-vehicle fast-charging networks.
>
> TenneT tests linking decentralized home storage solutions to stabilize the grid.

With the development of the new market, new opportunities and obligations will arise for TSOs willing to reinforce the classical system with the emerging transition system. New roles will emerge for TSOs in system operations, asset management, ecosystem facilitation and diversification (Koch, 2015; Baes & Carlot, 2018).

2.3.3 DSO

Distribution system operators (DSOs) are the operating managers of energy distribution networks, operating at low, medium and high voltage levels, where their main mission is providing a secure electricity supply and quality of service (EDSO, 2022). Transmission grids transport vast quantities of high voltage electricity across large distances, from power plants to large residential or industrial areas, where it is transformed into lower voltages distributed to all end-users through the distribution network. Overhead and underground cables leading to houses or businesses are operated by DSOs. To take advantage of these new opportunities and to keep pace with both the transformation of the power sector and changing customer needs, DSOs will need to adjust their current role. Conventional roles of DSOs included the connection and disconnection of distributed energy resources (DER), planning and maintenance of networks, management of supply outages, and managing energy billing. With the new power structure in the future energy market, emerging additional roles will arise for DSOs:

Peak load management through DERs

Network congestion management

Provide reactive power support to TSOs

Procure voltage support

Technical validation for power market

The new role of DSOs will have a significant impact on the way the power system is operated today. The change in role will bring key advantages such as an increasing flexibility in distribution networks, the reduction in network investments using DERs, and leveraging data to increase renewable energy penetration (IRENA, 2019).

2.3.4 Prosumers

Prosumers are people who consume some of the goods and services that they themselves produce (Wolfgang et al., 2018). A previously-mentioned, the supply of energy and flexibility services are two key services in the energy system. Prosumers taken into consideration generate at least one type of energy supply, for example, by installing solar panels in their roof or by coupling their house with a power battery. The shift to decentralized energy systems has been motivated by communities wanting to live in more sustainable ways, technological interest, and self-consumption, rather than by economic incentives (Wolfgang et al., 2018; Koons, 2022). Currently, energy storage (batteries, and mainly hydrogen) is not a cost-effective technology for electricity demand, and in the EU, national regulations for energy solutions in buildings should promote cost-efficiency. Nowadays, one of the main barriers for new prosumer business models is the lack of or immature regulatory frameworks, which might be a consequence of the lack of experience of large-scale market integration of prosumers (Koons, 2022). However, developing communities of prosumers can reduce challenges such as grid congestion, as it will reduce the need and usage of the transmission grid in a local and national level. Combined with an energy storage system, distribution network and smart meters, these individuals and communities can be self-reliant.

2.4 Applications of technologies to DES

In this chapter, a literature review has been conducted on the different elements of a decentralized energy system. First, the generation technologies in decentralized energy systems were discussed, presenting both electricity and heat generation. Then, the main energy storage technologies were divided into five categories, were the application of each technology to decentralized energy system was discussed. Lastly, the main actors involved in the energy system were discussed, where their roles in the future market were analyzed.

Two technologies for renewable electricity generation have been presented, photovoltaic panels and wind turbines. These technologies are dependent on weather conditions, and their implementation to DES differs from each other. Solar PV panels can be used in all different scales; from placing PV panels on the roof of the house and directly connected to the grid within the building, to district-scale solar farms. The implementation of PV panels has been widely studied in the past decades, and the investment costs are rapidly decreasing, making them the most viable technology for electricity generation in DES. On the other hand, wind turbines have higher investment costs and decreases the economic feasibility on a small-scale DES. This, as well as lack of social acceptance and the large space required to build these, decrease the feasibility of implementing wind turbines in small-scale decentralized energy system. Wind turbines are feasible when implemented in large-scale energy systems.

Furthermore, heat pumps and boilers were analyzed for heat generation in decentralized energy systems. Both technologies are utilized in DES, and are reliable solutions to reduce fossil fuel utilization by potentially only using water.

Storage technologies were reviewed and their application to DES were discussed. First, the four most used batteries, Pb-acid, Li-ion, Ni-Cd, and NaS were analyzed for short-term energy storage implementation in DES. While Pb-acid batteries have good properties, such as high efficiency, high reliability and low costs, their main disadvantage is that they have very short life and have low energy density. On the other hand, Li-ion batteries are playing an increasingly critical role in electrical energy storage. High efficiencies, long life cycles, no maintenance requirements, high energy and power density, are some of the main advantages of this battery. The costs of Li-ion batteries are higher compared to Pb-acid batteries; nonetheless, they are concluded to be the most suitable short-term storage technology in DES applications. Lastly, Ni-Cd and NaS batteries can be applied to DES, they have good energy densities, high efficiencies and long life cycles, but their high capital costs make them less feasible than Li-ion batteries.

Supercapacitors were analyzed for short-term energy storage. Supercapacitors are often compared with batteries, with beneficial properties such as long life cycles, no maintenance, high efficiencies and very fast charge and discharge rate. The main disadvantages of supercapacitors are the considerably low energy density and the extremely high costs, up to 30 times the costs of Li-ion batteries. Supercapacitors could be implemented in DES, but this technology finds its main applications in power factor correction and power quality control.

Similarly to supercapacitors, flywheels are a short-term energy storage technology with very long life cycles, high efficiencies, rapid response time, among with other advantageous properties. However, they suffer from very high self-discharge rate, low storage capacity, and significant high costs. Therefore, compared to other short-term storage technologies such as Li-ion batteries, their implementation in DES is not equally feasible.

Superconducting magnetic energy storage can only operate at rated power for only a few seconds, are highly expensive and must operate at cryogenic temperature to maintain superconductivity. Their main applications involve system stability, power quality improvement, an uninterruptible power supply.

For long-term energy storage, compressed air and hydrogen are the two methods analyzed. Compressed air energy storage is an attractive technology to mitigate intermittency of renewable sources. The main qualities of CAES are high power capacity, quick start-up time and relatively high efficiencies. However, the geographical dependence, the requirement for large-scale power storage to make the system feasible and low energy densities are some of the disadvantages of these systems. Small-scale CAES systems can be utilized in DES by implementing large underground steel tanks able to withstand high pressures at a considerably higher system cost.

Hydrogen storage systems require electrolyzers, hydrogen tanks, and fuel cells. The main disadvantage of hydrogen storage are the low round-trip efficiency and high investment costs. However, even with low round-trip efficiencies, the implementation of hydrogen system allows the integration of RES and allows higher flexibility than batteries for larger systems. A renewable hybrid storage system including Li-ion batteries for daily storage and compressed hydrogen storage for long-term storage is able to increase the self-consumption of PV energy and allows for a system with 100% energy self-sufficiency. Therefore, to mitigate the daily and seasonal intermittency of renewable sources in a decentralized energy system, Li-ion batteries and compressed hydrogen storage system are concluded to be the most feasible storage technologies for short- and long-term storage, respectively.

Chapter 3

Energy System Description

The energy system derived in Chapter 2 is designed with the goal of obtaining a self-sufficient energy system, capable of withstanding the daily intermittency of renewable sources with a Li-ion battery, and the long-term seasonal intermittency using a hydrogen system. As previously mentioned, hydrogen storage is an attractive option to compensate for the seasonal differences, as it is capable of developing a self-sufficient and independent energy system. In the designed energy system, excess production from PV panels can be directly stored into a battery, or transformed into hydrogen by means of electrolysis. The produced hydrogen is compressed and stored in a storage tank. When needed, the hydrogen can be used to produce electricity through a chemical reaction in a fuel cell. In this chapter, an overview of the energy system and the two use cases are presented. Furthermore, the generation and demand profiles, as well as the component parameters, are introduced.

3.1 Energy System Overview

The designed energy system must be fully decentralized, removing all connections with the national grid. The hydrogen storage system will function as the long-term storage medium, where it will be used as the emergency energy supply in winter months when the battery cannot supply the required energy. Since hydrogen is produced on-site, the PV generation capacity should be enough to fulfill the demand requirements and produce hydrogen in the electrolyzer during summer months. Thus, an oversized PV capacity is required, which is seen as feasible from an economic perspective as the PV generation components are significantly cheaper than the hydrogen components. Therefore, it is cheaper to have an oversized PV capacity than more hydrogen storage capacity.

Moreover, the system is assumed to be totally electrified, meaning that electricity will be used to cover the heat demand, using an electric boiler to obtain heat from electricity. At TGV, four of the houses are electrified, while the remaining three houses have heat pumps. However, to simplify the development of this research, it is assumed all houses in the community have electric boilers installed. The proposed energy system is displayed in Figure 3.1, where the final consumers could be one house or a local community, depending on the system scale. To design such a system, it is necessary to look at the generation profiles, demand profiles, and characteristics of each component included in the energy system.

There are two cases considered in this project. First, a system that is designed for a single household, i.e., the reference case. This system is designed based on the real-life pilot study at TGV. Next, this reference case is scaled-up to a community level.

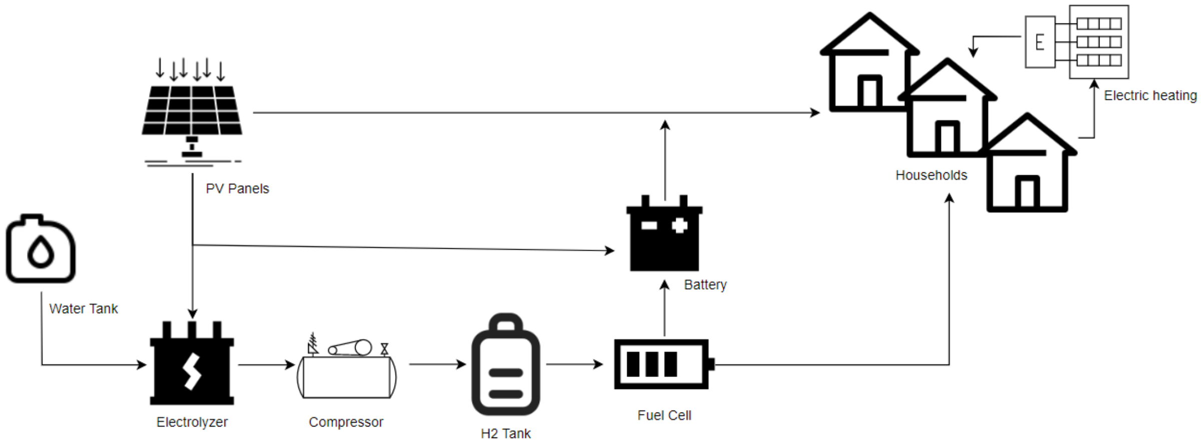

Figure 3.1: Design of a decentralized renewable energy system

3.1.1 Reference Case

As presented in Chapter 3.1, an energy system including PV panels, a battery for short-term storage, and a hydrogen system for long-term storage is proposed to fight the short-term and long-term variability of solar energy production. The reference case is based on the real life system at TGV, where the system shown in Figure 3.1 is implemented for a single household. The technical and economic parameters of every component are presented in Chapter 3.2. Nowadays, the goal of TGV is to obtain self-sufficiency in a community level, meaning they want to scale up the system to include the whole community. To achieve this objective, the components must be scaled up, but an adequate sizing of the components is required to minimize the costs.

3.1.2 Community-Scale

The reference case is scaled-up to include a larger group of households, taking the entire local community into consideration. The community consists of a group of 7 houses, comprised of 4 individual studios and 3 family houses. The characteristics of each house differs from one another, as the heat demand is fulfilled with different sources. Currently, the individual studios are fully electrified, while the family houses are still covered with heat. However, as mentioned above, it is assumed that all houses in the community are electrified. Therefore, the electric demand will include the heat demand, which will be transformed to the specific unit of electricity demand (kWh) to make this transformation.

In the design of such community-scale systems, the sizing of each component strongly affects the economic performance of the system. The demand behavior of the community affects the sizing of each individual component, as they each have their own specific requirements for the optimal sizing value. In this research, the optimal value of the components presented in Figure 3.1 will be found to develop a system with minimum costs.

3.2 Data Description

This section explains the data used for the design of a DES, including the generation profiles, demand profiles, and characteristics of each component of the system.

3.2.1 Generation Profiles

The solar generation data has been obtained from the European Comission Photovoltaic Geographical Information System (PVGIS). PVGIS provides information about solar radiation and PV system performance for any location in Europe and most parts of the world. This tool allows to extract the electricity generation potential for different PV technologies and configurations, solar radiation and temperature, as monthly averages or daily profiles, and full time series of hourly values of both solar radiation and PV performance. Specific data parameters are used as input to obtain the hourly solar production of a time spam of 10 years, where the location selected for this data set is TGV. Table 3.1 displays the necessary input parameters are shown. For the tilt and the azimuth of solar panels, PVGIS provides the optimal configuration for the selected time spam, meaning the values selected will achieve the highest electricity production.

Table 3.1: Data input for solar generation

Concept	Value
Longitude	4.378
Altitude	51.997
Data set	MERRA-2
Years	2010-2020
Capacity	6 kW
System loss	10%
Tilt	40 degree
Azimuth	0 degree

Generation profiles can be described based on daily and seasonal characteristics. On a daily basis, generation profiles are characterized by peak production at noon. Since solar production is influenced by weather conditions, there is a higher electricity generation during summer than during winter. The solar generation profiles can be seen in Figure 3.2, where the solar production is displayed for a winter and summer day (1st of January and 1st of June), and for a winter and summer month (January and June).

Figures 3.2 and 3.3 depict that there is higher electricity production in summer months, compared to winter months. Summer days have longer sun hours than winter days, with approximately 12 hours of solar production in a summer day, as seen in Figure 3.2a, compared to approximately 7 hours of solar production in a winter day. Furthermore, solar production tends to be more consistent in the summer, with lower variation of peaks as shown in Figure 3.2. In January, only a few days tend to have a high electricity production, as most days are cloudy or have adverse weather conditions. In June, weather is mostly sunny, meaning days tend to have a more similar solar production profile, as well as higher production due to solar irradiation being higher in summer. The total electricity production from solar panels in 2020 is shown in Figure 3.3, where these conclusions can be visualized. Starting from the middle of Match, solar production increases as well as its consistency, until the beginning of September, where weather tends to be more adverse, meaning less production and more variability.

3.2.2 Demand Profiles

The data presented in this section is the corresponding hourly demand data of the households at TGV, which was provided by the external advisor at TGV, Joep van der Weijden. The data provided corresponds to the year 2020; therefore, the yearly demand data will be replicated each year on the time span of 10 years. Since the four studios are fully electrified, only one demand data sheet is present, which includes the combined electricity and heat demand. For the three

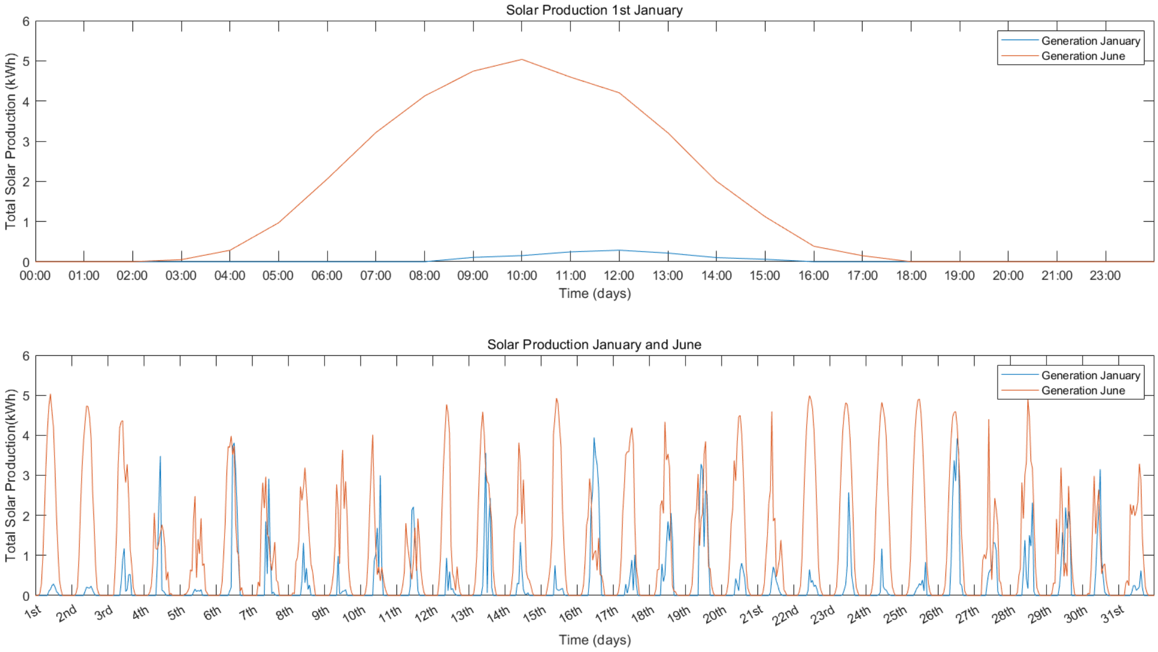

Figure 3.2: Solar production January and June 2020

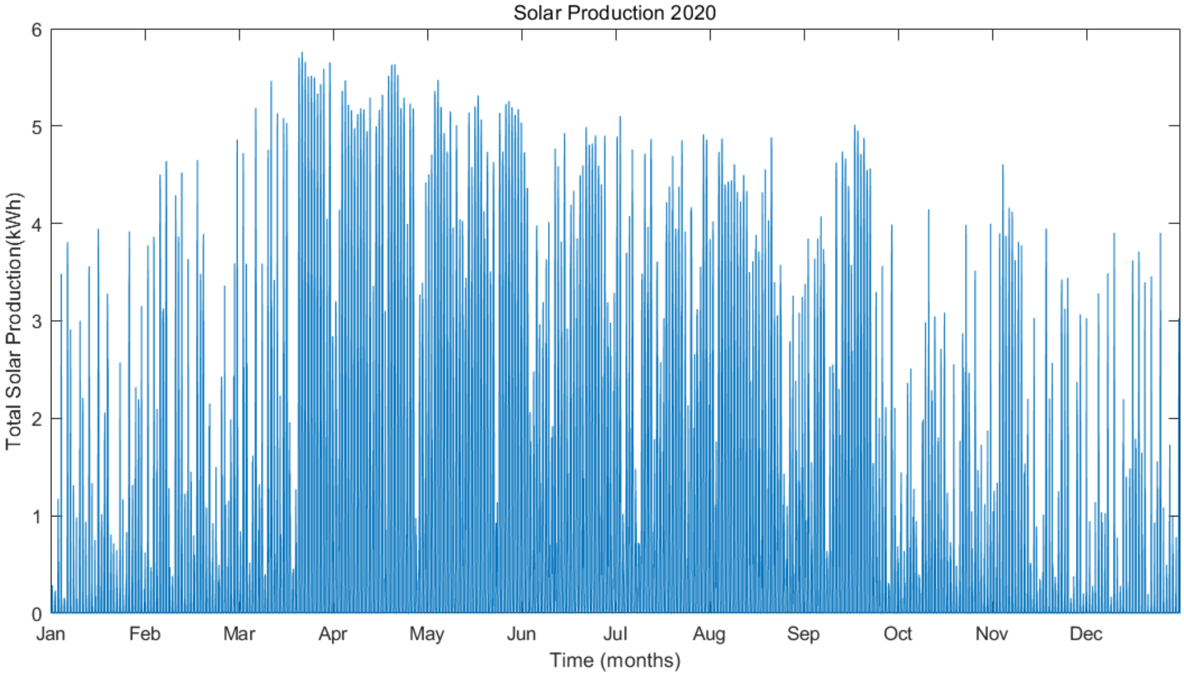

Figure 3.3: Solar production 2020

family houses, two data sheets are given, for both the electricity and heat demand. To simplify this research, for the three family houses the heat demand values were converted from m^3 to kWh, to assume the heat demand is fulfilled with electricity. The figures displayed in this section combines the electricity and heat demand of all households in the system.

Demand profiles, in a similar way as generation profiles, follow daily and seasonal patterns. A daily demand profile is characterized by peak demands in the morning and evening, as residents

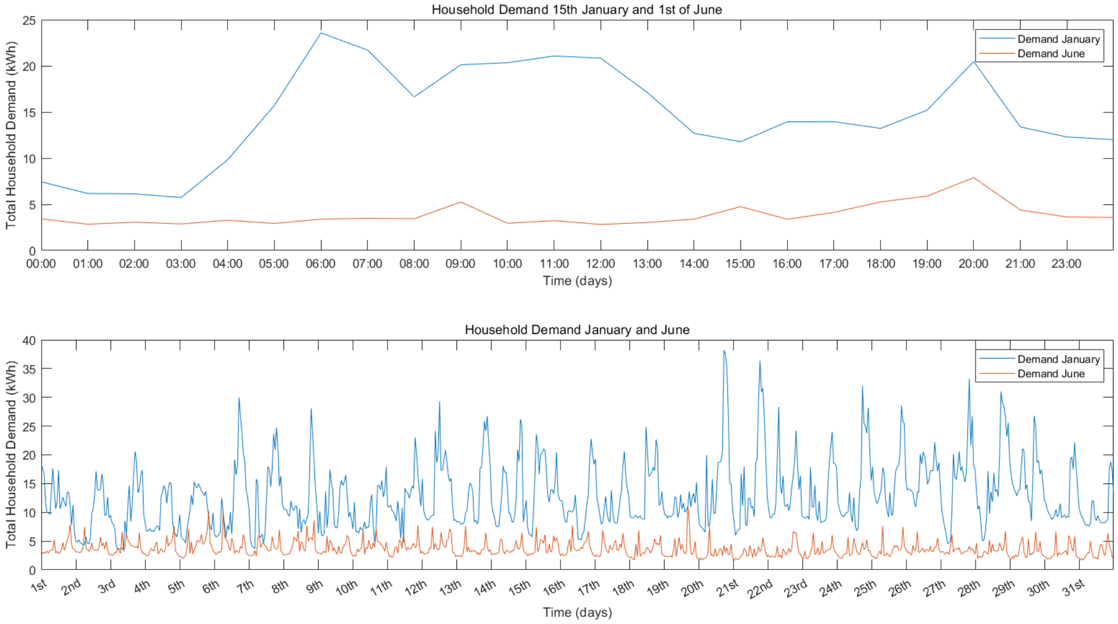

Figure 3.4: Demand consumption January and June 2020

are expected to go to work during the day. On the other hand, the weather conditions have a significant influence on the demand of residential buildings, resulting in a significant higher demand in the winter than during the summer, mainly attributed to higher heat consumption in winter months. This can be seen in Figure 3.4, where the energy demand is presented for a winter and summer day, and a winter and summer month.

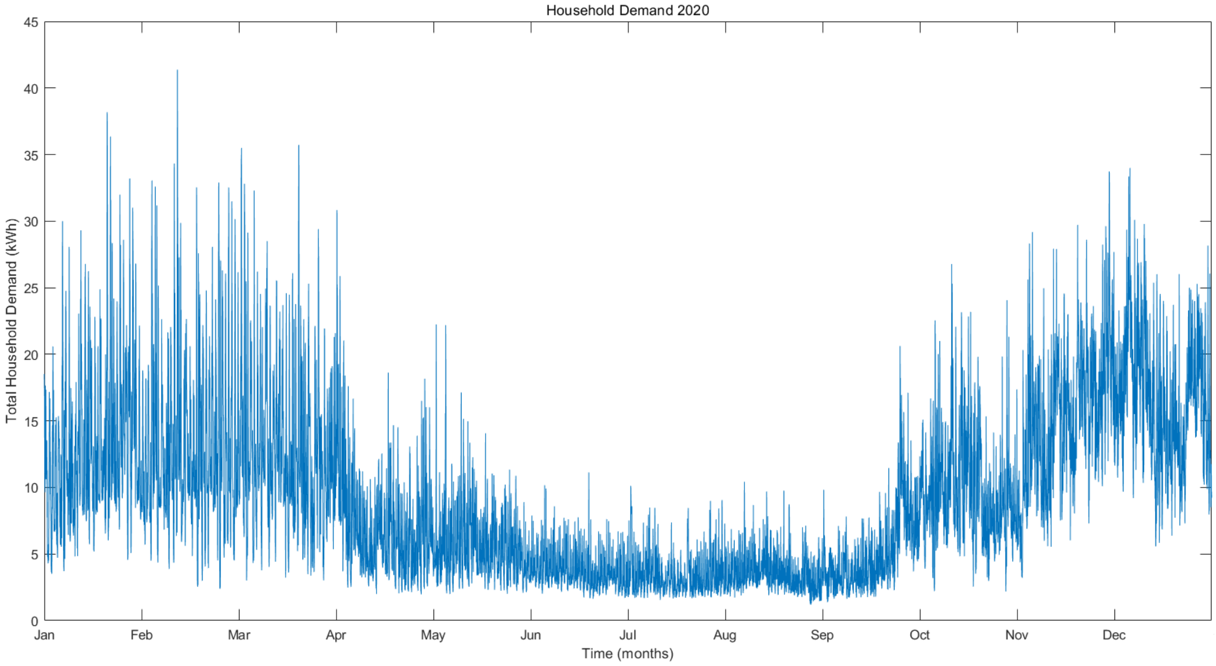

Figure 3.5: Demand consumption 2020

The figures above display the demand profiles throughout the year. In Figure 3.4a, the daily demand profiles show, as previously-stated, a peak demand in the morning and in the evening, as people usually work or leave the house during the day. The seasonal variation can be seen in Figure 3.4b, where it is noticeable that the energy demand is considerably higher in January than in June. The total demand of the community is displayed in Figure 3.5, where demand variability during winter and summer months is clear.

3.2.3 Component Parameters

The technical and economic parameters of each component are presented in this section. As previously-presented, two cases are considered in this research; a single household and an entire community. The parameters presented in this section are the parameters of the real-life equipment implemented at TGV. Therefore, the parameters extracted from reference case at TGV will be used to model the scaled-up community case, with an exception for the component capacities, which will be scaled accordingly.

PV Panels

The PV panels integrated for electricity generation at TGV are 260 Wp panels. Due to the unavailability of coherent cost data, a cost of 1000 €/kW is assumed based on Murray et al. (2018a); Abomazid et al. (2021), including surrounding equipment. The characteristics of the PV panels are presented in Table 3.2

Table 3.2: Technical and economic data of PV panels

Characteristic	Value	Units
Type	n/a	
System loss	10	%
Capacity	6	kW
Lifetime	20	years
Price	6000	€
Cost	1000	€/kW

Battery

The battery adopted at The Green Village is a LiFePo4 type (with a capacity of 15 kWh), in combination with an inverter which is integrated to the battery system. The cost for the battery is around €6,000 , and for the inverters is around €1,500, resulting in a total cost of €7500 . The technical and economic characteristics for the selected battery are summarized in Table 3.3. It is assumed that the maximum and minimum state of charge (SoC) of the selected battery are 95% and 15%, respectively, resulting in a maximum depth of discharge (DoD) of 80%.

Table 3.3: Technical and economic data of the battery

Characteristic	Value	Units
Type	LiFePo4	
Efficiency	90	%
Capacity	6	kW
Dissipation	0.006	%/hr
State of Charge minimum	15	%
State of Charge maximum	95	%
Depth of Discharge maximum	75	%
Lifetime	12	years

Table 3.3: Technical and economic data of the battery

Price	6000	€
Cost	400	€/kW

Electrolyzer

The electrolyzer present at TGV has been obtained from Enapter (2021). The power consumption is 2.4 kWh, and 49 kWh are required to produce 1 kg of hydrogen. The cost of the electrolyzer is €9000, resulting in 3750 €/kW. The electrolyzer data is shown in Table 3.4.

Table 3.4: Technical and economic data of the electrolyzer

Characteristic	**Value**	**Units**
Type	Enapter AEM Electrolyzer EL2.1	
Efficiency	41	%
Capacity	2.4	kW
Power consumption per kg of H2 produced	48.96	kWh/kg
Water consumption per kg of H2 produced	8.9	L/kg
Stand by power consumption	15	W
Lifetime	12	years
Price	9000	€
Cost	3750	€/kW

Compressor

The compressor available at TGV has been acquired from from Hyet (2021), at a cost of €24,000. The throughput capacity is 2kg hydrogen per 24h, which is considerably higher than the capacity needed at The Green Village for the reference case. The technical and economic characteristics are displayed in Table 3.5.

Table 3.5: Technical and economic data of the compressor

Characteristic	**Value**	**Units**
Type	HyET Hydrogen	
Efficiency	85	%
Throughput	2	kg
Power consumption	0.7	kWh
Lifetime	12	years
Price	24000	€
Cost	12000	€/kg

Hydrogen Tank

The capacity of the hydrogen storage tank present at TGV is 60 kg. The estimated cost for hydrogen storage tank in a Type 1 steel cylinder at 300 bar is 200 €/kg. The hydrogen storage tanks cost approximately €12,000, and the costs of the surrounding equipment, including hydrogen tubing, valves, and connectors cost around €12,000 as well.

Table 3.6: Technical and economic data of the hydrogen tank

Characteristic	**Value**	**Units**
Type	Type 1 Steel Cylinder	
Capacity	60	kg
Lifetime	20	years
Price	12000	€
Cost	200	€/kg

Fuel Cell

The selected fuel cell at TGV is from Nedstarck (2021), and is considered oversized (6.8 kW), compared to the required capacity for a single household (approximately 3 kW). This is due to the unavailability of a smaller fuel cell in the market. The cost of the fuel cell is €7,000 and the cost of the surrounding equipment is €6,000. The characteristics of the fuel cell are summarized in Table 3.7

Table 3.7: Technical and economic data of the fuel cell

Characteristic	**Value**	**Units**
Type	Nedstack PEM fuel cell stack	
Rated Power	6.8	kW
Maximum H2 consumption	5.45	kg/min
Efficiency	52	%
Lifetime	8	years
Price	7000	€
Cost	1030	€/kW

Chapter 4

Simulation

The designed system in Chapter 3, with the presented data for hourly generation, hourly demand, and the technical and economic parameters of components, is simulated to obtain the optimal sizing of the components. This chapter presents the approach taken for the simulation of the energy system, and outlines the technical and economic indicators used to asses the results of the system.

4.1 Approach

In this research project, a simulation is performed to determine the optimal capacities of the scaled-up community system presented in Chapter 3.1. A simulation of the energy system, conducted in MATLAB, is carried out with a detailed elaboration of the system dynamics, which will be assessed based on a technical and economic perspective. The reference case is the real-life pilot study implemented at TGV. The technical and economic parameters of each component presented in Chapter 3.2 will be used in the model, among with the generation and demand data obtained from PVGIS and TGV, respectively. The goal of the simulation is to determine the optimal capacity of the system components, with the objective to minimize the total costs of the system. First, the system control strategy will be developed to obtain the complete energy flow throughout the entire time period. As previously explained, the time period considered is 10 years, to take dynamic seasonal differences (which vary each year) into account, and the generation and demand data are displayed per hour. When the power flow through the system is obtained, an electricity pricing strategy is developed to arrive at the annual electricity bill for the community, along with the total costs of the system.

4.1.1 Control Strategy

In the energy system, when demand (P_{demand}) has been fulfilled with PV generation (P_{PV}), energy will be dispatched to the battery for daily energy storage when there is a surplus of solar production and the upper charging limit of the battery (SoC_{max}) is not met. On the contrary, the system will discharge the battery when solar production is not sufficient to meet load demand and the lower limit of the battery (SoC_{min}) is not met yet. When the battery's upper limit is met, the solar generation will be delivered to the electrolyzer, which will operate to produce hydrogen and store it in the hydrogen tank. If the power delivered ($P_{delivered}$) to the electrolyzer is larger than the maximum capacity of the electrolyzer (P_{ele}), the system will dump this energy, meaning no value gained from this energy. When the battery's lower limit is met, the fuel cell will start to produce electricity by consuming hydrogen. This electricity will be used to supply the load demand and use the remaining electricity to deliver power to the battery. The fuel cell will operate until the battery reaches a specific upper threshold. If hydrogen runs out, the system will fail to provide energy to the system. To avoid scarcity of hydrogen, it is necessary to have enough PV capacity to produce enough hydrogen to supply electricity when there is no PV generation and the battery storage runs out. The control strategy developed to operate the system is displayed in Figure 4.1.

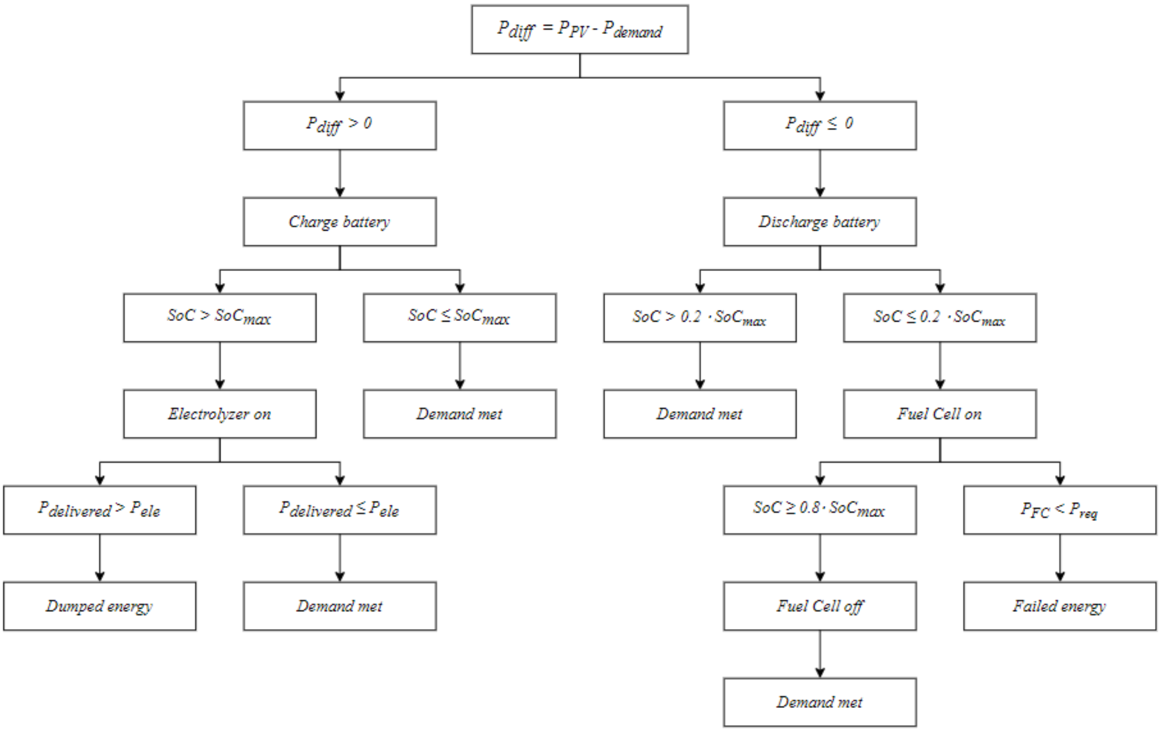

Figure 4.1: Control strategy of the system

By implementing this control strategy, along with data on hourly generation, hourly demand, and specific component characteristics, the energy flow throughout the whole system can be obtained. Additionally, a description of the fuel cell's dynamic operations is required for a thorough understanding of the system. The fuel cell is one of the most expensive components of the system, and the component with the shortest lifetime. To ensure the longest possible lifetime of the fuel cell, it is required to operate it in the most endurable way. Previous designs have been studied at TGV, similar to the presented control strategy, where the fuel cell would deliver the required demand when no solar generation and battery storage is in place. However, this would result in a very volatile fuel cell with a lot of peaks and high variations in the rated power. In reality, ramping limits would constrain this operation; therefore, a different operating strategy for the fuel cell has been proposed in this research.

Figure 4.2 displays the fuel cell control strategy, obtained from the bottom-right side of Figure 4.1. This diagram depicts that when the battery reaches 20% SoC, the fuel cell is turned on. To ensure the longest possible lifetime, the fuel cell operates at a constant power, assumed to be 70% of its maximum capacity. At this maximum capacity operating limit, the rated power would be enough to fulfill demand most time steps of the year, and the fuel cell would be operating at a reasonable capacity, which would not put the component on its maximum operating limits. The fuel cell would be connected to the battery to deliver the remaining electricity generated when the power of the fuel cell is higher than load demand. This will charge the battery and can be used to deliver electricity when the rated power of the fuel cell is lower

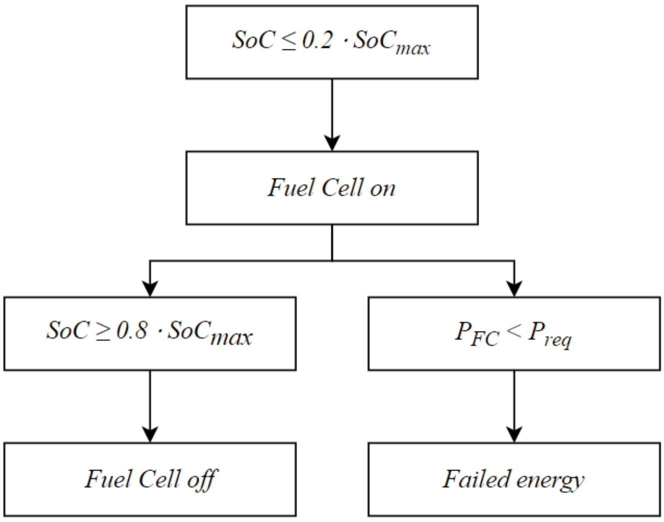

Figure 4.2: Control strategy of the fuel cell

than demand. When the battery reaches 80% charge, the fuel cell is turned off, and demand is met with battery and PV production until the battery level drops to the threshold of 20% charge.

Figure 4.3 shows a simple representation of three different scenarios for the energy flow from the fuel cell. Assuming the rated power of the fuel cell is a constant 3 kWh; if load demand is 2 kWh, the fuel cell will provide those 2 kWh of electricity and would deliver the remaining 1 kWh to the battery (Figure 4.3a). If the rated power from the fuel cell is the same value as demand, the battery doesn't charge or discharge at this time (Figure 4.3b). Lastly, if demand is higher than the rated power of the fuel cell, the battery has already been charged, and the required demand will be provided from the battery (Figure 4.3c). The battery's minimum SoC is 15%, which is 5% less than the threshold to turn the fuel cell on. This is in place as an emergency capacity in case the rated power of the fuel cell is not enough to fulfill demand at the time this threshold is met, meaning a 5% battery capacity would be available if needed.

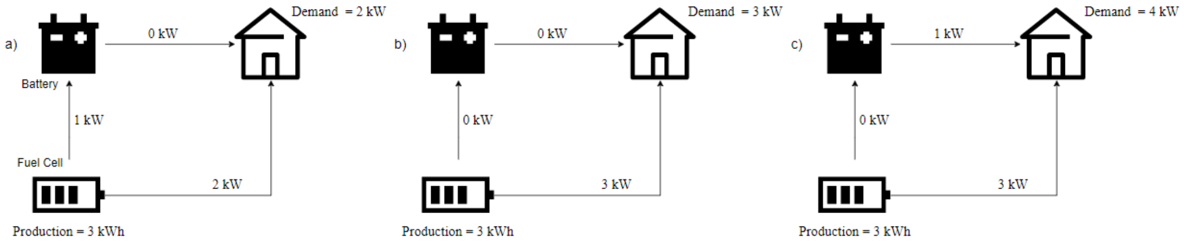

Figure 4.3: Energy flow from fuel cell with different demands

4.1.2 Modelling

After developing the control strategy, it is implemented in MATLAB along with all the required data and parameters to run the simulation, presented in Chapter 3. The control strategy regulates the behaviour of the devices and manages the entire energy flow throughout the system for the given time period. As mentioned in Chapter 4.1, the conducted simulation is assessed based on a technical and economic perspective. First, the control strategy determines the values for the energy flow streams, which will be the main input for the technical assessment. The energy values are later used to derive the final electricity prices for each energy source the electricity can come from: direct PV, power from the battery, and power from the hydrogen system. The electricity pricing strategy is developed in 4.2.2, which takes into account the total costs of the source and the energy consumption of the end-user in a given time period.

The model takes both cases presented in Chapter 3.2 and determines the optimum sizing capacity of four components in the community case. As previously-described, the energy system in the reference case is a representation of the real-life pilot study at TGV. The system is modelled and an assessment of the system is done following the performance indicators presented in the following section (see Chapter 4.2). Furthermore, the goal of this research is to scale up the reference case to include a community of 7 households, and in turn, find the optimum capacity of the components with the goal of minimizing the total costs of the system. The sizing of the components highly affect the economic performance of the system, specifically the components for hydrogen usage, which have a significant impact on the total investment costs. The high costs of the system will be paid by the end-users, as the cost of the equipment will be reflected in the electricity prices. Therefore, it is critical to determine the lowest possible costs of the system while also assuring self-sufficiency. The model developed to achieve these objectives has been divided in three sections to present a detailed and clear explanation: the technical modelling, the economic aspects, and the system optimization.

Implementation of the Control Strategy

The technical section of the system is the implementation of the control strategy to determine the hourly values of the energy streams and derive an overview of all the components of the systems. The energy flow streams are presented in Figure 4.4 and the results are discussed in Chapter 5, which are assessed based on the technical indicators presented in the following section. The obtained results from the control strategy, along with the economic features of the system, are key to determine the optimal capacity of the components.

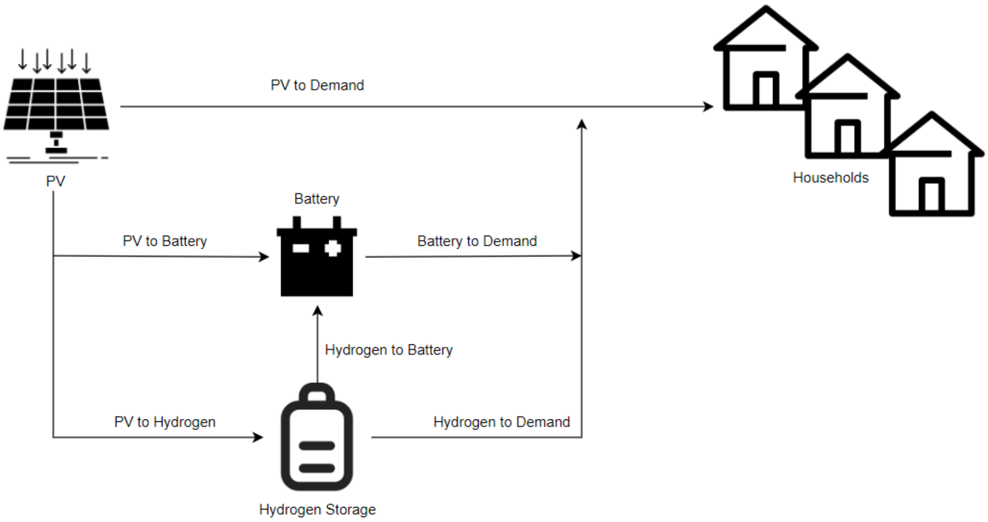

Figure 4.4: Energy flow through the energy system

Calculation of costs

An economic section is developed in the model to break down the costs of the system. The economic parameters presented in Chapter 3.2 are used to obtain the yearly system costs and electricity bill. For the calculation of the yearly system costs, it is necessary to consider the capital costs, the operating and maintenance costs, along with other costs such as surrounding equipment of each component. For the capital costs, the investment price is divided by its lifetime to obtain a yearly value for capital cost of the equipment. The operating and maintenance costs are assumed to be 1% of the investment cost, except for PV panels, which are assumed to be 0.5% of the investment cost due to its technological maturity. Other costs associated with each component are stated in Chapter 3.2. For the calculation of the yearly system costs, the following costs must be considered:

- Equipment capital costs, defined as the investment price divided by the equipment's lifetime
- Operating and maintenance costs, which are assumed to be 1% of the total investment cost, with an exception for PV panels, calculated as 0.5% of the investment cost due to its technological maturity
- Other costs, such as surrounding equipment of each component, which are stated in Chapter 3.2

Along with the total costs, the annual electricity bill is obtained for the whole community. To develop an electricity pricing strategy, a flat cost allocation method is used based on the energy consumption of the community within a year and the costs associated with the system. A detailed explanation of the pricing strategy is provided in Chapter 4.2

Optimal Sizing

When scaling up an energy system, the scaling of the equipment is not a straightforward procedure where the capacity increases linearly with an increase in the number of houses. The demand behavior of the community highly affect the sizing of the equipment. The main goal of this simulation is to minimize the costs of a system that never fails to provide energy. To do so, a method is employed to derive the optimal capacities of four components of the system. The four components that are optimized are the PV panels, the battery, the electrolyzer, and the hydrogen tank.

The selected four component are chosen due to their variability in sizing, which is dependant on demand behaviour. The sizing of the other equipment that has not been included in the optimization, i.e. the compressor and the fuel cell, are based on predefined constant parameters. In the case of the compressor, it must have enough capacity to compress the maximum output of the electrolyzer. Meaning the compressor capacity must be aligned with the electrolyzer capacity to make sure it has the adequate requirement. On the other hand, the fuel cell should produce sufficient electricity to supply the demand even on the worst weather day that there is no PV generation. Therefore, the highest peak demand value in the community when there is no PV generation from the given time period will be the required capacity of the fuel cell.

For the sizing optimization of PV panels, battery, electrolyzer, and hydrogen tank, a four-dimensional matrix is constructed, where each axis represents the capacity of a different component (see Figure 4.5). The model presented in this research is tested with 10 different capacities for each component, computing every combination, and the total system costs of each case are plotted in the four-dimensional matrix. Then, the minimum value is obtained, and the corresponding optimal capacities of each of the four optimised components are derived. The initial input capacity is multiplied by 10 different values (See Table 4.1). The system starts with an estimated capacity for each component, which is only used as input for the optimization to take place, as each component is analyzed with 10 different capacities. Lastly, the value is obtained when there is no failed energy in the system, which ensures that the chosen capacities are sufficient to achieve a self-sufficient system.

Table 4.1: Multiplier of capacities

Multiplier	1	2	3	4	5	6	7	8	9	10
Value	0.5	0.6111	0.7222	0.8333	0.9444	1.0556	1.1667	1.2778	1.3889	1.5

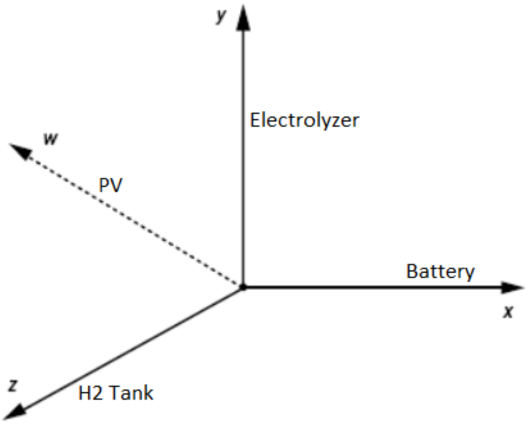

Figure 4.5: Representation of the four axis. Each axis represents the capacity of one component

4.2 Performance Indicators

To assess the designed system, it is necessary to analyze its performance from a technical and economic perspective. On the one hand, it is expected that the energy system can be fully self-sufficient, meaning it is essential to validate the design to see if the selected capacity meets the energy balance of the energy system. On the other hand, the current costs of hydrogen-related components, such as electrolyzer, compressor, hydrogen storage, and fuel cell are relatively high, therefore, it is also crucial to conduct an economic analysis to see if the energy system is economically feasible. Several indicators, classified between technical and economical, are proposed to assess the performance of the designed energy system.

4.2.1 Technical indicators

Three technical indicators are proposed to evaluate the performance of the designed energy system. Each indicator is discussed thoroughly to indicate the topic of focus.

System efficiency

The overall system efficiency is used to determine how much of the energy produced by PV is utilized by households. It is defined as the total demand met by the energy system divided by the total PV generation.

$$\eta_{sys} = \frac{E_{dem}}{E_{PV}} \tag{4.1}$$

where η_{sys} (%) is the overall system efficiency, E_{dem} (kWh) is the load demand met by the energy system, E_{PV} (kWh) is the PV generation.

Dumped energy

Dumped energy is the energy generated in the energy system, where the power cannot be used for load demand, nor used for charging the battery or delivered to the electrolyzer to produce hydrogen. Hence, it is energy that is thrown away with no use. In this research, the dumped energy is assumed to be wasted, meaning that no further utilization of this energy is present in the system. In real-life a connection to the national grid may be put in place, and this energy could be sold to obtain higher revenues. A detailed elaboration of this assumption is explained in Chapter 7.

Failed energy

Failed energy is the energy required by load demand that cannot be delivered by the energy system. Failed energy can occur in two ways. First, due to not having hydrogen stored. During times of no solar production and no charge in the battery, if hydrogen is unavailable, the failed energy will be the load demand during that time until demand is met, which will happen when there is solar production again. Secondly, failed energy may occur if demand is higher than the capacity of the fuel cell. During times of no solar production and battery storage, the fuel cell will operate to deliver energy to the community; therefore, if the community requires more energy than the maximum capacity of the fuel cell, the failed energy will be the difference between load demand and capacity of the fuel cell. Since the objective is to have a self-sufficient system, the foremost condition of the system is to have zero failed energy.

4.2.2 Economic indicators

Cash flow over the lifetime of the system is calculated after sizing the energy system with relevant costs of each component, resulting in lifetime capital expenditures (capital costs) and operational & maintenance expenditures (O&M costs). Three economic indicators are adopted to assess the economic feasibility of the designed energy system.

Total system costs

The total cost of the energy system includes the capital and operating and maintenance cost of each component, as well as other costs for each component. In the designed energy system, the most important cost drivers are the PV panels, batteries, electrolyzer, compressor, hydrogen storage, and fuel cell, where the hydrogen-related components cost are very high.

$$Costs_{total} = \sum \left(C_{capital}(i) + C_{O\&M}(i) + C_{other}(i)\right) \tag{4.2}$$

Where $Costs_{total}$ (€) are the total system cost, i is the set of the component included in the energy system (i= PV, battery, electrolyzer, compressor, hydrogen storage, fuel cell). $C_{capital}(i)$ (€) are the capital (investment) costs of each component, $C_{O\&M}(i)$ (€) are the operating and maintenance cost of each component, and $C_{other}(i)$ (€) are other costs, such as the cost for the surrounding equipment. For the O&M costs, they are assumed to be 1% of the capital costs, with the exception of PV panels, as this technology is very matured, and the O&M costs are assumed to be 0.5% of its capital costs.

Annual electricity costs for the community

To determine the annual electricity costs, a pricing strategy for each of the three sources is developed. The strategy is developed with the goal to recover the investment cost throughout the lifetime of each component. Therefore, the annual costs of each subsystem and the power delivered from each subsystem per year are necessary to obtain the electricity prices for each source. First, an overview of the different energy flow streams is presented in Figure 4.6 to present the developed pricing strategy.

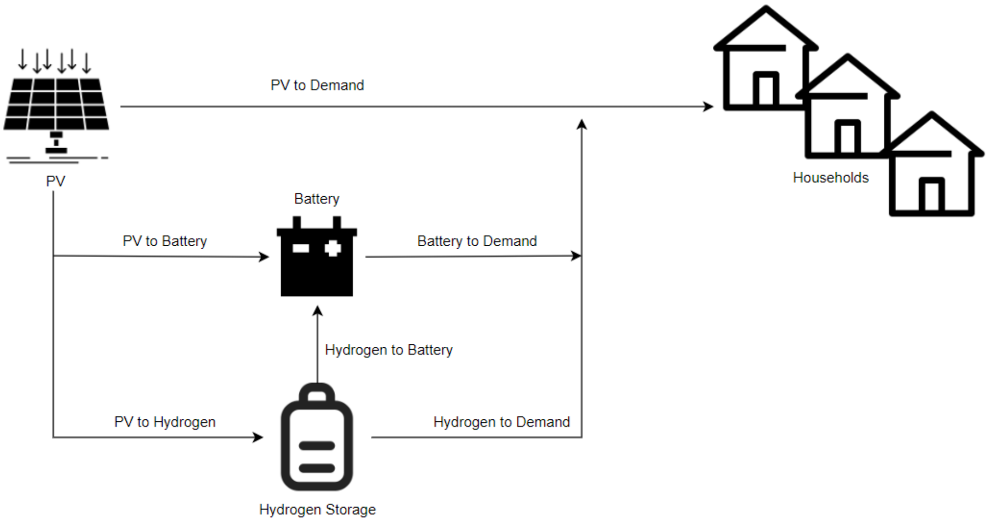

Figure 4.6: Energy flow through the energy system

As shown in this figure, there are numerous energy flows that must be taken into account in the electricity prices. For the pricing of each system (PV, battery, and hydrogen), all the related components and the energy flows in and out of the system must be considered. Below, the electricity prices for each subsystem are presented, where all of them are aggregated to arrive at the annual electricity costs.

First, the capital and surrounding equipment costs of each component divided by the lifetime are found using the following equation. With this, the investment costs are spread throughout the lifetime.

$$CC(i) = \frac{C_{capital} + C_{other}(i)}{Lifetime(i)} \tag{4.3}$$

Where $CC(i)$ (€) are the capital and surrounding equipment costs spread for one year for component i. The electricity pricing approach allocates costs based on the energy consumption of each subsystem within a time period (one year). The energy price is a flat rate per kWh during that specific time period. The flat energy price P_i (€/kWh) for each subsystem is calculated as:

$$P_{PV} = \frac{CC_{PV}}{E_{PV}} \tag{4.4}$$

$$P_{H2} = \frac{CC_{H2} + P_{PV} * E_{PVtoH2}}{E_{H2toDemand} + E_{H2toBat}} \tag{4.5}$$

$$P_{Bat} = \frac{CC_{Bat} + P_{PV} * E_{PVtoBat} + P_{H2} * E_{H2toBat}}{E_{Bat}} \tag{4.6}$$

Where P_{PV}, P_{Bat} and P_{H2} (€/kWh), are the price of electricity for each subsystem. E_{PV} (kWh) is the total solar energy produced in our year, without taking into account the dumped energy. CC_{H2} considers the costs of the electrolyzer, compressor, hydrogen tank and fuel cell. The total electricity costs of the community are calculated with the following equation:

$$TotalElectricityCosts = P_{PV} * E_{PVtoDemand} + P_{Bat} * E_{BattoDemand} + P_{PV} * E_{H2toDemand} \quad (4.7)$$

Levelized costs of energy

Capital and O&M costs are used to calculate the levelized cost of energy (LCOE) in €/kWh. To calculate this, a depreciation (r) of money is taken into account for capital and O&M costs costs, which is divided by the sum of annual electricity yield.

$$LCOE = \frac{\sum_{t=0}^{T}(\frac{C_t+M_t)}{(1+r)^t}}{\sum_{t=0}^{T}(\frac{E_t)}{(1+r)^t}} \quad (4.8)$$

Where T (years) is the lifetime of the energy system, r (%) is the discount rate, which is used to discount future costs and translates them into the present value. C_t (€) are the capital costs in year t, M_t (€) are the O&M costs in year t and E_t (€) is the electricity yield in year t. In addition, some components, such as the fuel cell, have a shorter lifetime than others. It is required to take the new investment cost in the year of replacement. By that time, the capital cost of that specific component might be significantly reduced, which must be taken into account in the calculation.

4.3 Assumption Overview

Throughout the report, several assumptions have been presented, which are necessary to develop the simulation. Below, the previously-stated and further assumptions are presented to have a clear overview of these:

- Heat demand in all TGV houses is electrified
- Due to only having demand data for 2020, the demand data remains the same each year
- The solar tilt and azimuth are based on optimal values of PVGIS
- The fuel cell constantly operates at 70% maximum capacity
- No heat is recovered from the fuel cell
- All surplus energy is dumped
- Economic parameters are the same for the reference case as for the scaled-up community case
- Space constraints in the system are not considered
- Costs of distribution network are not considered

These assumptions will be thoroughly discussed in Chapter 7.2, where the real-life relevance and possible further implementations to handle these limitations are discussed.

Chapter 5

Results and Analysis

In this chapter, the results from the simulation developed in Chapter 4 are presented. The goal of the simulation was to obtain the optimal capacity of PV panels, the battery, the electrolyzer, and the hydrogen tank, with the objective of minimizing total costs of the system. Chapter 4.1.2 introduces the optimization methodology, where a four-dimensional matrix was constructed, with each axis representing the capacity of one component. Each capacity starts with an initial magnitude and will be multiplied with 10 different values (presented in Chapter 4.1.2), to vary the capacity from 0.5 to 1.5 times the initial capacity. The initial input capacity is obtain by multiplying the reference case capacity by 20, as the average community demand is 20 times higher than the reference case. For the input capacity of PV and the battery, the first results showed that the capacity could be increased more than 20 times the reference case demand, as the results of the multiplier were 10. This means there can potentially be more capacity, as the maximum multiplier value can be a limiting factor; therefore, it was increased to 350 kW and 375 kW, respectively. The multipliers giving the optimal capacity result will be extracted from the matrix, and from this, the optimal capacity values will be derived for a system with no failed energy.

Throughout the development of the model, two simulation models were created on MATLAB. The first simulation is used to find the optimal values of the capacities. In this model, 10 years of generation and demand are considered, along with the four dimensions, one for each capacity, to determine the optimal position within the matrix. The code developed follows the described procedure in Chapter 4, and the data presented in Chapter 3.

A second simulation is then developed to graphically display the corresponding technical and economic results of the system, only considering one year (2020). Here, the four dimensions are not included, as only the optimal values for the capacities are needed as input. Both simulations develop the control strategy and the cost calculations in a similar way; the difference is that the first simulation finds the optimal value over a 10-year period, while the second simulation displays the results by only taking one year into consideration, to graphically interpret the results more clearly.

This chapter will first present the optimal capacities derived from the simulation model, followed by an overview of the system when the optimal capacities derived for the year 2020 are implemented. This section will be followed by a performance analysis on the indicators presented in Chapter 4.2, which will determine the technical and economic feasibility of the system. Lastly, a sensitivity analysis is conducted to determine how the prices of components and the level of self-sufficiency can affect the total costs of the system.

5.1 Simulation Results

5.1.1 Optimal sizing

The results for the optimal capacities are displayed in Table 5.1. The initial input capacities taken for the four components are multiplied by the 10 different values displayed in Table 4.1, which result in the optimal capacities of PV panels, battery, electrolyzer, and hydrogen tank. The minimum value of total costs displayed in this table refers to the total costs for the community scale in a one year period (2020), based on Equation 4.2.

Table 5.1: Optimal results of component sizing

Component	**Battery**	**Electrolyzer**	**PV**	**H2 Tank**	**Compressor**	**Fuel Cell**
Input Capacity	375 kW	40 kW	350 kW	1200 kg	-	-
Multiplier	6	3	7	5	-	-
Optimal Capacity	396 kW	29 kW	409 kW	1133 kg	10 kg	42 kW
Total Costs	61,746 €					

10 matrices are presented in Appendix B. As a four-dimensional space cannot be represented, MATLAB displays 100 2-dimensional matrices, where two values are changed within the matrix, and two values are kept constant in every table. The results of this matrix are displayed in Appendix B, where the results of 10 matrices are shown and the minimum value is indicated.

After obtaining the optimal capacity values for each of the four components, they are implemented in a one-dimensional model where the results of the system for the year 2020 are displayed. Chapter 5.1.2 displays the results of this simulation, which include the optimal capacities.

5.1.2 Energy Flow Overview

The energy flowing in and out of the components is crucial to determine the technical and economic feasibility of the system, since the efficiency of the system, the dumped and failed energy, and the electricity prices are based on these values. Figure 5.1 displays the SoC of the battery throughout the year 2020. As seen in this graph, the battery's SoC is very volatile during winter months, being charged and discharged in a regular basis as the battery is charged with the little PV generation available during these months and with the fuel cell when it is turned on. Since there is little PV generation, the battery is discharged also on a regular basis during winter months as load demand required electricity from it. On the other hand, the battery has a high SoC during summer months due to higher solar irradiation, longer sun hours in a day, and less load demand during these months. These results are shown in Figure 5.1, where it can be seen that the battery rarely drops below 80% SoC from April to September.

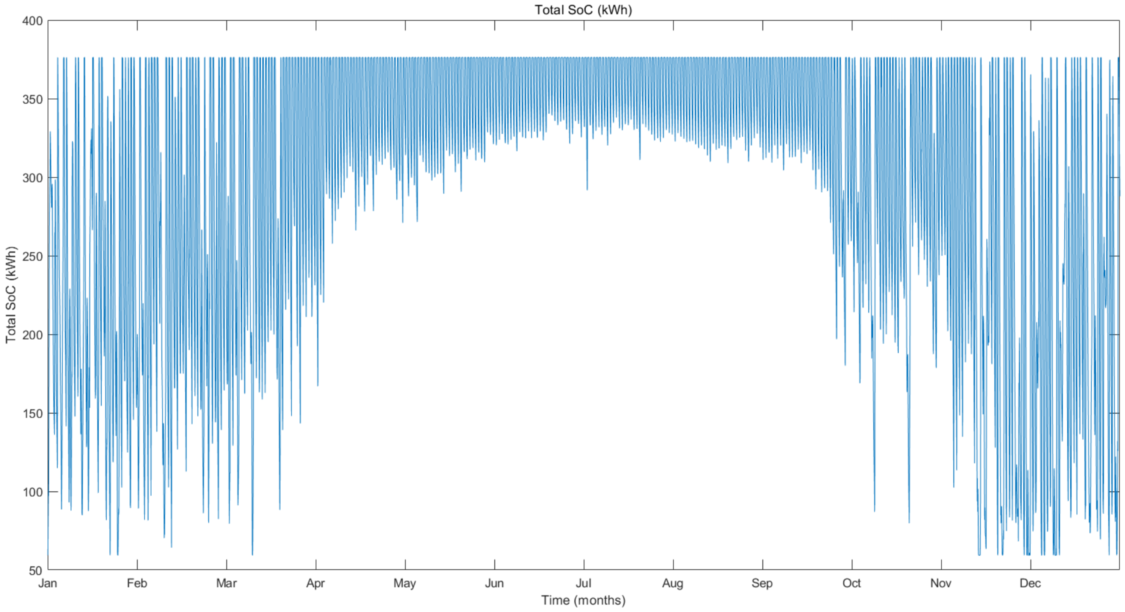

Figure 5.1: State of Charge in 2020

In a similar way as the battery, the hydrogen generation and consumption throughout one year follow specific dynamics due to the high variation in generation and demand between winter and summer times. Figure 5.2 represents the cumulative hydrogen generation in the year 2020. From January to March, and from November to December, hydrogen is consumed by the fuel cell to produce electricity, as during these months there is a high mismatch between the high demand and low generation. On the contrary, during summer months, hydrogen is produced by the electrolyzer, as the high PV generation during these months leaves enough electricity for the electrolyzer to produce hydrogen, filling up the hydrogen tank to be used again during winter months.

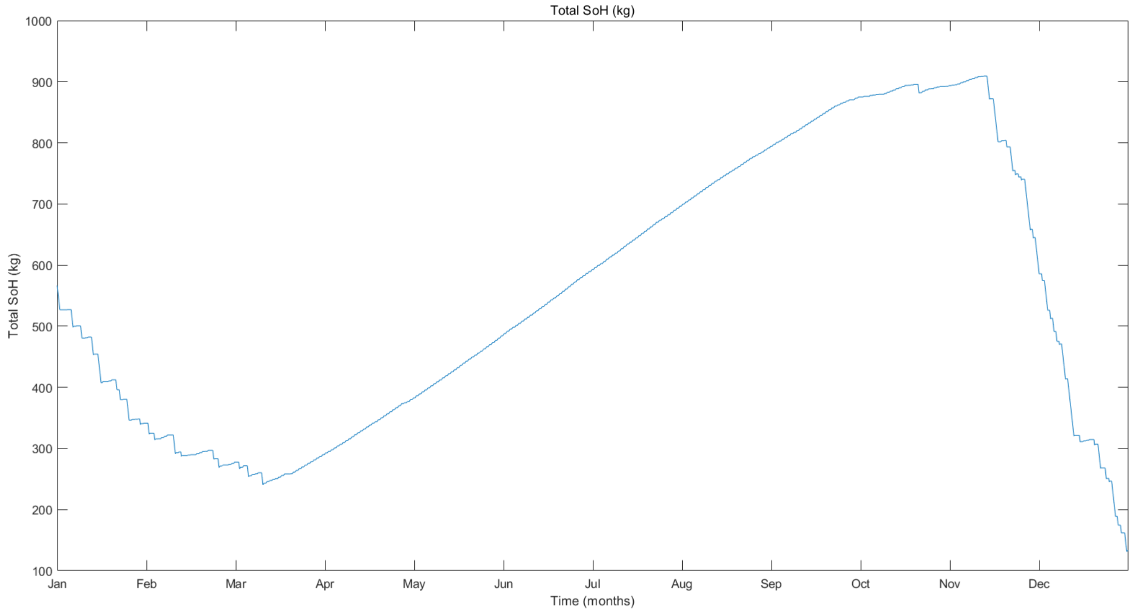

Figure 5.2: State of Hydrogen in 2020

The SoH represents a cycle, where approximately during 6 months of the year, when generation is considerably higher than demand, hydrogen is being produced and stored, and the later 6 months, when demand is higher than generation, hydrogen is being used in the fuel cell to produce electricity. Figures 5.3 and 5.4 display the performance of the electrolyzer in 2020 and the performance of the fuel cell in 2020.

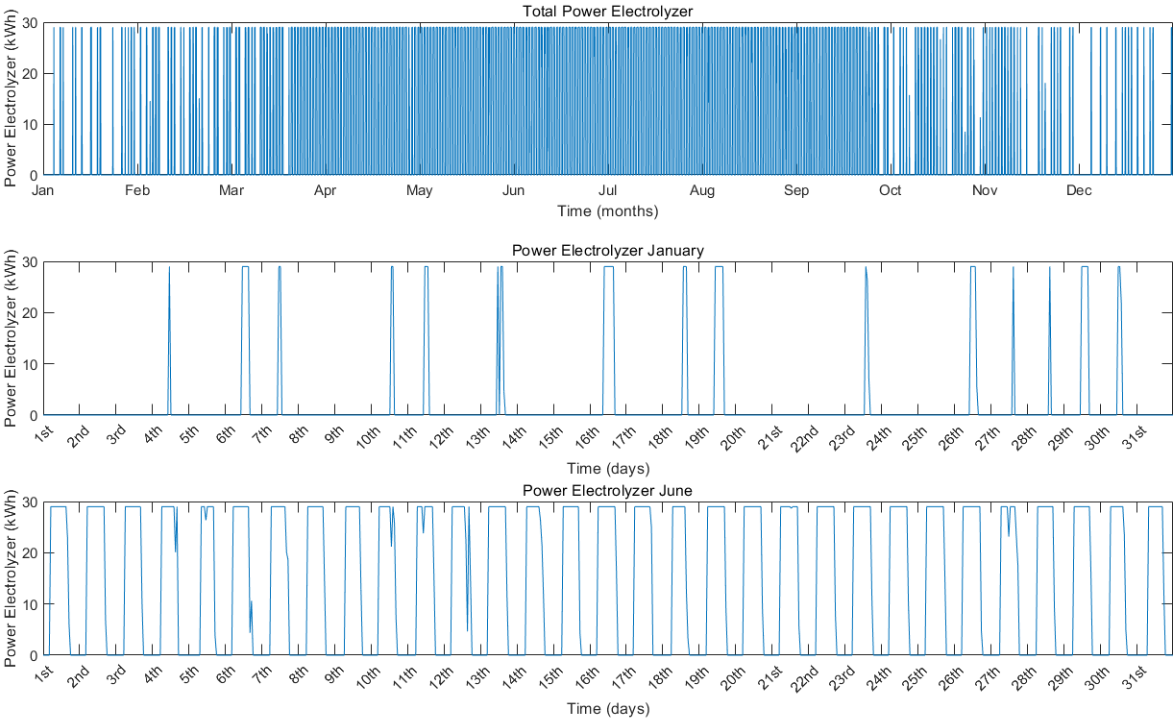

Figure 5.3: Performance of the electrolyzer in 2020

As seen in Figure 5.3, the electrolyzer mainly operates during summer months, when generation is much higher and demand is much lower than the winter months. In June, the electrolyzer produces hydrogen each day during sun hours, while in January, the electrolyzer operates during only a few hours of the month when there is high PV generation. Hydrogen is produced in January due to having a very oversized capacity of PV generation.

Similarly to the proposed fuel cell dynamics, new operating conditions may be applied to the electrolyzer to extend its lifetime and performance. The electrolyzer operates during winter months due to having a highly oversized PV capacity; to extend its durability, and avoid the electrolyzer operating at random peaks during winter months, a new approach may be proposed where the electrolyzer only operates during summer months, and the used electricity during winter months could be directly sold to the grid. This way, the electrolyzer could be available only from March to October, when the PV generation is consistent, and during November to March the surplus electricity could be sold to the grid. In this research, a connection to the grid is not included, and the surplus energy is assumed to be dumped. For future research, both the dumped energy and potentially the electricity used for the electrolyzer during winter months could be sold to the grid to make extra profit and to extend the lifetime of the electrolyzer.

The fuel cell, contrary to the electrolyzer, only operates during winter months, when there is a shortage of generation compared to load demand. As seen in Figure 5.4, from November to March (including two days in October), the fuel cell operates to provide electricity to the households. The fuel cell operates at a constant rated power (70% of its maximum capacity), as presented in Chapter 4.1.

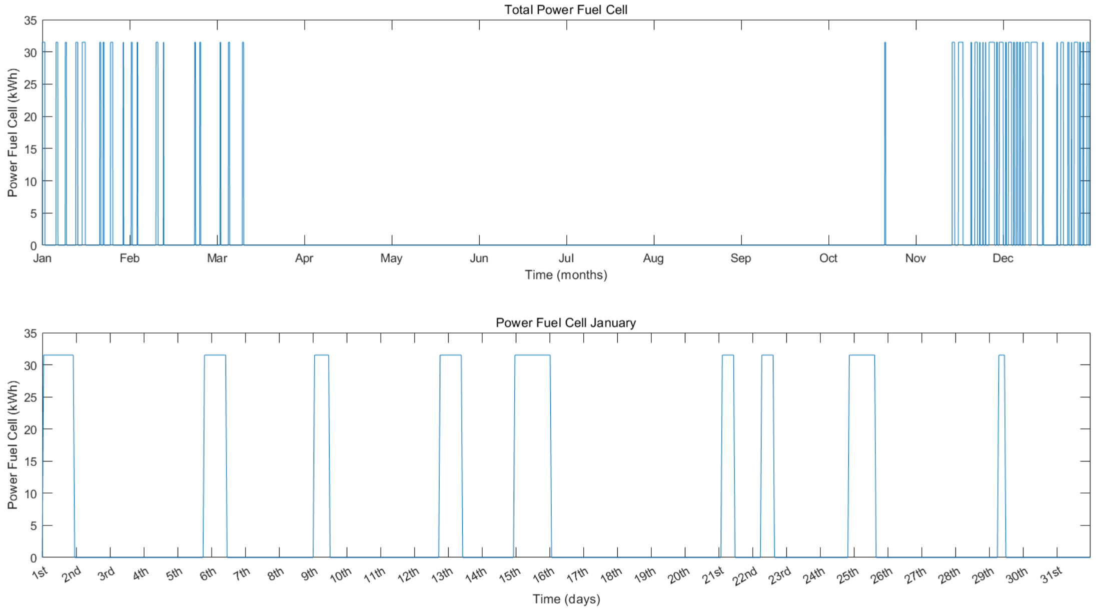

Figure 5.4: Performance of the fuel cell in 2020 and January 2020

Figure 5.5 displays a comparison between the SoC and the fuel cell performance, where it is observable that the fuel cell is turned on when the SoC reaches a lower limit threshold (20% SoC), and operates until the SoC reaches the upper limit threshold (80% SoC). As presented in Figure 4.3, the fuel cell provides electricity to both the households and the battery when there is enough electricity for it. This means the battery is charged while the fuel cell operates so it helps it reach the 80% SoC threshold.

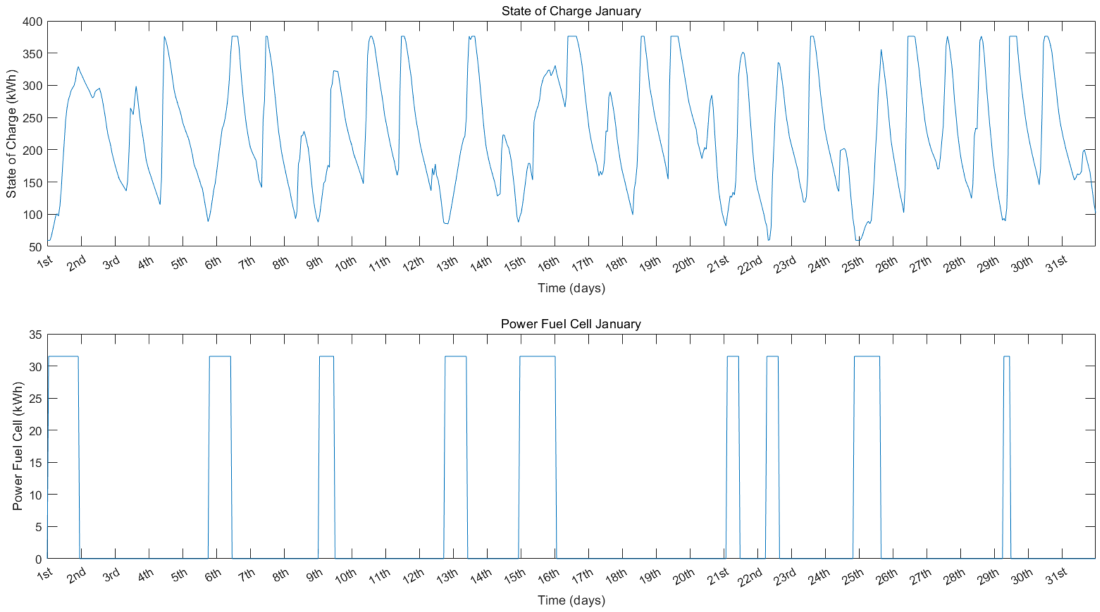

Figure 5.5: Fuel Cell and State of Charge Power in January 2020

5.2 Performance Analysis

In this section, the results presented in Chapter 5.1 are analyzed based on the technical and economic indicators presented in Chapter 4.2. On the technical aspects, the capacity matrix results will be analyzed first. Then, the system efficiency, the dumped energy and the failed energy will be discussed. Lastly, the technical indicators will be analyzed, based on the total costs of the system, the total electricity costs and the levelized costs of energy.

5.2.1 Technical Analysis

Capacity Matrix Analysis

The simulation, as previously-explained, derives the multipliers for each component at which the optimal capacity is achieved, to obtain the minimum total costs while ensuring zero failed energy.

As seen in Table 5.1, the optimal results are obtained by increasing the PV capacity and by minimizing the capacity of the hydrogen storage system. This is explained as the price of PV capacity is 1000 €/kW, while the combination of hydrogen system components increase the costs of the system by thousands of euros per kW (4780 €/kW of electrolyzer and fuel cell combined). The optimal capacity of PV generation is 409 kWh, a lot more than what the community needs; nonetheless, having an oversized PV capacity leads to the minimum system costs as the capacity of the highly expensive components is decreased. From a technical perspective, having an oversized PV capacity means that, in spite of achieving the lowest costs of the system, it decreases the efficiency of the system, as during summer months, when there is high PV generation, the system will have a lot of dumped energy. These points will be thoroughly discussed in the following sections.

System efficiency

The system efficiency is defined as the ratio of total energy consumption by total energy produced (See Equation 4.1). As the optimal results for the minimization of total costs are achieved by having an oversized PV capacity and by minimizing the capacity of expensive components, it is expected to have a high PV generation throughout the year, specially during summer months. This is expected to reduce the system efficiency as more energy will be dumped. The total system efficiency, without considering dumped energy, is calculated as:

$$\eta_{sys} = \frac{E_{dem}}{E_{PV}} = \frac{78,735.38}{129,796.13} = 0.6066 \tag{5.1}$$

The system efficiency without considering the dumped energy is $\eta_{sys} = 60.66\%$. If dumped energy is considered for the total PV generated, then the system efficiency is:

$$\eta_{sys} = \frac{E_{dem}}{E_{PV}} = \frac{78,735.38}{468,114.53} = 0.1682 \tag{5.2}$$

When considering dumped energy, the system's efficiency decreases by approximately 40%, to obtain an efficiency of $\eta_{sys} = 16.82\%$. This decrease indicates that there is a lot of dumped energy in the system. To understand this value of system efficiency, Figure 5.6 represents the direction of the electricity after it has been generated from PV panels. As it can be seen, 72% of the total energy produced is dumped, significantly decreasing the system efficiency. Furthermore, 16% of the energy generated is dispatched to the electrolyzer to produce hydrogen. As the hydrogen system has a round-trip efficiency of approximately 25%, the majority of the energy delivered will be lost in the process. A significant amount of heat is generated by the fuel cell while operating, equivalent to 45 to 60% of the total energy content of hydrogen entering the cells

(Nguyen & Shabani, 2020a). The generated heat can be removed effectively from the fuel cell by using a cooling system in order to further use heat and prolong its lifetime and performance (Nguyen & Shabani, 2020a). The integration of a cooling system will be discussed for future research (See Chapter 8.4). The remaining two streams, direct PV and energy dispatched to the battery, have low losses; however, they only constitute 6% of the total energy produced. By observing that 72% of the total energy produced is dumped, and 16% of the energy produced goes through a cycle where 75% of the total energy is lost in the process, it is comprehensible to have a system efficiency of 16.82% when considering dumped energy.

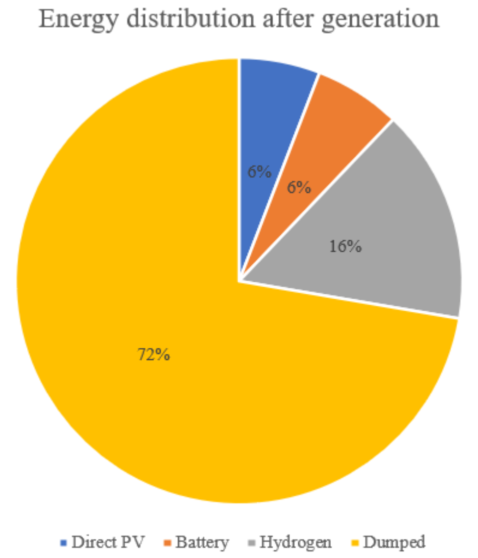

Figure 5.6: Energy distribution after PV generation

Dumped energy

The share of dumped energy in the system is high due to having a significantly oversized PV capacity. This benefits the economic performance of the system but leads to high amounts of dumped energy. The dumped energy is calculated using the following equation:

$$\eta_{dumped} = \frac{E_{dumped}}{E_{PV}} = \frac{338,318.40}{468,114.53} = 0.7227 \tag{5.3}$$

As seen in Equation 5.3, 72.27 % of the total energy produced is dumped. Due to the high PV capacity in the system, during summer months the value of dumped energy increases drastically as there is high PV generation, along with a battery which is mostly charged all summer, and an electrolyzer that operates on maximum conditions most days of the summer (See Figures 5.1 and 5.3). Consequently, 80.4% of the total dumped energy in a year happen between 1st of April to 1st of October (see Figure 5.7). To retrieve a certain value of the dumped energy, it may be sold to the national grid if a connection between both systems is present (see Chapter 8.4). Furthermore, a larger battery and/or electrolyzer may be implemented to dispatch the surplus energy, this is an adequate solution if the goal is to have an efficient system with the least dumped energy possible, while increasing the system costs.

Failed energy

The failed energy is the energy demanded by the households that the system cannot provide. Failed energy can occur in two situations. Firstly, during hours of no PV generation and a

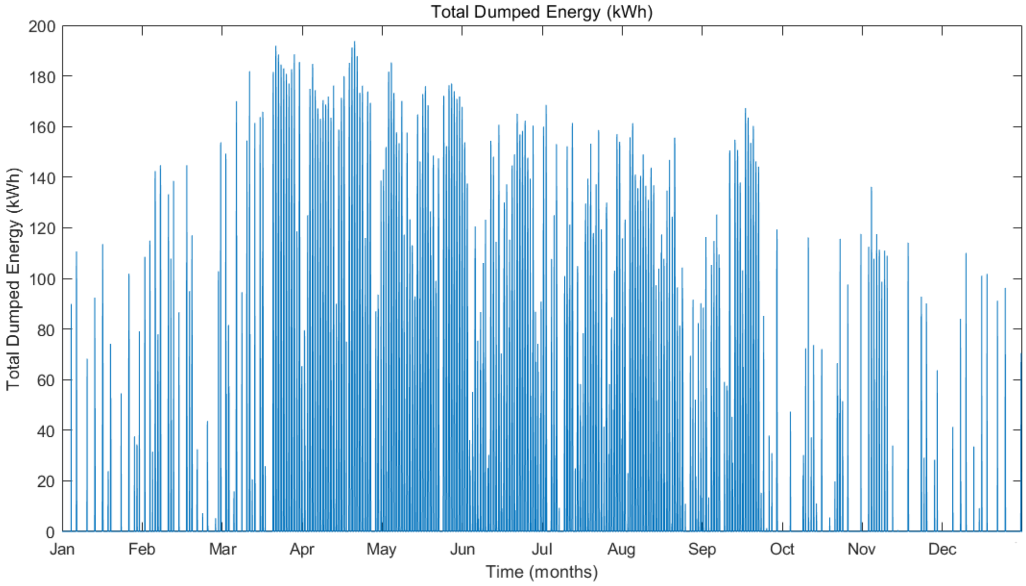

Figure 5.7: Dumped energy of the energy system in 2020

minimum SoC, if the hydrogen storage reaches the minimum storage requirement (10% of the total capacity), the system will fail to provide energy until electricity is generated from the PV panels. The 10% remaining capacity would not be used in this simulation and failed energy is given; in reality, this reserve capacity can be used as back-up for extreme circumstances. Secondly, if the fuel cell does not have enough capacity to fulfil the peak value of load demand, then the difference between load demand and maximum capacity of the fuel cell is the value of failed energy for the hours that energy cannot be provided. Therefore, a significant fuel cell capacity must be used to ensure security of supply.

In this simulation, these two situations which may lead to failed energy were implemented as constraints, therefore the derived optimal capacity values construct a system which would never fail to provide energy (See Figure 5.8). 10-year data sets were used to ensure that the selected capacity has taken the variability of climate conditions of that time spam into consideration, so that the system does not only take the weather conditions of a single year into account, and considers different weather patterns for determining the optimal capacities. Lastly, an analysis where 90% system self-sufficiency is presented in Chapter 5.4 to analyse the reduction in total system costs when a lower level of self-sufficiency is required.

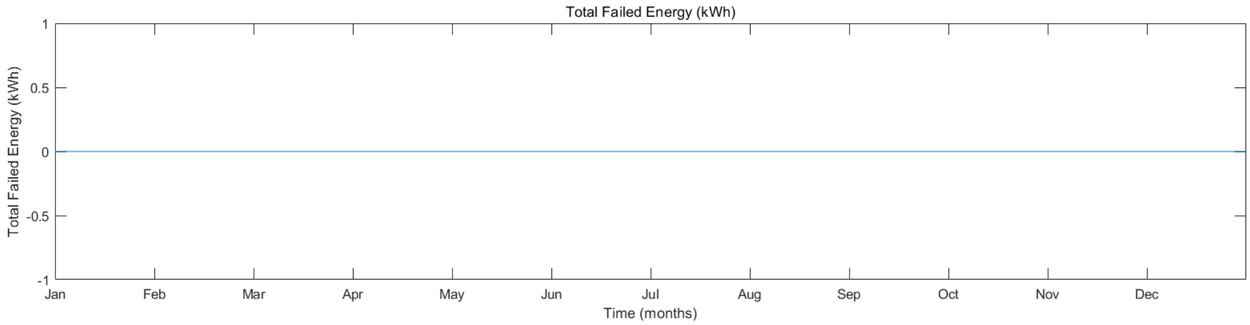

Figure 5.8: Failed energy of the energy system in 2020

5.2.2 Economic Analysis

Total Costs of the system

The total costs of the system are the sum of the capital, operation and maintenance, and other costs, for all equipment used in the system (see Equation 4.2). The capital costs and other costs (such as surrounding equipment) are fixed costs included in purchasing the equipment and surrounding utilities. On the other hand, the O&M costs are the fixed costs associated with operating, maintaining, and repairing the system. The O&M costs of each component are assumed to be 1% (€/year) of the capital costs except for PV panels, assumed to be 0.5 % (€/year). The results of the total costs are summarized in Table 5.2, where the capital costs, O&M costs and other costs are displayed for each component.

Table 5.2: Costs of the system overview

Component	Capital costs (€)	O&M costs (€/year)	Other costs (€)
PV	409000	2045	0
Battery	158400	1584	1500
Electrolyzer	108750	1087	0
Compressor	120000	1200	0
Hydrogen tank	226600	2266	12000
Fuel cell	46350	464	6000
Total capital costs	$1.0691 * 10^6$	-	-
Total O&M costs	-	8646	-
Total other costs	-	-	19500

By obtaining the total costs of the system, a strategy for the annual electricity prices and the levelized costs of energy can be calculated. To form an economic analysis of the system, the electricity prices and the levelized cost of energy developed in the following sections will be compared with the current electricity prices in the Netherlands.

Total electricity cost for households and levelized costs of energy

The electricity pricing strategy developed in Chapter 4.2 is implemented for the year 2020. To calculate the total electricity costs in one year, a pricing strategy for each energy source (PV, battery, and hydrogen system) is developed. The goal of this strategy is to obtain the costs back in the lifetime of each component. For that, the related costs per component in one year and the entire energy flow through the system in one year are considered. The price of electricity per source is calculated as:

$$P_{PV} = \frac{CC_{PV}}{E_{PV}} = \frac{16360}{129,796.13} = 0.126 euro/kWh \tag{5.4}$$

$$P_{H2} = \frac{CC_{H2} + P_{PV} \cdot E_{PVtoH2}}{E_{H2toDemand} + E_{H2toBat}} = \frac{32,186.25 + 9,172.67}{4,483.94 + 16,463.56} = 1.975 euro/kWh \tag{5.5}$$

$$P_{Bat} = \frac{CC_{Bat} + P_{PV} \cdot E_{PVtoBat} + P_{H2} \cdot E_{H2toBat}}{E_{Bat}} = \frac{13,200 + 3,689.66 + 32516.4}{49,807.29} = 0.992 euro/kWh \tag{5.6}$$

Once the electricity prices per source have been obtained, the total electricity consumption from that source is needed to obtain the total electricity bill. With the electricity price per source, and the annual consumption from that source, the annual electricity costs are calculated as:

$$B_{PV} = P_{PV} * E_{PVtoDemand} = 3,456.81 euro \tag{5.7}$$

$$B_{H2} = P_{H2} * E_{H2toDemand} = 8,855.70 euro \tag{5.8}$$

$$B_{Bat} = P_{Bat} * E_{BattoDemand} = 49,408.54 euro \tag{5.9}$$

$$TotalElectricityCosts = 61,721.05 euro \tag{5.10}$$

The total electricity costs for the whole community in 2020 are 61,721.05 €, and the electricity prices per source are $P_{PV} = 0.126$ €/kWh, $P_{Bat} = 0.992$ €/kWh, $P_{H2} = 1.975$ €/kWh. To form a clear comparison of the different prices, the electricity price in the Netherlands in March 2022 was 0.67 €/kWh (Hage, 2022).

As seen in these results, the electricity price of PV is noticeably cheap due to the low costs over the lifetime, as well as providing high electricity generation throughout the year. However, the hydrogen electricity price is expensive compared to the national grid electricity (1.975 €/kWh hydrogen and 0.67 €/kWh national grid). This is due to the very high costs of purchase for the hydrogen equipment. By spreading the total costs of the equipment throughout the lifetime, the total costs per year for the hydrogen system are €32186.25, while for PV and battery they are €16360 and €13200, respectively. This means that the annual costs for the hydrogen system are 10% higher than the costs of PV panels and the battery combined. This high costs are also reflected in the battery electricity price (0.992 €/kWh) as the battery obtains energy from the fuel cell (See Figure 4.3). This energy is reflected in the electricity price of the battery as approximately 65% of the electricity price comes from the energy obtained from the fuel cell.

The costs of the hydrogen system highly increase the electricity prices of the system as well as the total electricity costs of the year. To ensure the total costs of the system are obtained over its lifetime, the levelized cost of energy (LCOE) is used. The levelized cost of energy can be defined as the average minimum price at which the electricity generated by the system is required to be sold in order to offset the total costs of production over its lifetime (CFI, 2022a). The levelized costs of energy for the year 2020 are calculated following Equation 4.8:

$$LCOE = \frac{\sum_{t=0}^{T}(\frac{C_t+M_t)}{(1+r)^t}}{\sum_{t=0}^{T}\frac{E_t)}{(1+r)^t}} = \frac{70210}{78735.38} = 0.8917 euro/kWh \tag{5.11}$$

As seen from the equation above, the average minimum price at which the electricity generated by the system is required to be sold in order to offset the total costs of production over its lifetime is 0.8917 €/kWh. Therefore, the electricity price necessary to recover purchase costs of the system is 33% higher than the national electricity price in March 2022.

5.3 Validation of Model and Results

Validation of the model is performed to ensure that the simulation model and conceptual model represent the real world. As quoted from Sargent (2010), "Conceptual model validity is determining that (1) the theories and assumptions underlying the conceptual model are correct and (2) the model's representation of the problem entity and the model's structure, logic, and mathematical and causal relationships are 'reasonable' for the intended purpose of the model". To ensure the model is developed successfully, two methods presented by Sargent (2010) are utilized for validation.

- Using 'structured walk-through' policy, in which more than one person with a professional level in MATLAB read the program
- Checking the simulation model output using various input combinations

Similarly, the validation of results is a key phase in research that ensures that the results achieve the underlying objective that form the research in the first place (Kibin, 2022). Various methods for validation of results are found in literature; however, due to time constraints, only two methods are used. The results validation method used in this research are:

- Degenerate tests in which the model's behavior is tested by varying the input and internal parameters for plausible values variables in the system
- Face validity where knowledgeable individuals are asked whether the model and its behaviour is reasonable

In addition to varying input parameters to analyze the validity of the model and results, several meetings were conducted with the external advisor from TGV, Joep van der Weijden, to analyze the validity of the presented outcome. In these meetings, the obtained results were discussed and usually concluded to be valid, while a few times feedback was given to point at the right direction on smaller issues. Moreover, it was mentioned in these meetings that the results of simulations performed by Joep obtained similar results on the electricity prices of hydrogen. This confirmed and served as validation that the model and results were obtained in a successful way.

5.4 Sensitivity Analysis

Sensitivity analysis is a tool used to determine how changes in different input variables affect other target variables (CFI, 2022b). When conducting a sensitivity analysis, the goal is to observe how the target variable is affected by changes in the input variables. In this research, two input variables are analyzed to observe the changes it has on both the total costs of the system and the electricity costs for the household. First, the price of components (€/kW) is found to be higher for the components selected at TGV than those found in literature. Therefore, the first sensitivity analysis will focus on changing the costs of certain components. Second, a system with a 90% self-sufficiency requirement is present to analyze the reduction in system costs and electricity prices when the level of self-sufficiency decreases by 10%.

5.4.1 Components Pricing

Some of the parameters presented in Chapter 3.2 were found to be considerably higher for the equipment of TGV than the parameters found in literature. More specifically, the costs per kW for the battery, the electrolyzer, and the fuel cell, purchased at TGV are higher. Furthermore, an assumption was made in this research to take the same price (€/kW) for the components presented in the reference case and the components in the community scale. In reality, when purchasing higher capacity equipment, the cost per unit of capacity should decrease. Therefore, the capital costs of the three mentioned components, battery, electrolyzer and fuel cell, are varied to analyze the reduction of total costs of the system and total electricity costs. An overview of the pricing of components is presented in Table 5.3.

Table 5.3: Pricing of components

Component	TGV Pricing	Literature Pricing
PV	1000 €/kW	1000 €/kW
Battery	400 €/kW	125 €/kW
Electrolyzer	3750 €/kW	1500 €/kW
Compressor	12000 €/kg	12000 €/kg
H2 Tank	200 €/kg	200 €/kg
Fuel Cell	1030 €/kW	450 €/kW

The new cost values obtained from literature are used as input in the simulation. An economic overview of the system is presented in Table 5.4, where the total costs of the system, the total electricity costs, and the electricity prices are displayed for the community case and the cost-reduction case in the year 2020.

Table 5.4: System Costs Sensitivity Analysis

	Community Case	Cost-reduction case
Total Costs of the System	61,746 €	43,971 €
Total Electricity Costs	61,721 €	43,936 €
P PV	0.126 €/kWh	0.126 €/kWh
P Batt	0.992 €/kWh	0.672 €/kWh
P H2	1.975 €/kWh	1.559 €/kWh

As seen in Table 5.4, a cost reduction of approximately 33% of the total costs of the system is observable when decreasing the prices of the three components. This is also observable in the electricity costs as the community would have a similar price reduction. The high cost reduction occurs as the cost reduction in the three components is noticeably high, as the electrolyzer price is reduced by 60% compared to the community-case, the battery is reduced 70%, and the fuel cell approximately 55%. Furthermore, the electricity prices of the battery and the hydrogen system are considerably reduced, yet the electricity price of the hydrogen system is too high to compared with the national electricity price. The PV electricity price is similar to the community case as the PV costs are not modified.

In conclusion, even with the cost reduction of these components, the hydrogen components are still costly in comparison to the national electricity price. Due to the high research focus hydrogen is receiving, it is expected that the costs of the hydrogen system are reduced in the next years (IRENA, 2020). Nowadays, it is not easy to find the relevant cost data for the components, specially for the hydrogen tank, compressor and fuel cell, as the manufacturers for the components at TGV only provide the current component cost. There is literature regarding prediction cost data of the components, which is valuable to form an estimate economic analysis of what the costs in the future might look like. The current costs for electrolyzer, compressor, hydrogen storage tank and fuel cell are so high that they make the system not feasible. However, it is yet to be seen how the hydrogen system costs are reduced and analyze if they can compete with traditional technologies.

5.4.2 Self-Sufficiency

When selecting the capacity of the equipment, the foremost condition is that the system is able to provide energy even under the most extreme circumstances. This comes from a trade-off between system costs and level of self-sufficiency. When designing a 100% self-sufficient system, the costs are highly increased as energy must be ensure during demand peaks. In this section, a

90% self-sufficient system is analyzed based on the total costs of the system and the electricity costs, same as Chapter 5.4.1. Firstly, the simulation is run to obtain the optimal capacity of the system components. The results of total costs of the system and electricity prices are obtained with the optimal capacities for the year 2020. An overview of the matrix results are displayed in Table 5.5. Lower values were used as input capacity compared to the results presented in Chapter 5.1, as during a first run, the multipliers for electrolyzer and hydrogen tank were 1, meaning lower values could be achieved by lowering the input capacity.

Table 5.5: Optimal results of component sizing: Sensitivity Analysis

Component	**Battery**	**Electrolyzer**	**PV**	**Hydrogen Tank**	**Compressor**	**Fuel Cell**
Initial Capacity	396 kW	29 kW	409 kW	1133 kg	10	42
Input Capacity	300 kW	15 kW	300 kW	500 kg	n/a	n/a
Multiplier	7	4	5	2	n/a	n/a
Optimal Capacity	350 kW	12.5 kW	285 kW	305 kg	4 kg	25kW

Table 5.5 displays the optimal capacity results to obtain a 90% self-sufficient system. Compared to the results presented in 5.1, the capacity of the components is significantly reduced, obtaining high reductions of 55% in the electrolyzer and 70% in the hydrogen tank, while also reducing the battery and PV capacity. As it can be observed in these reductions, the system minimizes the capacity of the hydrogen system as much as possible as they are the most expensive components. The capacity of PV and the battery is reduced to a lower level as they are not as costly as the hydrogen system. Table 5.6 presents the results for total costs of the system and electricity costs for the year 2020.

Table 5.6: System Costs Sensitivity Analysis

Level of self-sufficiency	**100%**	**90%**
Total Costs of the System	61,746 €	35,577 €
Total Electricity Costs	61,721 €	35,566 €
P PV	0.126 €/kWh	0.135 €/kWh
P Batt	0.992 €/kWh	0.636 €/kWh
P H2	1.975 €/kWh	0.786 €/kWh

In line with the results presented in Chapter 5.4.1, a cost reduction of 42% of the total system costs occurs from decreasing the level of self-sufficiency by 10%. This is a high decrease in costs only by decreasing self-sufficiency by 10%. In addition, the electricity prices are significantly reduced, specifically the hydrogen electricity price, which is reduced by 45%. This happens due to the high reduction in hydrogen capacity, which means less costs and less energy flowing through the hydrogen system, achieving a lower electricity price. The electricity price of the battery is also reduced, contrary to the price of PV, which is slightly higher than the community-case.

Chapter 6

Institutional and Social Analysis

The integration of renewable energy sources in DES is linked with the utilization of hydrogen for long-term storage of energy. This, as explained throughout the report, is due to the high variability of renewable sources in daily and seasonal patterns, which gives rise to the need for short-term and long-term storage technologies. However, the results from the simulation developed in this research concluded that the costs of such system and the electricity prices of the hydrogen system are significantly higher than those of the national grid, making hydrogen less attractive than other options. The high costs regarding hydrogen implementation are a drawback for the energy transition towards decarbonization, and potential policy instruments can be utilized to face this challenge.

In this chapter, an institutional analysis is performed based on policy instruments that could be implemented to assist with the implementation and success of fully-decentralized energy systems and sustainable technologies. Instruments such as subsidy schemes and CO2 tax, and an analysis on scarce materials required for certain system components, are developed with the goal of arriving at policy recommendations. Furthermore, the social factors affecting the development of DES will be analyzed in this section, with the goal to understand what social characteristics drive the success of DES. The chapter will conclude with a list of institutional and social recommendations for the success of DES.

6.1 Institutional Analysis

Many countries have implemented renewable energy promotion policies to support the implementation of renewable energy sources. These promotion policies include regulatory policies, such as feed-in tariffs, net meetings, and biofuels obligation, and fiscal incentives and public financing, such as subsidies, investment tax credits, and reduction in VAT. In this section, three instruments are analyzed in their implementation to DES and hydrogen technologies.

6.1.1 Subsidy schemes

A subsidy is a form of payment to an individual or business entity, usually by the government, which are generally seen as a privileged type of financial aid, as they lessen an associated burden against the receiver, or promote a particular action by providing financial support (Investopedia, 2022). Due to the high costs involved with the hydrogen production, storage and consumption equipment, which are translated into high electricity prices, subsidy schemes could be one of the most advantageous instruments to increase the implementation and utilization of hydrogen in many fields. European member states have started drafting subsidies for green hydrogen generation to further boost renewable energy sources and quadruple current 2030 targets for green hydrogen supplies (Lee, 2022). The objectives focus greatly on the need to electrify sectors using renewable energy sources and increase the profile of hydrogen in the EU economy.

Recent subsidy packages for hydrogen have been imposed. Germany has a 7 billion euro support package, France a €7.2 billion support package, while a €7 billion package is expected to be allocated to the Portuguese strategy (IRENA, 2020). Some of the investment support has already been translated into concrete calls for proposals. In the Netherlands, a subsidy scheme, namely the Stimulating Sustainable Energy Production and Climate Transition (SDE++), is aiming to increase green hydrogen production, with a budget of €13 billion for the SDE++ 2022 (Brooks, 2022a; RVO, 2022). Aiming to appeal to more applicants of hydrogen projects, the upcoming (2022) SDE++ subsidy round features subsidies for different kind of hydrogen project, namely electrolyzers which are directly linked to decentralized wind or solar farms rather than to the grid. To reach the 2030 objective of green hydrogen production, the electrolyzers' output capacity in Europe must increase drastically in the next seven years. Hence, the European Commission is looking to present a subsidize scheme to support the production of electrolyzers to accelerate the production and implementation of hydrogen in industrial scales (Collins, 2022). As a result, several member states are preparing for such subsidy schemes, and the European Commission has already granted state aid approvals.

In the built environment, subsidy schemes have the potential to make significant contributions to the hydrogen costs. Although the costs of producing green hydrogen are expected to fall sharply in the long term, it is still difficult to predict at what price hydrogen will actually become available and whether that price will also lead to an affordable option for the built environment (RVO, 2021). However, strong demand from end users and financial support with subsidy schemes will stimulate the rapid development of the market for hydrogen.

6.1.2 CO2 Pricing

Another instrument to make hydrogen more attractive would be the implementation of a CO2 tax, so polluters pay a higher price for their carbon emissions. Nowadays, polluters pay too little for the costs of their carbon emissions, slowing the implementation of more expensive sustainable technologies (Brooks, 2022b). Consequently, firms and individuals worldwide have fewer financial incentives to swift to green technologies. The implementation of a CO2 price is a potential solution. If governments introduce this tax, emitters will pay more for their impact on carbon emissions, and will enhance the switch to sustainable alternatives.

Some examples of CO2 pricing instruments include emissions trading systems (ETS), carbon taxes, carbon offset mechanisms, results-based climate finance (RBCF), and internal carbon pricing (Koons, 2021). The adoption of CO2 pricing instruments has been increasing globally in the past decade, with 61 carbon pricing initiatives implemented or scheduled for implementation in 2020, considerably higher than the 19 in 2010 (Koons, 2021). However, only 22% of the global GHG emissions were under a pricing instrument in 2020. Figure 6.1 represents the countries that have adopted a carbon pricing instrument as of 2019.

One of the main advantages of CO2 pricing instruments is the promotion of cleaner energy technologies. In Europe, the price of carbon has increased by 200% since the start of 2021 , reaching a price of 100 €/ton in February 2022 (Chestney et al., 2022). When the carbon price was approximately 30 €/ton, patents for renewable energy technologies and carbon sequestration increased by 30% (Koons, 2021). In the US, similar trends were observed when the state of New York implemented a carbon price instruments, as investments in renewable energy courses increased directly after. Therefore, carbon pricing instruments are valuable tools to accelerate the

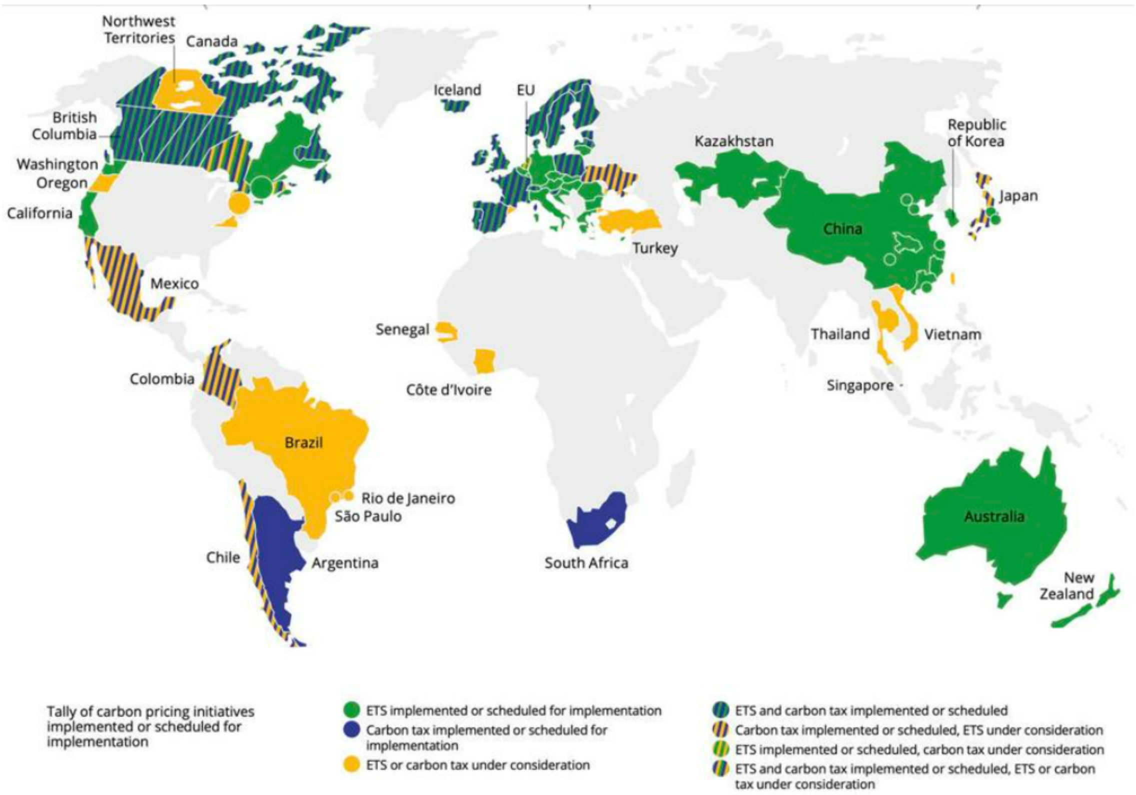

Figure 6.1: Countries with implemented CO2 pricing instruments as of 2019. Retrieved from Koons (2021)

implementation of sustainable technologies in the energy system. By implementing a CO2 tax, electricity prices of fossil fuel sources would increase, and the increased investments in renewable sources would make a decrease in the costs of these. This would increase the attractiveness of technologies such as hydrogen storage in the built environment, as the high costs of electricity associated with this technology would be closer to those of competing technologies.

6.1.3 Critical Materials

This section, contrary to the previous two sections presenting institutional tools to incentive the development of sustainable technologies in energy system, analyzes the criticality of raw materials required for producing green hydrogen. More specifically, it identifies potential critical materials in electrolyzers and fuel cells that might be critical in regard to their future energy supply. These metals are platinum, iridium, titanium, scandium and yttrium.

Platinum itself is used in PEM electrolyser cells and PEM fuel cells as the preferred cathode material. Platinum is a rare metal on earth, and the production of which is limited due to the challenges in obtaining platinum. For comparison, in 2018 three tons of gold were produced, compared to 0,7 tons of platinum (Oilprice, 2020). Most of the studies performed to minimize the use of this metal have been successful, but a complete replacement is not yet available. Furthermore, an analysis on the state of platinum production and platinum demand in future decades was done by Kiemel et al. (n.d.), where it was seen that the total global platinum demand exceeds the supply from primary production already today. With the growing demand of electrolyzers and fuel cells, it is yet to be seen what possibilities exist for replacing platinum.

Iridium is another metal used as the main catalyst material for the anode. For now, there are no materials with acceptable prospects for substituting iridium, as the resistance to the high corrosion involved in PEM electrolyzers is only satisfied with iridium (Kiemel et al., n.d.). Other materials used in PEM electrolyzers and PEM fuel cells, such as titanium, scandium and yttrium, are rare materials whose supply can be threatened by an increase in demand in electrolyzers and fuel cells. Nowadays, all these metals are classified as non-critical as the demand prospects of these materials in 2050 could be covered with today's production or with enough reserves (Kiemel et al., n.d.); however, it is advantageous to bring up these materials so that future policy makers take them into consideration.

In today's literature, a criticality assessment of the scarcity of raw materials involved in the energy transition is missing. There are no potential solutions uncovered in literature to solve this issue. The recycling of electrolyzers and fuel cells is already present; however, the extraction and further utilization of these rare materials is more complex (Kiemel et al., n.d.). A further evaluation of the effective recycling of electrolyzers and fuel cells is still needed to evaluate and solve the challenge of scarcity of materials. Therefore, it is noted that a critical assessment of raw materials for producing green hydrogen is still overlooked in literature. This being said, it is clear that now is time to put this topic on the agenda of governments to take action, as it will influence their political decisions in the future.

6.2 Social Analysis

In recent years, numerous studies have been performed exploring the opportunities and barriers faced by decentralized energy systems. However, there has been a lack of focus on social value associated with these systems. In this section, the social factors and characteristics influencing the success of decentralized energy systems are identified. Aspects of participation, engagement, and trust are especially relevant to the social acceptance of DES. Therefore, the analyzed factors include willingness to participate, engagement of participants and trustworthiness among actors.

6.2.1 Willingness to Participate

One of the most important social aspects for a decentralized energy system to be implemented is the willingness of the participating households. The willingness of participants depend on a series of geographical and demographic characteristics. First, the willingness to participate can vary between regions. Interviews conducted by (Müller & Welpe, 2018) with people living in decentralized energy communities showed the difference in willingness to participate, modeled by the social, cultural and behavioural barriers to the adoption of these systems by each community. Another factor affecting the willingness to participate is the age of the participants. Studies have shown that most people willing to participate are younger than 60 years of age (Mengelkamp et al., 2019). This could be explained due to the complexity of the technologies, as older people are more likely to resist the adoption of unfamiliar technologies. Willing participants also tend to be more educated and less politically conservative (Hahnel et al., 2020). Furthermore, household characteristics have an influence on the success of decentralized energy systems, as larger households tend to have a higher willingness to participate in these systems (Adams et al., 2021). Studies also mentioned that participants willing to participate in DES tend to be homeowners and more financially secure (Wilkinson et al., 2020; Adams et al., 2021).

6.2.2 Household Engagement

Critical to the success of DES is the participating household engagement. First, people must be well aware of the concept of decentralized energy system or energy community. Studies have shown that participant engagement in energy communities have improved with engagement strategies. In the study by Klein et al. (2020), it was concluded that engagement strategies were effective in increasing the engagement of users in energy communities, mainly by raising their awareness of the system and technologies and by raising their capacity to participate. It was stated that taking user input into consideration increases the engagement of participants in energy communities.

Besides engagement strategies, households with interest in renewable energy and climate concerns tends to participate more in DES. The most important factor associated with interest in participation is a concern about climate change and transitioning to decarbonized energy systems (Adams et al., 2021). Participant engagement increases when the individuals have a positive view of technologies such as PV and energy storage technologies, and are willing to invest in relevant infrastructure for the decarbonization of the energy market. Furthermore, the identification with the local community is seen as an important factor for citizens to actively participate and support DES (Ecker et al., 2017). The sense of 'being part of a community' is identified as a relevant factor which could help increase the trustworthiness among the community which would help reduce the impact of a third-party central authority in whom participants could otherwise place their trust (Adams et al., 2021)

6.2.3 Trust between actors

DES often require a high level of communication among the participating individuals. This involves well-functioning cooperation between the entire community. Research on community-based energy initiatives revealed that interpersonal and social trust between local people and groups is advantageous for the realization of the projects, as the people feel positive about getting involved and about the development process in general (Yildiz et al., 2015).

Nowadays, little focus is given to the role of trustworthiness in energy communities. Walker et al. (2010) studies the concept of trust in relation to the development of community renewable energy systems, highlighting the fact that trust is a characteristic of the community approach or a project outcome that builds social capital. The conclusion suggests that although trust is one key component of the necessary conditions for a successful community energy project, it cannot be either assured or assumed under the wide diversity of contexts, conditions and arrangements under which DES are being pursued and practiced (Walker et al., 2010).

Table 6.1 summarizes the social factors and characteristics influencing the development of DES.

Table 6.1: Summary of social factors affecting the development of DES

Concept	**Description**
Geographical factors	Social, cultural, and political differences among regions may drive different attitudes towards the implementation of DES
Demographic factors	Age, education, and financial status of people drive the interest of DES
Engagement of participants	Engagement strategies and a concern for climate change increase the level of participation of actors in DES
Trust among participants	Trust is one of the key conditions to ensure the uptake and success of DES

6.3 Recommendations

From the analyzed institutional and social topics affecting the development and implementation of sustainable technologies, a list of potential tools and characteristics are recommended for future consideration.

From an institutional perspective, two policy instruments may be used to assist with the implementation of sustainable technologies. First, governments could stimulate renewable sources with subsidy schemes. Subsidy schemes are being studied by countries for the implementation of hydrogen in many areas and would considerably help with the high costs associated with certain technologies. In the future, the costs of hydrogen are expected to decrease, but subsidy schemes may accelerate the transition towards cleaner energy. Secondly, CO2 pricing is a suitable tool to decrease the attractiveness of fossil fuel sources, which would consequently increase the attractiveness of sustainable technologies. Lastly, since demand for critical materials used in electrolyzers and fuel cells is rapidly increasing, it is crucial to take measures that ensure the future availability of those components, specifically platinum.

From a social perspective, several factors were analyzed that drive the implementation and success of DES. Geographical factors, such as social, cultural and political differences among regions, as well as demographic factors, such as age, education, and financial status of individuals drive the interest of communities towards DES. Furthermore, to ensure the success of DES, engagement of participants through engagement strategies was found to be successful tool. Lastly, trust among participants was identified as a key factor in the success of DES.

Chapter 7

Discussion

7.1 Interpretation and discussion of results

The results presented in Chapter 5 show that batteries and hydrogen can be implemented in a decentralized energy system as short-term and long-term storage mediums. However, the high costs associated with this system make it very hard to be implemented in practice, as right now it is far from competing with traditional technologies. Hydrogen has the potential to overcome obstacles in the energy transition, for instance, with an increase share of renewable energy sources, it has the ability to handle the increasing intermittency in generation in the future energy market. From the simulation several conclusions can be derived, which will be explained in this section.

Firstly, the simulation started with the minimization of total costs of the system by obtaining the optimal capacities of four components of the system. As seen in the results, the minimum costs are obtained by maximizing the PV capacity and by minimizing the hydrogen storage capacities. This, while achieving minimum costs, derives on an inefficient system with a lot of dumped energy. From an economic perspective, the system achieves minimum costs, which is translated into lower electricity costs for the households and lower costs for the governing party (TGV in this case). From a technical perspective, 75% of the generated energy is lost, either to dumped energy or to the low inefficiencies of the hydrogen components.

Since the designed system has an excessive amount of dumped energy, further utilization of this energy should be arranged to decrease the losses of the system. First, the implementation of a charging station of electric vehicles could be implemented, which could benefit from the remaining energy that would otherwise not be used in any way. This would also incentivize the members of the community to acquirer electric vehicles as it could potentially bring down the fuel costs of their vehicles, and would assist the country on an environmental perspective. Second, a connection to the national grid could be implemented so that the otherwise dumped energy can be sold. This would be beneficial for both parties, as the grid can benefit from renewable energy and the community can obtain a higher revenue. If the grid does not need the energy at that given time, grid-scale energy storage can support grid stability and the energy can be used in a further moment in time.

The electricity prices for households is a critical topic in the analysis of DES. As seen in section 5.2.2, the electricity prices highly vary from PV, battery, and hydrogen electricity. The electricity prices form PV are very cheap (0.126 €/kWh), this is due to the low costs associated with PV panels, their long lifetime (25 years), and the high generation obtained from them. The battery has a high electricity price (0.992 €/kWh) due to the high costs involved with the hydrogen

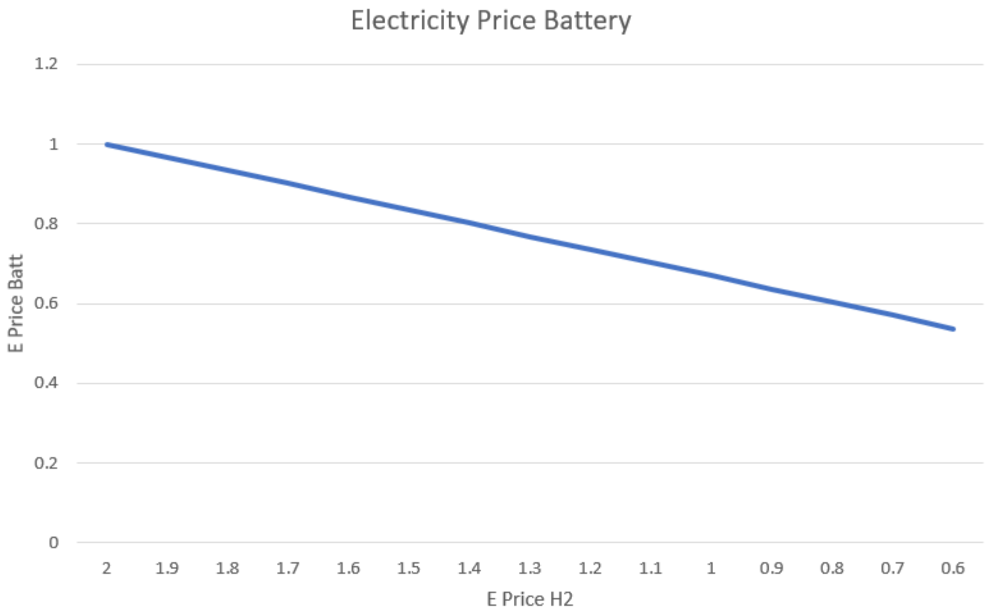

Figure 7.1: Electricity price battery vs electricity price H2

system. As seen in the energy flow represented in a Sankey Diagram (Figure 7.2), the battery obtains electricity from the fuel cell, which constitutes 69% of the total electricity price from the battery. Figure 7.1 displays the change in electricity price of the battery when changing the electricity price of the hydrogen system. As it can be observed, the electricity price of the battery is highly reduced when reducing the price of the hydrogen system. Lastly, the electricity price from the hydrogen system is excessively high, this is due to the very high capital costs of the components and low lifetime in some of the components (specially the fuel cell, 8 years). This is the main economic challenge faced in decentralized energy system that want to achieve self-sufficiency. Nowadays, the implementation of hydrogen for long-term storage involves very high costs which make the system be economically unfeasible.

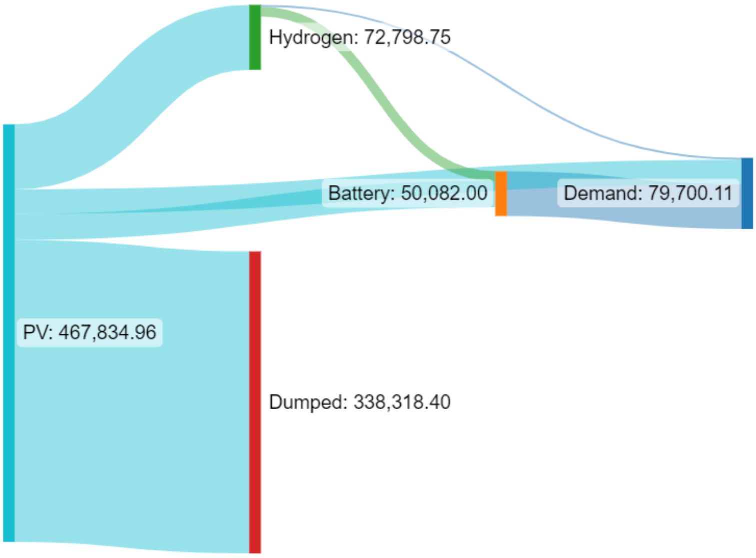

Figure 7.2: Sankey Diagram with the energy flow through the system

A sensitivity analysis was performed to analyze the alteration in results when varying input variables. The two input variables changed in this analysis are the pricing of components (€/kW) and the level of self-sufficiency of the system (100% vs 90%). These two analysis showed a high decrease in system costs when changing the input variables. For the components pricing analysis, the pricing of components found in literature were higher than the components purchased at TGV. Furthermore, economies of scale (a proportionate saving in costs gained by an increased level of capacity) were not considered for the community case, meaning the costs of purchase of bigger equipment can be lower. Due to the lower costs of the electrolyzer, fuel cell, and battery, the total costs of the system and the electricity prices of the battery and hydrogen are highly reduced, which is expected due to a decrease in the costs of components. Moreover, the costs of the system are reduced by approximately 36% when decreasing the level of self-sufficiency by 10%. This demonstrates that demand peaks are what highly increase the costs of the system, as you must invest in higher capacities to reach these peaks. When decreasing the level of self-sufficiency by 10%, demand peaks can be achieved with electricity from the grid, meaning the components can have a highly reduced capacity compared to a system with 100% self-sufficiency. Since demand peaks happen mostly in the winter, the capacity reduction comes mainly from the hydrogen system, also since these are the most expensive components. The results are seen in a 55% reduction in capacity in the electrolyzer, 70% reduction in the hydrogen tank, 40% reduction in the fuel cell, while the PV and battery capacity are reduced, but in a much lower scale.

Since demand peaks highly increase the costs of the system, one method to minimize peaks would be demand response. Demand response is a change in electricity consumption by end-users to help balance the electricity grid during peak production or peak consumption times. By utilizing demand response methods, the capacities of the components can be reduced as lower peaks would be present in extreme conditions, which would result in lower costs of the system and lower electricity prices. However, without grid balancing operators, the system can be vulnerable to fluctuations in demand and supply, which can lead to issues such as power outages and even blackouts (Sympower, 2021). Nowadays, there are no grid balancing operators at TGV; therefore, the implementation of demand response is defined for future work recommendations. Secondly, peak shrinking is another method that could help reduce peak demand. It is done by implementing equipment that uses less energy. This could be done by mainly replacing high energy consuming equipment for more efficient equipment, effectively shrinking the entire demand curve in a downward direction. Nonetheless, this would require an investment on more sustainable equipment which means an analysis must be performed to conclude the technical and economic feasibility of this method.

From an institutional perspective, two policy instruments can be implemented to assist with the implementation of hydrogen in energy communities. First, subsidy schemes are being studied by countries for the implementation of hydrogen in many areas and would considerably help with the high costs associated with hydrogen technologies. In the future, the costs of hydrogen are expected to decrease, but subsidy schemes can accelerate the transition towards cleaner energy. Secondly, CO2 pricing is a suitable tool to decrease the attractiveness of fossil fuel sources, which would consequently increase the attractiveness of sustainable technologies. From a social perspective, several factors drive the implementation and success of DES. Geographical factors, such as social, cultural and political differences among regions, as well as demographic factors, such as age, education, and financial status of individuals drive the interest of communities towards DES. Engagement of participants through engagement strategies and trust among the community are also found to be successful tools.

In conclusion, the electricity costs for the community are about 70% higher than those from the national energy grid. Therefore, it is difficult for consumers to accept these high electricity costs. Nowadays, it would be more beneficial for both TGV and the community consumers to accept a lower level of self-sufficiency, such as 90% of the total energy consumption of the community, as it would reduce the total costs of the system and the annual electricity bill by approximately 36%, as seen in the sensitivity analysis conducted in this research. In the future, hydrogen and decentralized energy system require assistance through regulations and policy to support such kind of community energy system, and when hydrogen technologies become less expensive then it could be feasible to achieve for a fully-sufficient system.

7.2 Assumptions and Limitations Discussion

The results from the simulation show that batteries and hydrogen can be implemented in a decentralized energy system as short-term and long-term storage mediums; however, some assumptions were made due to the duration and complexity of this research. In this section, some of the assumptions made are discussed and their real-life relevance are explained.

In the designed system, there is no limit in the available space for implementation of the system components. The most important concern regarding the availability of space is for the implementation of PV panels. As seen in the results, the capacity of PV generation is 409 kWp, and assuming a capacity per PV panel of 260 Wp, this would mean over 1200 panels installed in the community. In reality, the community could first determine what is the space available for implementing PV panels and maximize the capacity of PV panels based on their available space. Since the minimization of costs comes from maximizing the PV capacity, the solution would be to recognize what is the maximum PV capacity available with the required space and derive the capacity of the remaining components with the fixed PV capacity. Since space constrains were not implemented in this research, there is no maximum capacity limit for PV generation.

For the simulation of this research, a 10-year time set was used to consider the variations in weather conditions of the different years, which highly affect the optimal sizing of components. However, limited demand data is available for the community of TGV, as the only year with complete demand data is 2020. Therefore, the generation data considers the actual hourly generation of the past 10 years, but the demand data of the year 2020 was used for every year. For the real-life design of an energy community system, the demand data of each year should be used.

To simplify the design of this research, it was assumed that all household of the system had the same characteristics. Hence, the heat demand was fulfilled completely with electricity by implementing an electric boiler which utilizes electricity to heat water. At TGV, the four studios are electrified, but the three family houses have heat pumps as heat demand sources. Due to the complexity of modeling the different heat sources and the limited time for this research, the assumption of a fully-electrified community was done. For future research, a more elaborated design can be performed taking the different heat generation sources into consideration.

Another assumption concerning heat sources was done with regard to the fuel cell. In real life, a significant amount of heat is generated by the fuel cell while operating, equivalent to 45-60% of the total energy content of hydrogen entering the cells (Nguyen & Shabani, 2020b). The generated heat can be removed effectively from the fuel cell by using a cooling system in order to provide this heat to the households. However, the integration of a cooling system was assumed to not be in place in this system. The implementation of heat recovery from the fuel cell will highly increase the efficiency of the fuel cell and save a lot of costs if the heat generated by the fuel cells can be properly utilized.

In this energy system, surplus energy from PV panels is dumped when the maximum capacity of the electrolyzer is met or the hydrogen tank has achieved its maximum capacity. As mentioned in this report, this energy can be sold to the national grid to obtain value from this energy. Therefore, a connection with the national grid should be study to conclude on the economic feasibility of the system when the dumped energy is sold.

One of the economic assumptions was that the pricing of components (€/kW) are the same for the reference case than the community case. In this research, the pricing of components are taken from the purchase costs of TGV, which includes the designed system for a single household. For the scale-up of the system, the costs per capacity unit were assumed to be the same. In practice, when purchasing higher capacity components, it is expected that the cost per capacity unit is reduced. Therefore, an economic analysis where the pricing of components consider economies of scale is required to conclude on the economic feasibility of the system.

For this research, the economic analysis is performed by taking all the required costs of all components, including the capital, O&M, and other costs (such as surrounding equipment). However, other costs such as the distribution network costs, implementation costs or manpower costs are not considered. From the results obtained in this simulation, the real-life costs would be higher, as these other costs are not considered.

Lastly, the simulation is done based on the system of TGV, which means it is limited to this specific system. The model done in this research can be described as a template, where input parameters such as generation and demand data, component capacities, costs of equipment, and others, can be varied depending on the parameters. Therefore, to validate the model, it can be implemented and analyzed in another location, where different data can be used to determine the optimal capacities and the techno-economic feasibility of the system. Furthermore, the model can be scaled-up to a neighborhood or city level, or even a national level, where the techno-economic feasibility of the system can be analyzed based on larger scale projects.

Chapter 8

Conclusion

The Paris agreement has set European countries on a path towards decarbonization of the energy market, with policies such as having a share of 40% renewable energy sources by 2030. Due to the high dependence of natural gas in the Netherlands, various challenges will be faced when facing out fossil fuels. The major drawback of RES is that they are non-dispatchable, meaning their output generation fluctuates over time with respect to weather conditions, resulting in a temporal mismatch of supply and demand. In order to allow shifting of non-dispatchable loads, energy storage is required. With this current issue and the need to set a sustainable path towards decarbonization, this research focuses on the integration of energy storage systems to handle the intermittency of renewable energy sources in a decentralized energy system.

The goal of this research was to provide insights of the integration of short-term and long-term energy storage systems in local energy communities. To reach this objective, a simulation was done to determine the capacities of the components that achieve the minimum costs of the system. The main research question focuses in this objective with the assist of three research sub questions. This chapter focuses on answering the research question and discussing the scientific and societal relevance of this research. Lastly, future work recommendations are given to ease possible research paths.

8.1 Answering the research questions

What are potential technologies to be implemented in decentralized energy systems for short-term and long-term storage?

This research has studied the feasibility of potential short-term energy storage technologies, such as batteries, flywheels, supercapacitors, among others, as well as long-term energy storage technologies, such as compressed hydrogen and compressed-air energy storage, for implementation in DES. While the majority of technologies could be implemented in these systems, batteries and hydrogen were concluded to be the most feasible solutions to be implemented for short-term energy storage and long-term energy storage, respectively. Properties of batteries that make them the most suitable short-term energy storage technology are the high efficiencies, low costs, long life cycle, high energy and power density, along with others. It was concluded that Lithium-ion batteries are the most feasible type of battery. Furthermore, hydrogen is proposed for long-term energy storage as it is capable of increasing the self-consumption of PV energy and allows for a system with 100% energy self-sufficiency. The major drawback of hydrogen are the noticeably high costs and low round-trip efficiencies.

How can the capacity of the different components of the short-term and long-term energy storage system at TGV be optimized to achieve the minimum costs of the system?

The energy system was designed with PV panels for electricity generation, a battery for short-term storage, and a hydrogen system for long-term storage, including an electrolyzer, a compressor, a hydrogen tank and a fuel cell. To understand the dynamics of the system, a control strategy was developed that determines the behavior of the system at any moment in time. With the necessary data to design the system, including generation data, demand data of a given community, and the technical and economic parameters of each component, a model was created representing a real-life simulation of the system present at TGV. The objective of this model was to determine the optimal capacities of the components, with the final goal to minimize the total costs of the system. The results from this simulation showed that the minimization of total costs is obtained by minimizing the capacities of the hydrogen system, as these represent the most expensive components of the system, and maximizing the PV generation, as it is the cheapest component throughout the lifetime. However, the results showed very high costs due to the high costs associated with the hydrogen system, which makes these systems with hydrogen storage impossible to compete with traditional fossil fuel sources. The electricity prices for households of the energy coming from the fuel cell can be greater than three times the electricity price of the national grid.

What recommendations can be given based on institutional and social factors that affect the development and implementation of decentralized energy systems in the Netherlands?

Due to the high costs associated with hydrogen technologies, and the great need to set a sustainable path towards decarbonization, innovative policies and social factors influencing the success of DES were analyzed. Two policy instruments could be implemented to make hydrogen be more feasible in DES. First, subsidize schemes could be utilized as a tool to lower the high costs associated with hydrogen. European countries have already started drafting support packages for green hydrogen and electrolyzers. Second, the implementation of CO2 prices could help decrease the attractiveness of fossil fuel sources, which are characterized to be cheaper than greener alternatives. Lastly, an analysis on scarce materials show that some critical material included in electrolyzers and fuel cells, such as platinum, might lack supply in the future. From a social perspective, three factors are analyzed to take into consideration in DES. First, the willingness to participate of household is affected by a set of factors such as age, culture, financial well-being, and others, which highly affect the success of DES. Moreover, household engagement is critical to the success of these systems, which can be enhanced with engagement strategies that increase the confidence and trust of individuals. Lastly, one of the most critical factors to take into consideration is trust between actors, where the communication and cooperation between the whole community is key to have a well-functioning system.

Main research question: How can the short-term and long-term storage capacity in a decentralized renewable energy system be optimized to guarantee security of supply?

With the combination of a battery and a hydrogen system, an energy system with 100% self-sufficiency is achievable. To optimize the capacities of these components, a model should be developed which takes into account the generation and demand patterns. By maximizing the capacity of PV generation, and minimizing the capacities of the hydrogen system, the capacities of the system are optimized to achieve minimum costs. The selected capacities must be enough to ensure a system which never fails to provide energy.

8.2 Scientific relevance

Research gaps found in literature were stated in this research, were it was pointed out that the integration of a hybrid short-term and long-term storage system in the built environment has not been widely studied. Literature discussed the combination of RES, such as PV and/or wind, with a hydrogen system or with batteries to handle the intermittency of these. However, a techno-economic analysis of a self-sufficient system with short-term energy storage and long-term energy storage is not present. It has been concluded that a self-sufficient system can be achieved with batteries and hydrogen energy storage, although the costs of this system are very high. Besides the technical and economic challenges of DES and hydrogen, institutional and social issues are found to be overlooked in literature, which are critical to shape the development of DES and hydrogen technologies in the upcoming years. Policies such as financial support for green hydrogen production and the implementation and increase of CO2 pricing can highly affect the successful development of DES and hydrogen.

8.3 Societal relevance

The results from this research shows that the combination of RES with a battery and hydrogen as energy storage mediums is possible. The battery will be used on a daily basis to handle the short-term intermittency of solar generation, while hydrogen will be used on a seasonal basis, where hydrogen is produced in the electrolyzer in the summer and is consumed in the fuel cell to produce electricity in the winter. However, the costs associated with this system makes it impossible to compete with fossil fuel sources. To ensure a successful energy transition, hydrogen must be the focus of study on future research in many areas, as it has the potential to be utilized as fuel in hydrogen vehicles, synthetic fuels, heating, metal refinery, power generation, and energy storage. This research studies the implementation of hydrogen as energy storage medium at TGV, and can be studied in other communities or cities, and on smaller and larger scale projects.

8.4 Future work recommendations

For future work, it is recommended to implement other heat generation technologies such as heat pumps and hydrogen boilers in the optimization, and further study the techno-economic feasibility of the system. Moreover, a cooling system for heat recovery of the fuel cell should be the focus of future research, as it could increase the efficiency of the system and reduce costs.

As mentioned in previous chapters, the surplus energy is assumed to be dumped when the maximum electrolyzer capacity or the maximum hydrogen tank capacity are reached. To obtain value from this energy, a connection with the national grid to feed the surplus energy should be studied in future research to conduct an economic analysis.

Due to the complexity and length of this research, certain subsystems in DES, such as the distribution network, had to be excluded. Therefore, a future work recommendation is to study and optimize the distribution system, which can include the distributing network of electricity or to study the development of a hydrogen distribution network. The distribution system should be considered in the economic analysis of the system.

Lastly, although a concise institutional and social analysis has been developed in this research, a future work recommendation is to thoroughly analyze the institutional and social issues affecting the development of DES and hydrogen production. This is due to the extensive issues that can be discussed regarding institutional design and policy-making in the energy transition, which can be the topic of a whole research paper.

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Appendix A

Relevant Literature

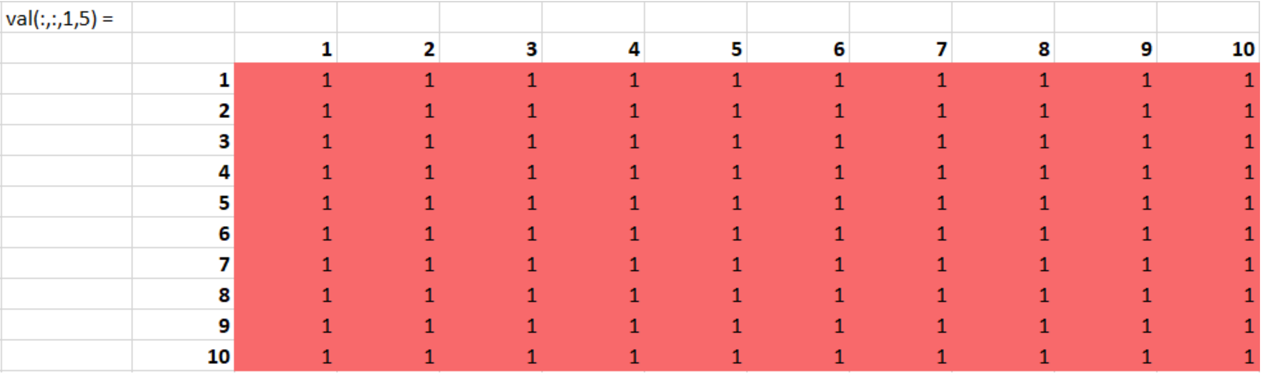
Table A.1: References used for the literature overview

Source	Authors	Year	Reference
Assessment of a fuel cell based-hybrid energy system to generate and store electrical energy	Wang J., Sun X., Jiang Y., Wang J.	2022	Wang et al. (2022)
Electrical energy storage from a combined energy process based on solid oxide fuel cell and use of waste heat	Lin G., Wang X., Rezazadeh A.	2021	Lin et al. (2021)
Determining the appropriate size of the electrical energy storage system of an energy process based on a solid oxide fuel cell and wind turbine	Guo Y., Yousefi A.	2021	Guo & Yousefi (2021)
Thermal analysis and optimization of stand-alone microgrids with metal hydride based hydrogen storage	Kumar S, Sharma R., Dutta P., He W., Wang J.	2022	Kumar et al. (2022)
Optimal sizing of off-grid hybrid energy system based on minimum cost of energy and reliability criteria using firefly algorithm	Sanajaoba S.	2019	Sanajaoba (2019)
Planning stand-alone electricity generation systems, a multiple objective optimization and fuzzy decision making approach	Rivera-Niquepa J., De Oliveira-De Jesus P., Castro-Galeano J.	2020	Rivera-Niquepa et al. (2020)
A Short Assessment of Renewable Energy for Optimal Sizing of 100% Renewable Energy Based Microgrids in Remote Islands of Developing Countries: A Case Study in Bangladesh	Akter H., Howlander H. O. R., Nakadomari A., Islam M. R., Senjyu T.	2022	Akter et al. (2022)
Techno-economic assessment of hybrid energy flexibility systems for islands' decarbonization: A case study in Italy	Hoseinzadeh S, Astiaso Garcia D.	2022	Hoseinzadeh & Garcia (2022)
Levelling renewable power output using hydrogen-based storage systems: A techno-economic analysis	Chen C., Lu Y., Xing L.	2021	C. Chen et al. (2021)
Energetic and economic analysis of a stand alone photovoltaic system with hydrogen storage	Marino C., Nucara A., Panzera M., Pietrafesa M., Varano V.	2019	Marino et al. (2019)
Hydrogen Energy Storage: New Techno-Economic Emergence Solution Analysis	Becherif M., Ramadan H., Cabaret K., Picard F., Simoncini N., Bethoux O.	2015	Becherif et al. (2015)
Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options	Kalinci Y., Hepbasli A., Dincer I.	2015	Kalinci et al. (2015)
Analysing economic and environmental sustainability related to the use of battery and hydrogen energy storages for increasing the energy independence of small islands	Groppi D., Astiaso Garcia D., Lo Basso G., Cumo F., De Santoli L.	2018	Groppi et al. (2018)

Appendix B

Matrix Results

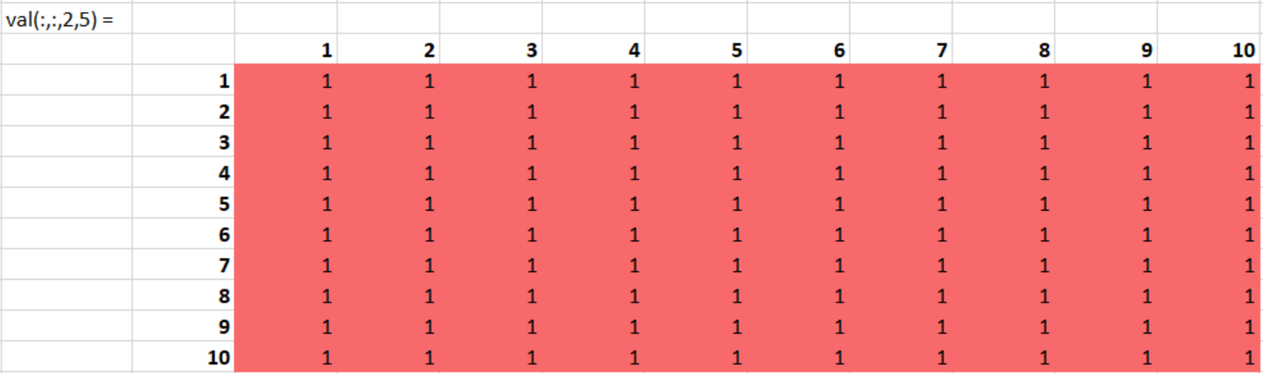
The results displayed in this section correspond to the total costs of the system. If the result in the matrix is ’1’, it means the system has failed energy. The values displayed in each figure must be multiplied by 1^5 to obtain the total costs of the system in a period of 1 year. The X axis represents the multiplier values of the electrolyzer and the Y axis represents the multiplier values of the battery. The third value in the vector represents the PV multiplier values, while the fourth value in the vector represents the hydrogen tank multiplier value, which is fixed in multiplier 5. The minimum costs of the system is highlighted in Figure B.7.



val(:,:,1,5) =

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1

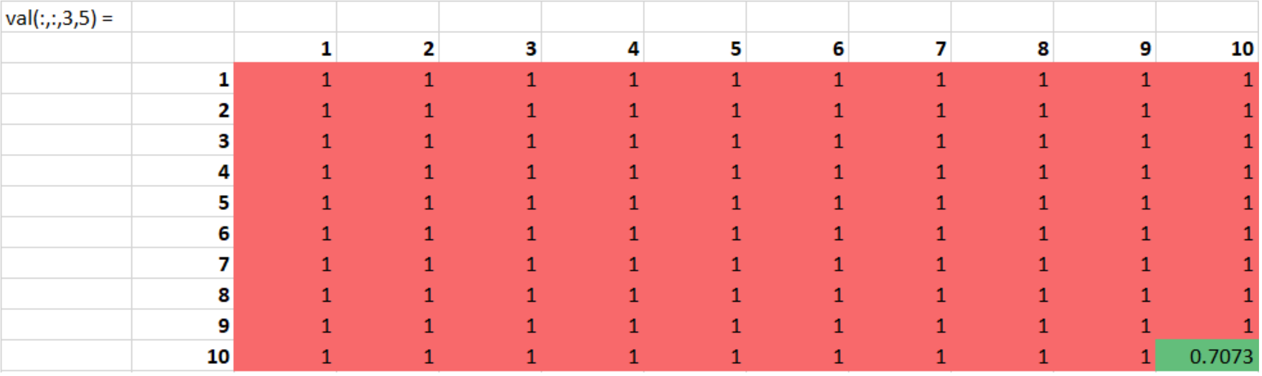
Figure B.1: Matrix results: PV multiplier 1



val(:,:,2,5) =

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1

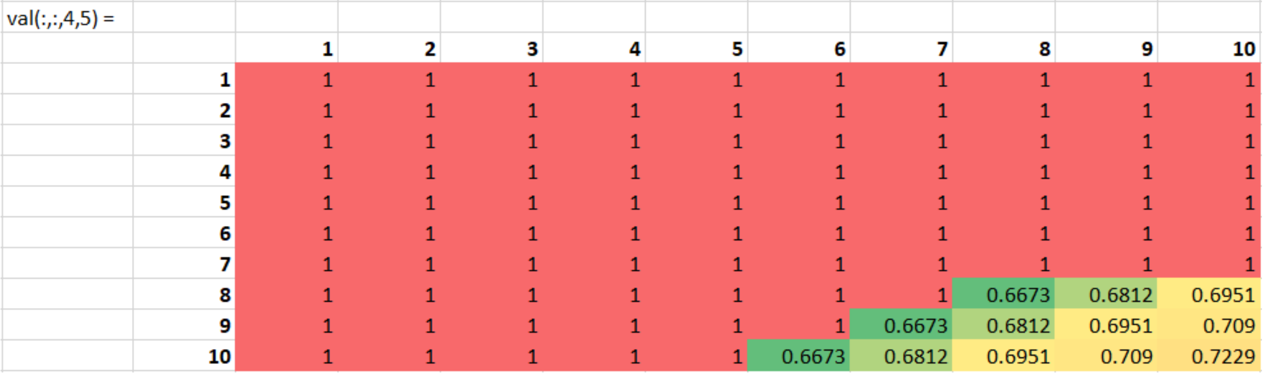
Figure B.2: Matrix results: PV multiplier 2



val(:,:,3,5) =

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	1	1	1
9	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	0.7073

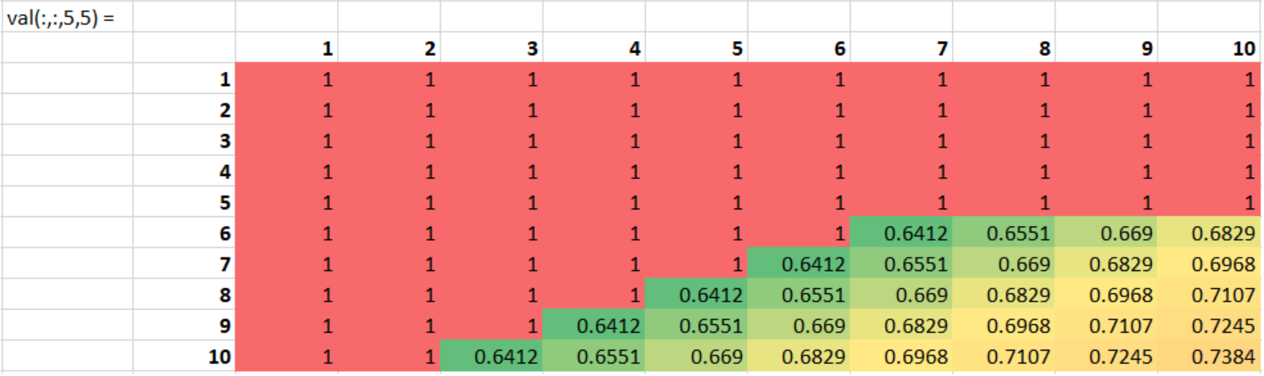
Figure B.3: Matrix results: PV multiplier 3



val(:,:,4,5) =

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1	1	1
7	1	1	1	1	1	1	1	1	1	1
8	1	1	1	1	1	1	1	0.6673	0.6812	0.6951
9	1	1	1	1	1	1	0.6673	0.6812	0.6951	0.709
10	1	1	1	1	1	0.6673	0.6812	0.6951	0.709	0.7229

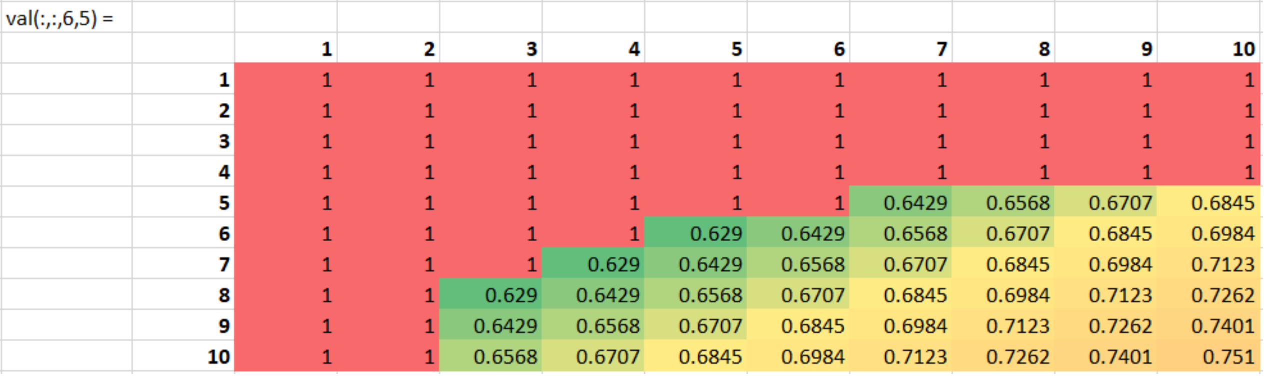
Figure B.4: Matrix results: PV multiplier 4



val(:,:,5,5) =

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	1	1	1	1
6	1	1	1	1	1	1	0.6412	0.6551	0.669	0.6829
7	1	1	1	1	1	0.6412	0.6551	0.669	0.6829	0.6968
8	1	1	1	1	0.6412	0.6551	0.669	0.6829	0.6968	0.7107
9	1	1	1	0.6412	0.6551	0.669	0.6829	0.6968	0.7107	0.7245
10	1	1	0.6412	0.6551	0.669	0.6829	0.6968	0.7107	0.7245	0.7384

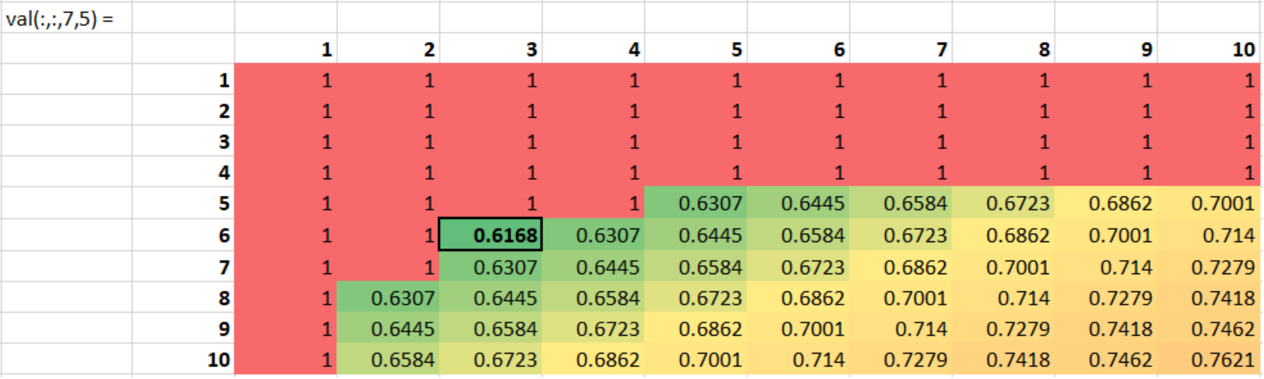
Figure B.5: Matrix results: PV multiplier 5



val(:,:,6,5) =

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	1	1	0.6429	0.6568	0.6707	0.6845
6	1	1	1	1	0.629	0.6429	0.6568	0.6707	0.6845	0.6984
7	1	1	1	0.629	0.6429	0.6568	0.6707	0.6845	0.6984	0.7123
8	1	1	0.629	0.6429	0.6568	0.6707	0.6845	0.6984	0.7123	0.7262
9	1	1	0.6429	0.6568	0.6707	0.6845	0.6984	0.7123	0.7262	0.7401
10	1	1	0.6568	0.6707	0.6845	0.6984	0.7123	0.7262	0.7401	0.751

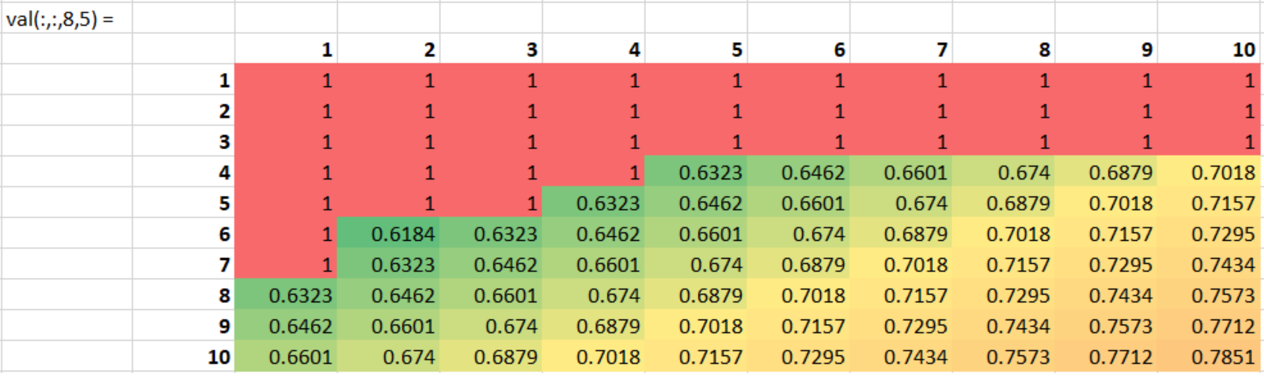
Figure B.6: Matrix results: PV multiplier 6



val(:,:,7,5) =

	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	1	1	1	1	1	1
5	1	1	1	1	0.6307	0.6445	0.6584	0.6723	0.6862	0.7001
6	1	1	**0.6168**	0.6307	0.6445	0.6584	0.6723	0.6862	0.7001	0.714
7	1	1	0.6307	0.6445	0.6584	0.6723	0.6862	0.7001	0.714	0.7279
8	1	0.6307	0.6445	0.6584	0.6723	0.6862	0.7001	0.714	0.7279	0.7418
9	1	0.6445	0.6584	0.6723	0.6862	0.7001	0.714	0.7279	0.7418	0.7462
10	1	0.6584	0.6723	0.6862	0.7001	0.714	0.7279	0.7418	0.7462	0.7621

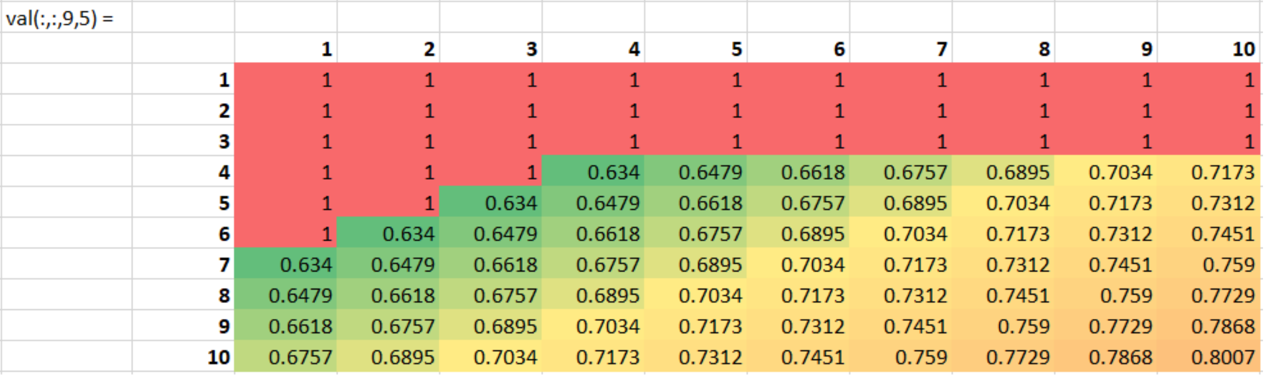
Figure B.7: Matrix results: PV multiplier 7



val(:,:,8,5) =

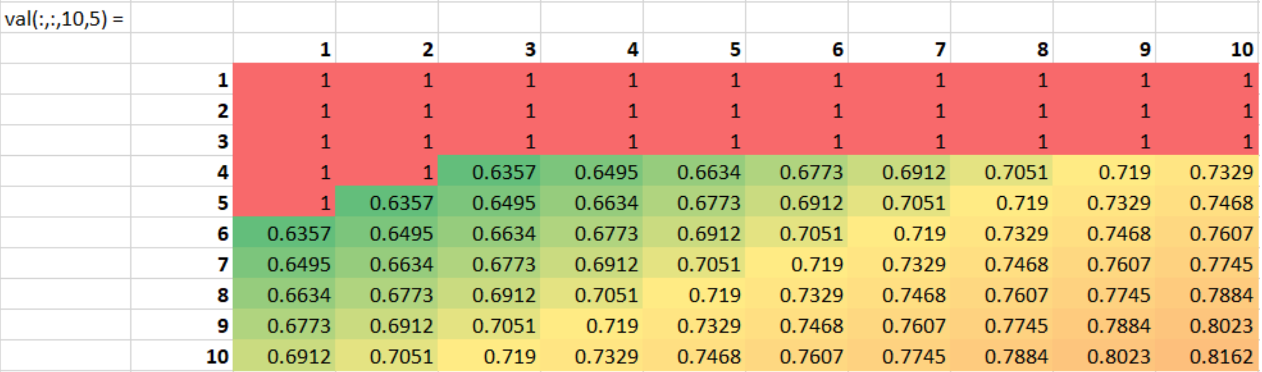
	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	1	0.6323	0.6462	0.6601	0.674	0.6879	0.7018
5	1	1	1	0.6323	0.6462	0.6601	0.674	0.6879	0.7018	0.7157
6	1	0.6184	0.6323	0.6462	0.6601	0.674	0.6879	0.7018	0.7157	0.7295
7	1	0.6323	0.6462	0.6601	0.674	0.6879	0.7018	0.7157	0.7295	0.7434
8	0.6323	0.6462	0.6601	0.674	0.6879	0.7018	0.7157	0.7295	0.7434	0.7573
9	0.6462	0.6601	0.674	0.6879	0.7018	0.7157	0.7295	0.7434	0.7573	0.7712
10	0.6601	0.674	0.6879	0.7018	0.7157	0.7295	0.7434	0.7573	0.7712	0.7851

Figure B.8: Matrix results: PV multiplier 8



val(:,:,9,5) =	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	1	0.634	0.6479	0.6618	0.6757	0.6895	0.7034	0.7173
5	1	1	0.634	0.6479	0.6618	0.6757	0.6895	0.7034	0.7173	0.7312
6	1	0.634	0.6479	0.6618	0.6757	0.6895	0.7034	0.7173	0.7312	0.7451
7	0.634	0.6479	0.6618	0.6757	0.6895	0.7034	0.7173	0.7312	0.7451	0.759
8	0.6479	0.6618	0.6757	0.6895	0.7034	0.7173	0.7312	0.7451	0.759	0.7729
9	0.6618	0.6757	0.6895	0.7034	0.7173	0.7312	0.7451	0.759	0.7729	0.7868
10	0.6757	0.6895	0.7034	0.7173	0.7312	0.7451	0.759	0.7729	0.7868	0.8007

Figure B.9: Matrix results: PV multiplier 9



val(:,:,10,5) =	1	2	3	4	5	6	7	8	9	10
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1	1	1
4	1	1	0.6357	0.6495	0.6634	0.6773	0.6912	0.7051	0.719	0.7329
5	1	0.6357	0.6495	0.6634	0.6773	0.6912	0.7051	0.719	0.7329	0.7468
6	0.6357	0.6495	0.6634	0.6773	0.6912	0.7051	0.719	0.7329	0.7468	0.7607
7	0.6495	0.6634	0.6773	0.6912	0.7051	0.719	0.7329	0.7468	0.7607	0.7745
8	0.6634	0.6773	0.6912	0.7051	0.719	0.7329	0.7468	0.7607	0.7745	0.7884
9	0.6773	0.6912	0.7051	0.719	0.7329	0.7468	0.7607	0.7745	0.7884	0.8023
10	0.6912	0.7051	0.719	0.7329	0.7468	0.7607	0.7745	0.7884	0.8023	0.8162

Figure B.10: Matrix results: PV multiplier 10