# The Financial Impact of Decentralized Energy Systems on Households

## A case study: The Green Village

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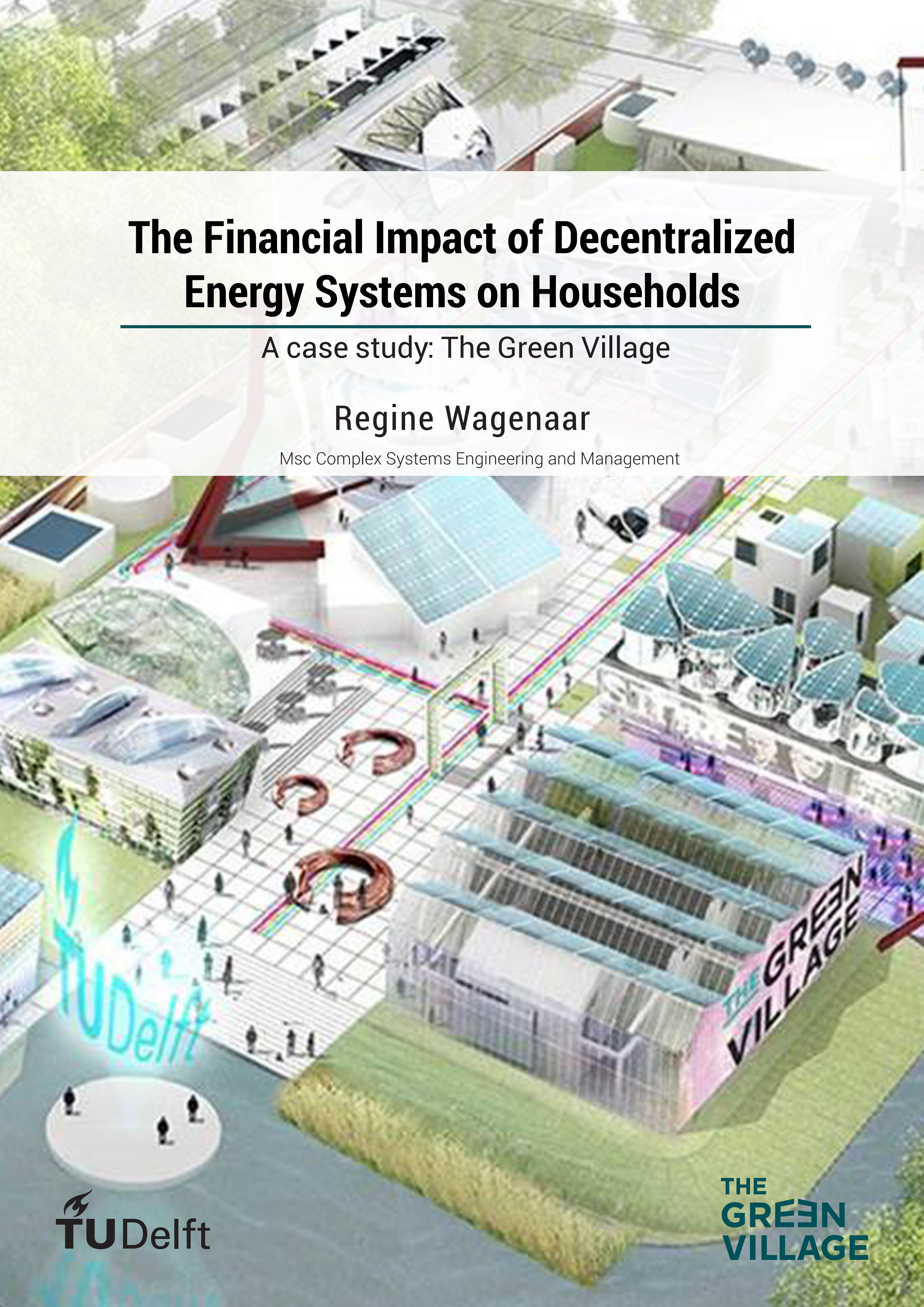
Msc Complex Systems Engineering and Management



# The Financial Impact of Decentralised Energy Systems on Households

## A case study: The Green Village

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# Preface

This thesis is my final work as a student at the TU Delft to obtain my master's degree in Complex Systems Engineering and Management. I started my time in Delft with a bachelor's in Architecture, Urbanism and Building Sciences. In 2022, I am ending my time in Delft with a research that combines these two studies perfectly.

I would like to thank my graduation committee. To Zofia Lukszo, thank you for giving me the opportunity to do my research at the Green Village. To Stefan Pfenninger, thank you for being my first supervisor and vice versa, letting me be your first graduate student at the TU Delft. To Özge Okur, thank you for your feedback in all the meetings with had over the past months. You were always able to ask the right questions to improve my work. Last but not least, to Na Li, many thanks for helping me structure my research and for all the times we sat together. You managed to make time for me on short notice and was always willing to read my chapters.

Besides my graduation committee, I would like to thank Joep van der Weijden. Although we did not often sit together, the times we did were very useful. Besides the substantive discussions about my research, you also helped me with my thesis process by sharing your own experiences when you were graduating. In addition, I want to thank my family and friends, who were supporting me during this graduation project, but more important, who made sure I also got enough distraction from my graduation project.

*Regine Wagenaar*
*Delft, July 2022*

# Summary

The need to reduce $CO_2$ emissions leads to changes in the current centralised energy system, relying on conventional fossil fuel-based power plants. The shift toward a 100% renewable energy system is associated with the emerging Decentralised Energy Systems (DESs) in the built environment due to the increasing amount of Distributed Energy Resources (DERs). Moreover, since 2016, the right to produce and trade energy is also given to small energy communities. With this right, citizens can comply with their desire to be more independent from the central grid. This independency leads to the concept of autonomous energy systems, where the DES operates without importing energy from the main grid. These changes have a significant impact on households and result in challenges. In the 100% renewable-based DES, the generation is intermittent. Therefore storage is needed to balance the energy supply and demand. In addition, the natural gas as heat supply must be replaced by a renewable energy source (RES). In literature, the relevance of research to self-sufficient DESs is also apparent. However, there is a lack of focus on the impact on households. The people working at the Green Village, a field lab for developments in the built environment, have also acknowledged this knowledge gap. Therefore, the main research question addressed in this thesis is:

*”What is the financial impact of a small scale decentralised energy system on households?”*

This question is answered by designing potential DES configurations. A systematic heuristic design method is established to determine the needed capacities of the components for self-sufficient DESs. The sizing method aims for 100% self-sufficiency, however, it is a heuristic sizing method. Subsequently, the system’s technical performance and financial performance are analysed. A case study of the Green Village is used to gain insights into the financial impact of a small scale autonomous decentralised energy system on households in the Netherlands.

Four DESs are studied: |1| a hydrogen-based fully electrified energy system, |2| a hydrogen-based hybrid energy system without a fuel cell, |3| a hydrogen-based hybrid energy system with a fuel cell, and |4| a compressed air energy storage-based fully electrified energy system. In addition, five different demand cases are used: single apartment, corner house, terraced house, apartment community, and terraced house community. These demand cases differ with respect to housing type and scale.

The technical performance analysis looks at the reliability and the energetical performance of the DESs for each demand case. The reliability of the system is analysed by looking at the loss of load probability and the failed energy ratio. The energetical performance is analysed with the dump ratio, the storage ratios and the system efficiencies. From the technical analysis, it is concluded that all the DESs are operating 100% autonomous, except for the hydrogen-based hybrid energy system with a fuel cell. However, this system has the best energetical performance. In addition, improvements can be made to the sizing of the PV panels and the storage capacities.

The financial impact is determined by calculating a consumer energy price. This price is used to compare the DESs with the current energy prices in the Netherlands. From the financial outcomes, it is concluded that these 100% autonomous DESs are not competitive with the current energy system. However, the cheapest configurations are the hydrogen-based hybrid energy system with a fuel cell and

compressed air energy system-based fully electrified energy system. For the compressed air energy-based system, this is due to the cheaper components than the hydrogen-based energy systems. The hydrogen-based hybrid energy system with fuel cells is cheaper than the other two hydrogen-based configurations as the components are better sized. Furthermore, three main insights are obtained from these outcomes:

- A community scale DES is cheaper than a single household scale DES. Due to the combination of different households with varying consumption behaviours, the productivity of the DES increases, resulting in lower costs per kWh.
- A grid connection is preferred over an off-grid DES. In that case, the design is not based on the peak demand but on a lower value. This results in higher productivity of the system and lower consumer energy prices.
- The reduction of investment costs of the components contributes to a lower consumer energy price. However, this reduction of investment costs has less impact than the previously mentioned insights.

Thus, based on this study, the compressed air energy storage-based fully electrified energy system is the best configuration looking at the technical and financial results. In addition, a DES design based on an apartment community scale and with a grid connection results in the least negative financial impact on households.

From this research, it is recommended to start with adopting apartment communities and find an optimal autonomy level to design the capacities of the components. In addition, based on this research, a configuration is advised that is not based on hydrogen. However, in the Netherlands, the political preference is going towards hydrogen. In that case, the components, used in a hydrogen based energy system, must be less expensive for households to be more attractive.

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# Nomenclature

## Abbreviations

| | |
|---|---|
| ASHP | Air-source heat pump |
| CAES-FEES | CAES-based fully electric energy system |
| CEP | Consumer Energy Price |
| CF | Capacity factor |
| CHP | Combined Heat and Power |
| COP | Coefficient of Performance |
| DERs | Distributed energy resources |
| DES | Decentralised Energy System |
| DHW | Domestic Hot Water |
| DoD | Depth of Discharge |
| DR | Dump ratio |
| DSO | Distribution System Operator |
| DSO | Transmission System Operator |
| EC | External Combustion |
| EF | Electricity fraction |
| FER | Failed energy ratio |
| GSHP | Ground-Source Heat Pump |
| $H_2$-FEES | Hydrogen-based fully electric energy system |
| $H_2$-HES | Hydrogen-based hybrid energy system |
| HF | Heat fraction |
| ICE | Internal Combustion Engines |
| ICES | Integrated community energy system |
| KPI | Key Performance Indicator |
| LCOE | Levelized Costs of Energy |
| $LiFePO_4$ | Lithium iron phosphate |
| LLP | Loss of load probability |
| MMS | Method of Manufactured Solutions |
| MOFC | Molten Carbonate Fuel Cell |
| PEMFC | Proton-Exchange Membrane fuel cell |
| PHS | Pumped Hydro Storage |
| RES | Renewable Energy Sources |
| RFB | Redox Flow Battery |
| SE | Stirling Engine |
| SE | System Efficiency |
| SI | Spark Ignation |
| SoC | State of Charge |
| SOFC | Solid Oxide Fuel Cell |
| SR | Storage ratio |
| TGV | The Green Village |
| WSHP | Water-source heat pump |
| P | Capacity [kW] |

## Acronyms

| | |
|---|---|
| CAES | Compressed Air Energy Storage |
| NIMBY | Not In My BackYard |
| SMES | Superconducting Magnetic Energy Storage |

## Other symbols

| | |
|---|---|
| $\eta$ | Efficiency [-] |
| $F$ | Fuel costs [€/year] |
| $M$ | Maintenance costs [€/year] |

| | |
|---|---|
| r | Discount rate [%] |
| SF | Sizing factor [-] |

**Physicals symbols**

| | |
|---|---|
| $m$ | mass [kg] |
| c | calorific value [kWh/kg] |
| E | Energy [kWh] |
| P | Power [kW] |
| Q | Heat [kWh] |
| t | time step [h] |

**Subscripts**

| | |
|---|---|
| ave | Average |
| bat | Battery |
| com,air | Air compressor |
| com,$H_2$ | Hydrogen compressor |
| D | Demand |
| d | Day |
| $d_{year}$ | Total amount of days in one year |
| DH32 | DreamHus 32 |
| el | Electricity |
| Ele | Electrolyser |
| FC | Fuel cells |
| g | Generation |
| gen | Generator |
| hb | Hydrogen boiler |
| HP | Heat pump |
| max | Maximum value |
| min | Minimum value |
| peak | Peak demand |
| PV | Photovoltaics |
| Q | Heat |
| s | Summer (t=2197 till t = 6588) |
| Ts | Time steps during summer |
| Tw | Time steps during winter |
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# 1

# Introduction

On December 11, 2019, a goal to minimise climate change and adapt to it was presented by Ursula von der Leyen, president of the European Commission (European Commission, 2019). In this so-called 'Green Deal', the European Commission commits herself to Europe being the first climate-neutral continent in 2050. To achieve this goal, the European Union must reduce $CO_2$ emissions. Various sectors contribute to these emissions. Among them are transport, industry, agriculture, and residential/commercial. Depending on the sector, solutions to reduce these emissions must be designed and implemented. The $CO_2$ emission in the past three decades for each of these sectors, depicted in fig. 1.1, show different trends.

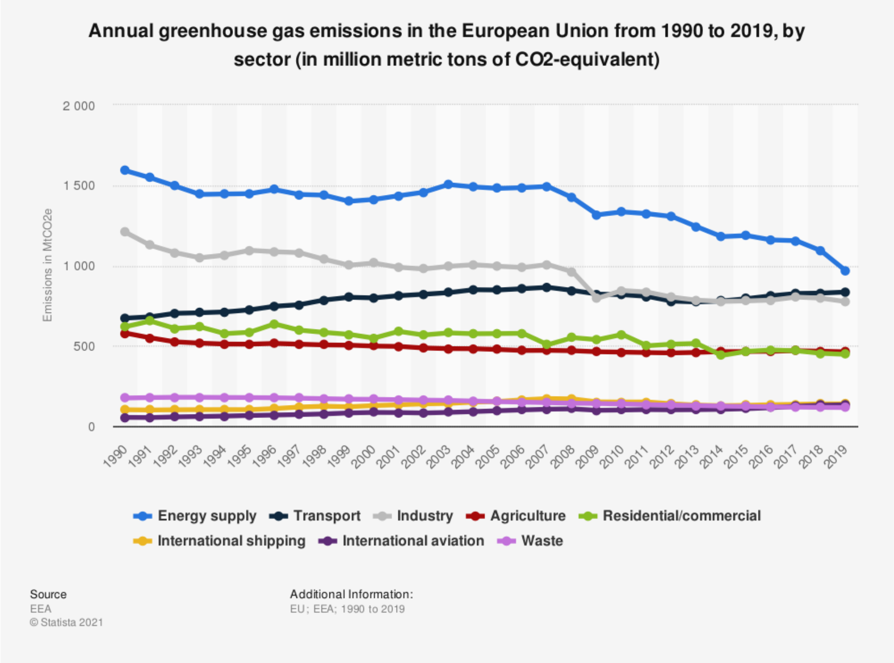


Figure 1.1: Annual $CO_2$ emissions per sector (Statista, 2021)

### The built environment

The built environment is responsible for a large part of the $CO_2$ emissions. The first steps are taken, resulting in a reduction of 28%. Just as in the other sectors, the built environment is complex to change as multiple actors are involved with different stakes. However, the residential built environment is perceived as even more complex as it also concerns citizens who must adapt to new systems. Moreover, there is a high interdependency within neighbourhoods, and there are relatively high costs associated with the adaptation.

By changing the energy system towards 100% renewable energy, a shift from a centralised energy system to multiple decentralised energy systems (DESs) will occur (Murray et al., 2018). A DES is an energy system where the source of the energy generation is relatively close to the energy consumption (Rafea et al., 2017). So, the energy produced at location A will also be consumed at location A instead of being transported to location B. The development of DESs is emerging due to the increasing amount of (renewable) distributed energy resources (DERs). Besides the technical developments, there is also a sociopolitical shift toward DESs. Since 2016 small energy communities have had the right to produce and trade energy (Bauwens et al., 2022). Moreover, citizens desire to be more independent from the central market and play a more active role themselves (Weinand et al., 2020). This potential development toward sustainable autonomous DESs will come with challenges.

These self-sufficient energy communities encounter the problem of matching demand and supply. The current energy system, dominated by conventional fossil fuel-based power plants, can operate without storage as the system operator can control the energy output of those power plants. However, the future energy system will be dependent on variable renewable energy sources (RESs), such as solar and wind energy (Stančin et al., 2020). These energy sources only generate power when the weather conditions are sufficient. Therefore, these RESs are unpredictable and non-dispatchable. To solve this problem, storage is crucial.

Finally, if a DESs is entirely sustainable, there must be a change in how to satisfy the heat demand. Currently, around 92% of the buildings in the Dutch built environment are dependent on burning natural gas ($CH_4$) for their heat consumption (Centraal Bureau voor de Statistiek, 2021). During that process, $CO_2$ is emitted, contributing to global warming. Green energy sources must replace natural gas to make the energy system 100% renewable.

So, the changes in the energy system come with challenges. These challenges are social relevant because there is an urgent need to replace fossil fuel-based power plants to minimise global warming. In addition, all households are being affected by these changes.

These developments will change the role of the different actors in the energy system. Currently, the energy system is operated centrally. The Transmission System Operator (TSO) is in charge of the transmission network (high voltage grid / large gas pipelines), and a Distribution System Operator (DSO) is in charge of the distribution network (medium/low voltage grid / smaller gas pipelines). Energy producers use the network to transfer electricity or gas to the consumers. Subsequently, the consumer pays for the energy consumption. In future energy systems, decentralised energy generation using small scale RESs, such as solar panels and district heating, will be more common. This shift results in decentralised energy consumption as well.

## 1.1. Background information

### 1.1.1. Energy Systems

An energy system is defined by Eriksson and Gray (2017) as a system that collects energy from multiple sources and distributes it among the consumers using different types of energy carriers. A division can be made between the energy supply and demand sides within this definition.

### Energy demand side

The energy demand can be divided into two subcategories: energy in the form of electricity (kW$_e$) and energy in the form of heat (kW$_h$).

In the residential sector, electricity demand is caused by lighting and appliances such as a TV and a fridge. The heat demand is coming from space heating, Domestic Hot Water (DHW), and cooking. According to an analysis performed by International Energy Agency (2020), the division between heat and electrical consumption is respectively 84% and 16% in the Dutch residential energy system. In other words, the heat demand dominates the energy demand in the residential sector.

### Energy supply side

The energy supply side consists of technical subsystems that can generate energy. Within these technical subsystems, a threefold can be made. Some technologies deliver electricity, others deliver heat, and some subsystems provide both electricity and heat, the so-called Combined Heat and Power (CHP) systems.

**Heat supply** Heat subsystems are technologies that can deliver heat to a building. Heat can have multiple carriers. The Dutch residential heat supply system currently relies on natural gas ($CH_4$). 92% of the residential buildings are connected to this system (Centraal Bureau voor de Statistiek, 2021). Natural gas must be replaced by RESs and other heating sources and carriers in future energy systems.

**Electricity supply** Electricity subsystems are technologies that can deliver power to a grid in the form of electrons, unlike the heat supply systems, which can have multiple carriers. Therefore, the electricity grid must be balanced. Otherwise, a blackout occurs. Within the Netherlands, the grid reliability is very high. According to TenneT (n.d.), the grid operates 99.99% of the time in a year.

**CHP systems** CHP systems are subsystems that produce heat and power from one single energy stream. When applied for residential use, the capacity should be between 5 and 100 kWh$_e$ (Bianchi et al., 2011). According to Murugan and Horák (2016), these small scale CHP systems are very promising in DESs. Especially combined with residential use, CHP systems that can deliver heat and power have an efficiency of around 80%, compared to 35% when not both heat and power are used (Onovwiona & Ugursal, 2006).

### Energy balance

The balance of the energy system is crucial for the system's performance. As mentioned in the introduction, the current energy system primarily relies on dispatchable power plants running on fossil fuels. These power plants can be regulated. However, a change is emerging towards more RESs, that generate electricity, and are variable and non-dispatchable. This results in a mismatch between energy supply and energy demand. On a daily scale, this mismatch is commonly referred to as the duck curve problem. An average demand curve is low during the night, as people are asleep, starts to increase when people wake up in the morning, and the peak demand is during the evening. Due to the installation of photovoltaic (PV) panels, the demand during the middle of the day can be met with solar irradiation (Rahman et al., 2020). Figure 1.2 visualises the duck curve problem, where the increasing amount of installed solar panels is included.

Besides the daily imbalance, there is also a seasonal imbalance. The outside temperature significantly influences the heat demand in Dutch residential buildings. This results in a higher heat demand in the winter than during the summer. This can be seen in typical load profiles in the Dutch built environment. In addition, looking at the solar generation during a year, it can be concluded that during the summer, the energy generation is higher than during the winter period (Converse, 2012). This means a higher energy demand during the winter, while there is lower energy generation when using PV panels. This results in a seasonal imbalance.

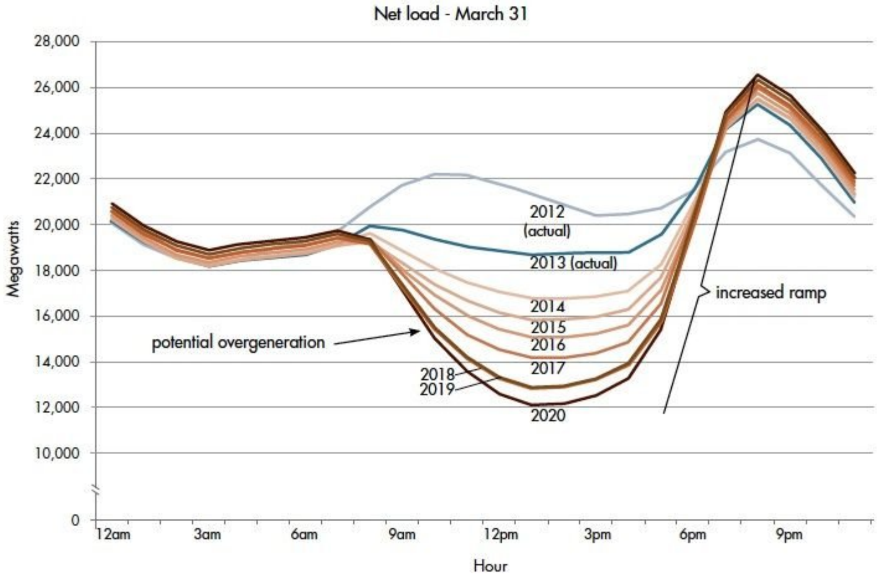


Figure 1.2: Daily energy imbalance with the increasing amount of installed PV panels: ”Duck curve” (Rahman et al., 2020)

### Actors in the energy market

The Dutch energy market is divided into two markets: electricity and gas markets. Both these energy markets are fragmented and partly regulated by the government to prevent high energy prices and ensure the quality of the network is guaranteed. In the Dutch energy market, a division can be made between three different actors:

- Energy producers
- System operators
- Consumers

**Energy producers** Energy producers are the actors who generate the energy and sell it to the consumer. They own the power plants and are profit driven. Therefore, the energy producers offer their energy at a specific price to the market. In the Dutch energy system, there are multiple energy producers. This stimulates the competition between the producers, resulting in lower prices.

**System operators** System operators are responsible for the energy network. There are two scales of system operators; the TSO and the DSO. In the Netherlands, there are two TSOs, one for the gas network and the other for the electricity network. The TSO is responsible for three tasks:

1. Balance the grid
2. Transport energy across the network
3. Manage import

The grid balance is essential, especially in the electricity network. Gas can easily be stored, while electricity is difficult to store. In addition, the TSO from the electricity network is not allowed to store electricity as this influences the energy price. The second task is based on the operation and management of the network. For the electricity network, the TSO uses the high voltage grid to minimise the energy losses during transport. The TSO in the natural gas network uses pipelines. Their task is to ensure enough grid capacity to prevent congestion. Their last job is to ensure the electricity or gas can be implemented in the grid.

The TSO is monopolised and partly owned by the government. Therefore, their goal is not to make a high profit but to ensure the network operates at the desired level.
The DSO is responsible for the distribution network, which is the local, small scale network. Mostly consumers are connected to the distribution network, but some small generators are also connected to the distribution network directly.

**Consumers** A consumer in an energy system is the actor who consumes the energy. In developed countries, energy supply is perceived as a service that is always available and also at an affordable price. Therefore, the consumer is used to getting the needed energy at any time. Due to the increasing amount of PV panels on top of residential buildings owned by the homeowners, the consumer can produce their own power. In Engelken et al. (2016) and Parag and Sovacool (2016) the prosumer is defined as an actor in the energy system that both consumes and produces electricity. Prosumers often have a storage option included in their energy system, as their load profile is mostly not the same as the generation profile. This makes a prosumer energy system suitable for energy systems with a high penetration of variable RESs.

## 1.2. Literature overview

Substantial research has already been done in the field of DESs and the accompanying challenges, emerging changes and grid autonomy. In appendix A, it is explained how the articles are found and selected and a complete overview of all the articles is included. This section discusses the current literature.

First of all, the question of ”what are DESs” is addressed in literature. In these articles the term ”energy communities” is frequently discussed. Bauwens et al. (2022) looks into the definition of ”energy community” and includes synonyms to describe the concept as the term is not completely unambiguous. Bahret and Eltrop (2021) approach the community definition based on scale. The scale should be determined by looking at smart energy neighbourhoods. Gui and MacGill (2018) discuss different types of ”Clean Energy Communities”, with also a focus on scale. In addition, de São José et al. (2021) maps out the relations between actors in the energy community, including the legal side. Furthermore, Maroufmashat et al. (2016) looks into the relation between energy communities from an economic perspective, with the focus on energy trading.

Secondly, many articles focus on understanding why DESs are emerging. According to Engelken et al. (2016) self-sufficiency is an important aspect, as people strive for independence from private companies. This self-sufficiency is also researched in an article of Gstöhl and Pfenninger (2020). Mckenna et al. (2017) focus on the scale of this desired autonomy and the accompanied issues. In this research, the DES is not completely renewable. The key issues accompanied within self-sufficient sustainable energy grids is reviewed by Rae and Bradley (2012). Important insights are the political challenges and the social impact.

Related to DESs, is the smart grid. The developments of the smart grid is discussed by Majeed Butt et al. (2021). For further research, it is recommended to look into renewable energy forecasting, interoperability of networks, economics, and automation of the system. These concepts focus on influencing the consumption pattern of consumers to flatten the peak load demand, also referred to as demand-side response or demand-side management.

The technical side of demand-side response is tackled in Kolahan et al. (2021) with the optimisation of energy consumption. An economic side is discussed by Scheller et al. (2018) with research into the effect of variable tariffs. Calver and Simcock (2021) discuss the concept of energy justice. They increase the understanding of barriers to demand side-response for low-income households. Davarzani et al. (2021) discusses the recent developments in demand-side response and also acknowledges the need for further research. One of the knowledge gaps they identify is the role of consumers. The article of Perger et al. (2021) looks into this knowledge gap, by a research into the willingness-to-pay concerning PV energy trading. Parag and Sovacool (2016) looks at how prosumers can participate in the market with different market designs and trading options. In addition, with the role of the prosumer, research is also done into cost allocation in energy communities by Li, Hakvoort, et al. (2021) and M. B. Roberts et al. (2022). From both studies, it is clear that there must be more research into implementing different tariff types to see which methods are accepted by citizens. This social acceptance is further specified in Li, Hakvoort, et al. (2021) in a follow-up article in the same bigger research.

Other scholars looked into the DESs configurations. First of all, Karunathilake et al. (2019) answers the question on how to design a renewable DES configuration. The combination of potential renewable energy technologies and accompanied costs should be used to come to the right configuration, taking into account optimisation criteria. These criteria contain technical aspects and economic aspects. These criteria are also used to analyse specific configurations.

Khalid et al. (2016), Peláez-Peláez et al. (2021), S. Singh et al. (2020), and Song et al. (2021) have their focus on the economic optimisation of one single configuration. The article of Milan et al. (2012) is the only one found that compares the costs of different configurations. The technical research is mostly done into hydrogen systems, where the role of hydrogen as energy vector is researched. Eriksson and Gray (2017) and Fonseca et al. (2019) make an overview of the current research and others look into specific cases, but from a broad perspective (Arsalis & Georghiou, 2018; Gstöhl & Pfenninger, 2020; Little et al., 2007; Maroufmashat et al., 2016). In addition, Murray et al. (2018) compared hydrogen storage with other long term storage options, both from technical as economic point of view. All of them mention further research. In the conclusions of Arsalis and Georghiou (2018) and Gstöhl and Pfenninger (2020), the general need for further research into this subject is stated, Eriksson and Gray (2017) mention a lack of hydrogen based models to analyse DESs and Fonseca et al. (2019) refers to a lack in research approaches focusing on different data uncertainties. Gstöhl and Pfenninger (2020) identify a follow-up research into different locations and other configurations that not only consider full electrification of the DESs.

The need for further research is clear. DESs and autonomous energy communities are currently relevant subjects to help the development of smart and renewable energy systems. Multiple scholar did research into different designs of DESs with various case studies and different approaches. However, most of them mention that additional case studies are needed. In addition, the economic studies are done from an investor side perspective, not taking into account the effect on the users.

## 1.3. The Green Village

The Green Village (TGV) is a field lab for developments in the built environment on the campus of the Delft Technical University. The field lab stimulates experiments that are not yet possible or feasible in real life due to regulations, technical barriers or high costs. With this testing site, research can be done to overcome these barriers. The people at TGV work on various innovation projects. One of these projects connects seamlessly with the challenges mentioned above. The 24/7 energy lab looks at designing an autonomous small scale energy system. The autonomous energy system design at TGV generates the needed energy with solar panels. It is based on hydrogen as an energy vector for the long term storage, and for short term storage, a battery is used. The first steps are already taken. One apartment at TGV is almost self-sufficient. The follow-up questions are related to the scale-up of the systems and the accompanying costs. The technical expertise at TGV and available data are an opportunity to do research and experiments to design a future DES.

At TGV is an extraordinary mix of residential buildings with different housing types, installed energy systems and energy labels. Figure 1.3 is a bird's-eye view of TGV, where the different buildings can be identified by name.

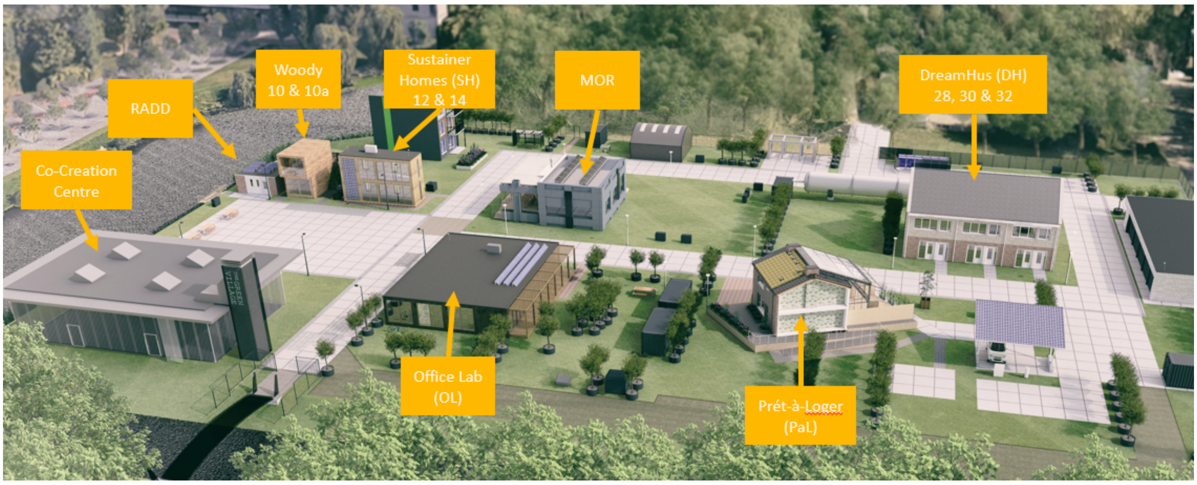


Figure 1.3: Test site: The Green Village (The Green Village, n.d.)

In total there are eight residential buildings; Woody 10 & 10a, Sustainer Homes 12 & 14, DreamHussen 28, 30 & 32, and Prêt-à-Loger. From all of these eight buildings, consumption data is collected.

## 1.4. Problem statement

The change towards DESs has a significant impact on households. Buildings need to be adapted, and a new sustainable energy system must be implemented. Technical expertise is already there, but the socio-economic focus is missing. As the energy system changes, the price people pay for their consumed energy changes as well. However, the real estate portfolio of the Dutch built environment includes a variation of houses. This means that the starting point of these houses differs, and there is not a *”one-size-fits-all”* solution for the residential sector. This means that considerations must be made on a small scale level to determine the most suitable solution. Therefore, the research question is formulated as follows:

***”What is the financial impact of a small scale decentralised energy system on households?”***

This main research question is divided into three sub-questions.

1. What are the potential energy configurations for decentralised energy systems for household scale?
2. How to design an autonomous decentralised energy system for different configurations?
3. What are potential energy costs for households with different energy system configurations at the Green Village?

The three sub-questions are the path to answering the main research question. The research approach is explained in the next part, followed by a report outline.

## 1.5. Research approach

This research aims to gain insights into the potential financial impact for households in the future when adapting to a DES. From these insights, lessons can be learned regarding a small-scale DES design. In addition, these insights can be used for further research at TGV. Furthermore, the approach applied in this research can be an example of determining the size of an energy system configuration. Subsequently, the cost calculation can be used to make an initial plan for small scale DES. A mixed-methods research approach is chosen to answer the research question *”What is the financial impact of a small scale decentralised energy system on households?”*. Both qualitative and quantitative methods are used (Johnson & Onwuegbuzie, 2007).

The qualitative data, acquired by literature and expert knowledge, is used to answer the first sub-question in this research. A literature study is performed to identify different energy technologies. In addition, expert knowledge is consulted to develop an energy system configuration that could be installed as an autonomous small scale DES.

The second sub-question is answered with a quantitative model. The sizing of the different components in the DES configuration is done based on assumptions and equations, resulting in a heuristic optimisation of the system. The size of the components only reflects the capacity size and does not take into account the physical sizing. In addition, TGV has quantitative demand data of the residential buildings on their site. This demand data is used as case study. Different demand cases are created based on different scales and different housing types. Afterwards, technical analyses are performed to see if the sizing of the components results in a DES design that operates autonomous and is not oversized. The answer to sub-question three is based on the financial analysis. The technical energy system's performance is analysed using a simulation in an own built Python model. For the financial analysis, the total costs for the energy system are calculated, and a price per kWh is obtained. This value is used to compare the different DESs. To give an answer on the main research question, the DESs are compared with the Dutch energy system prices.

## 1.6. Report outline

In chapter 2, the first sub-question is addressed. The rationale of designing different DES configuration is discussed, and at the end of this chapter, potential DES configurations are defined and explained. In chapter 3, the model is described. The first part explains the sizing process for each of the components. The second part goes into technical performance indicators. The third part is about the financial performance indicator. In chapter 4, all the input data and assumptions used in the model are stated and described. In chapter 5, the case studies are performed. The results are presented, followed by a discussion. To finalise the report, chapter 6 concludes the research as a whole, where it is finished with some final recommendations. In fig. 1.4 the research flow diagram for this research is shown.

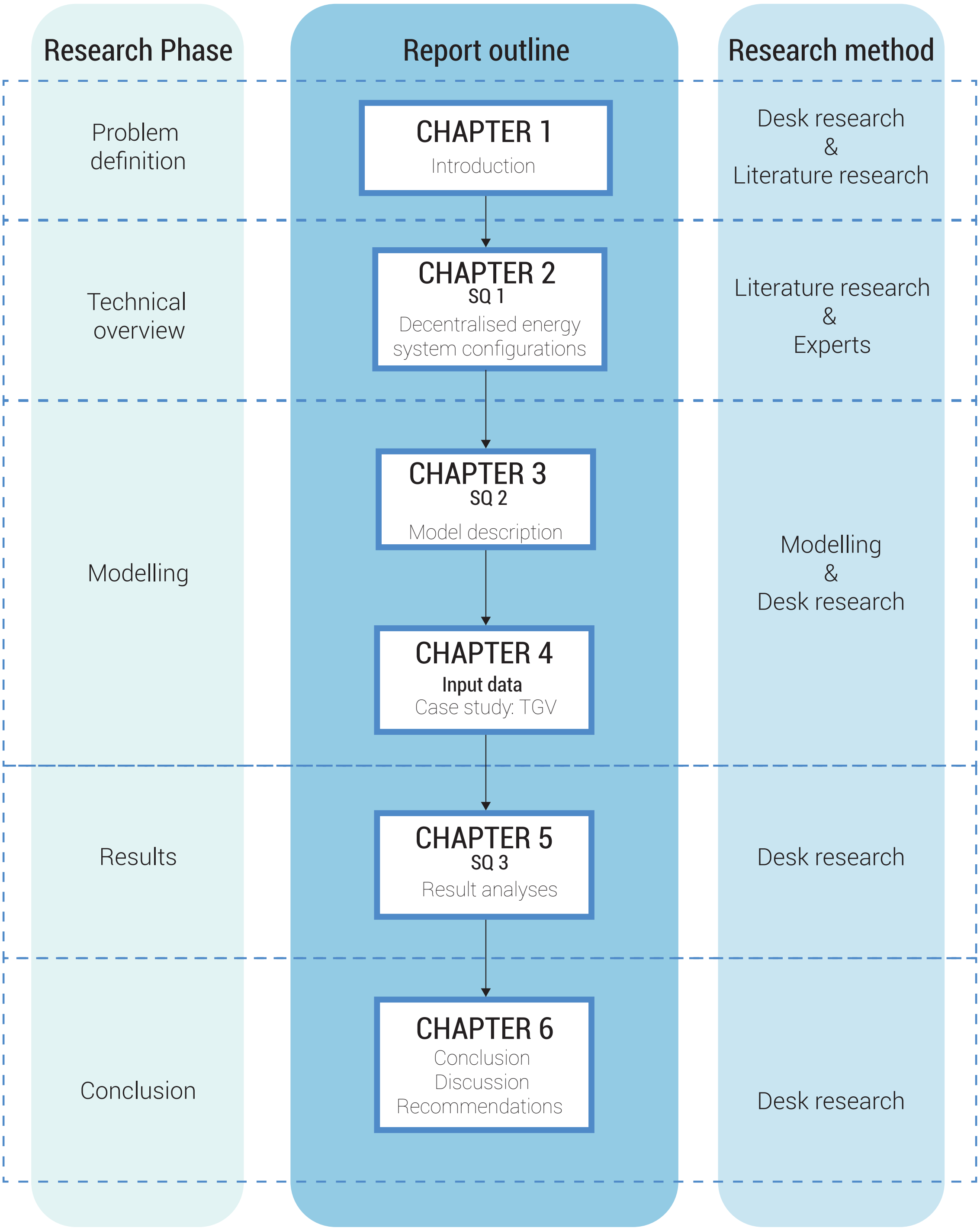


Figure 1.4: Research flow diagram

# 2

# Decentralised energy system configurations

In this chapter, four different potential DES configurations are defined based on a literature study and expert knowledge. These DES configurations are combinations of different technologies that are able to supply the energy demand of one or more households. Firstly, the rationale behind the decision for these four systems is explained in section 2.1. Subsequently, the four designs are described one by one, discussing the components and control strategy in section 2.2, section 2.3, section 2.4, and section 2.5.

## 2.1. Selection rationale

The selection of components to make DES configurations is based on a three starting points. First of all, a DES is an energy system where the source of the energy generation is relatively close to the energy consumption, and only the distribution network is needed to transport energy (Rafea et al., 2017), therefore not all power plants are suitable in a DES. An overview of applicable technologies is explained and discussed in appendix B.

Secondly, in this thesis the DES is autonomous. If a DES is 100% self-sufficient, the system can operate without connecting to the main grid and all the energy is locally generated. Therefore, a DES must comply with the total energy demand of one or more households. Different technologies are needed to fulfil this demand. Moreover, various components can be used to meet this demand.

Thirdly, the DES configurations in this thesis are based on the Dutch environment. For Dutch residents, the heat demand is the largest contribution to energy consumption.

To design a DES configuration, the heating system is determined at first, based on the contribution of heat demand. In addition, Due to the large share of heat demand, a combination of separate heat and power subsystems, including a storage facility, is chosen. Combined heat and power (CHP) systems are not considered, as their primary focus is on electricity, where heat is a bypass product. From the heating subsystems, either a heat pump or a boiler must be installed. For an electricity supply system, PV panels are more suitable for small-scale DES than wind turbines. Therefore solar panels are used in the DES design. Concerning storage, there is a differentiation between short-term storage and long-term storage. The Dutch government promotes hydrogen technologies. Therefore, hydrogen is used as a long term storage carrier. However, besides hydrogen, compressed air energy storage (CAES) is also a suitable option. Moreover, the design of hydrogen storage and CAES is quite similar. Instead of hydrogen, the air is being compressed, resulting in stored energy as well. For short-term storage, a battery is most commonly used. Based on this information, the following four different DES configurations are designed:

1. Hydrogen-based fully electric energy system ($H_2$-FEES)
2. Hydrogen-based hybrid energy system without fuel cells ($H_2$-HES)
3. Hydrogen-based hybrid energy system with fuel cells ($H_2$-HES-FC)
4. Compressed air energy storage-based fully electric energy system (CAES-FEES)

The four systems all rely on solar energy and short-term electricity storage in batteries. The PV panels are responsible for electricity generation. The batteries are needed to solve the intraday imbalance. The first design is the $H_2$-FEES. This configuration is also implemented at TGV. This fully electric system is based on hydrogen as an energy vector, where hydrogen is produced to store the energy and when it is needed, it will be converted back to electricity. Based on the first DES design, the second two options are designed. In the second design, $H_2$-HES, the hydrogen is directly used in the system as fuel for heat. The third design combines the first two designs. The hydrogen is used as storage for electricity and also directly as a heat source. The fourth design, CAES-FEES, is also a variation on the first design. In the CAES-FEES, the hydrogen storage is replaced by a CAES solution. Figure 2.1 shows the relationship between the different designs.

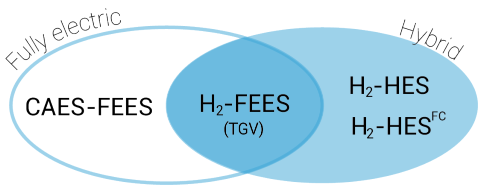


Figure 2.1: A visualisation of the relationship between the decentralised energy systems configurations

## 2.2. A hydrogen-based fully electrified energy system

The $H_2$-FEES configuration is a fully electrified energy system based on hydrogen. The hydrogen is produced with an electrolyser and can be stored long-term and therefore gives a solution for seasonal imbalance. Subsequently, fuel cells convert the hydrogen back to electricity, where it is used to comply with the electricity and heat demand. Figure 2.2 displays a simplified overview of the energy system configuration. The upper two energy flows are the same in each configuration. The bottom energy flow represents the flow via the electrolyser, the compressor, the storage tanks, and the fuel cells. This configuration is already applied at TGV.

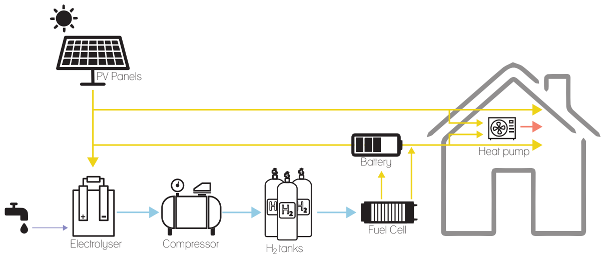


Figure 2.2: A simplified overview of a hydrogen-based fully electrified energy system

The simplified control strategy for the $H_2$-FEES is shown in fig. 2.3. In this figure, the energy flows are depicted. The electricity generated with the solar panels will first go directly to the household. The energy surplus is stored in the battery or the hydrogen tanks if the battery is full. If there is not enough solar energy, the energy demand is met with the battery or electricity from the hydrogen tanks. In addition, there is also a flow from the hydrogen storage to the battery to charge the battery, as the battery is better at solving short-term electricity shortages, due to the long ramping time of the fuel cells.

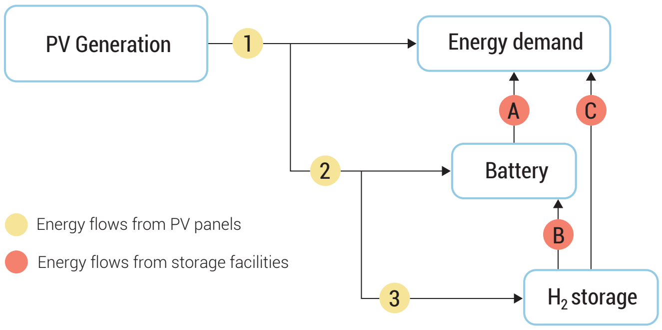


Figure 2.3: A simplified control strategy of a hydrogen-based fully electrified energy system

A more extensive control strategy for the $H_2$-FEES is shown in fig. 2.4. On the upper left side of the figure ’start’ is found. Per time step this flowchart is followed. The first question is whether there is an energy surplus. If this is the case, the energy demand is met with the solar PV generation for a specific time step. Subsequently, the battery can be charged with the available electricity from the PV generation if the battery’s state of charge(SoC) is not already at its maximum. The follow-up question is if there is still electricity left and if there is space in the hydrogen tanks to store the hydrogen produced with an electrolyser. Otherwise, the energy must be dumped.

On the other side, if there is no energy surplus, there is an energy shortage, assuming that PV generation and energy demand are never completely equal. In this case, the energy demand is not met solely with PV generation. If the fuel cells are on, the fuel cells can generate electricity to deliver additional electricity to fulfil the energy demand. However, when the capacity is not sufficient enough to satisfy the total electricity shortage, the battery discharges as well, if electricity is stored in the battery. If there is enough electricity stored in the battery, the energy demand is met, however, when there is not enough electricity stored, the energy demand is not met. If the fuel cells are off, the battery is being discharged to solve the energy shortage. If there is not enough electricity stored, the fuel cells can operate at half of their capacity. If this capacity is large enough, the energy shortage is solved, otherwise, the energy demand is not met. In addition, the fuel cells are also responsible to ensure enough energy is stored in the battery. If the fuel cell is not yet operating, the middle flow from fig. 2.4 is followed. First, it checks if the SoC from the battery is at a certain percentage. If the battery is below that point, it checks if there is enough hydrogen stored. If this is also true, the fuel cells generate electricity for the battery.

At the end of each flow, there can be either dumped energy or failed energy. Dumped energy occurs when energy is left that can not be stored in the battery or the hydrogen tanks. Failed energy is the part of the energy demand that could not be met with the battery or fuel cells.

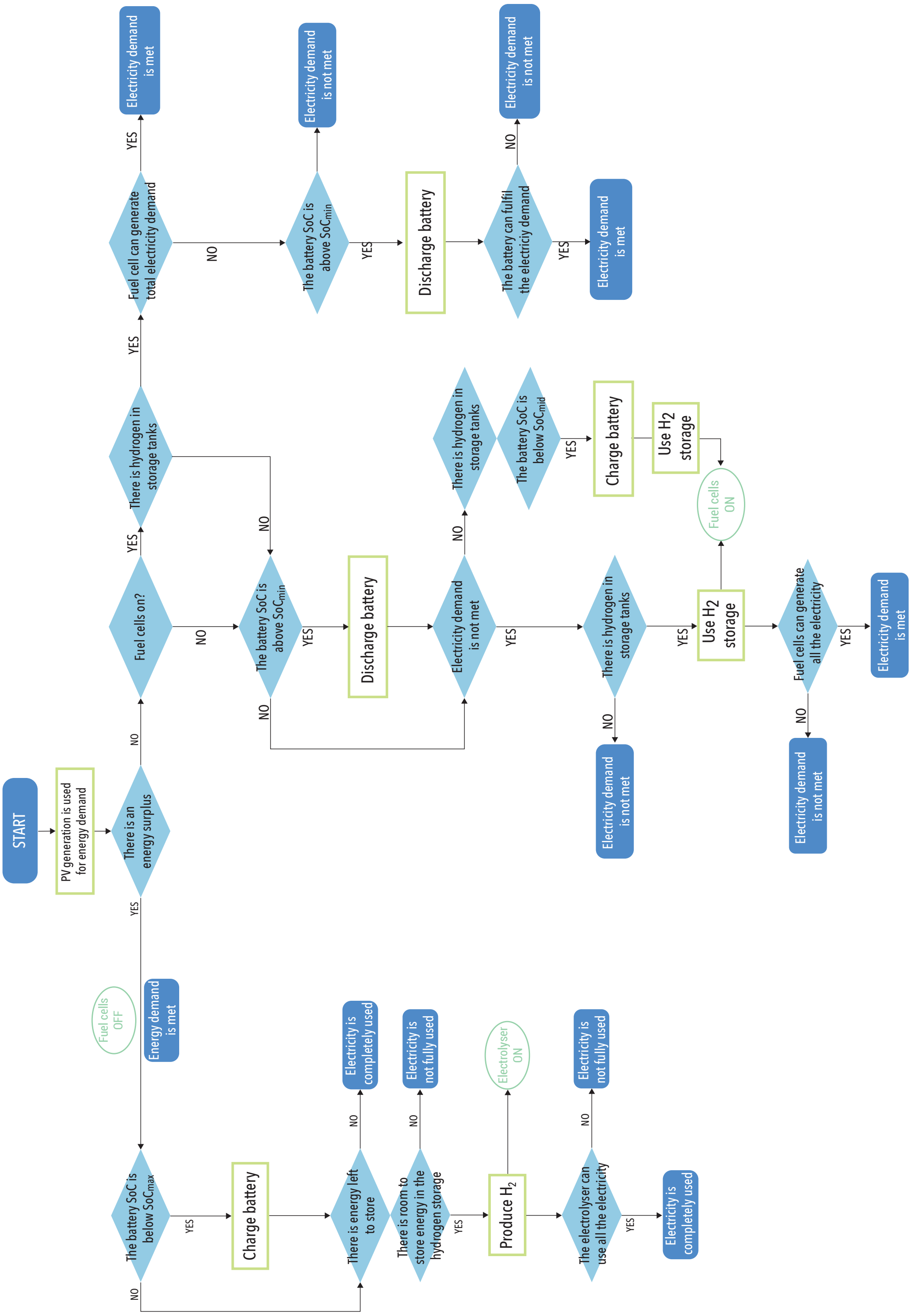


Figure 2.4: An extensive control strategy of a hydrogen-based fully electrified energy system

## 2.3. A hydrogen-based hybrid energy system without fuel cells

The second energy configuration is an hybrid energy system based on hydrogen. In this configuration the electricity and the heat flow are two separate stream. The hydrogen-based hybrid energy system without fuel cells is shown in fig. 2.5. The PV panels and the battery are responsible for the electricity supply. The hydrogen is used as fuel for the boiler to generate heat. The hydrogen production is the same process as described at the $H_2$-FEES with an electrolyser and compressor.

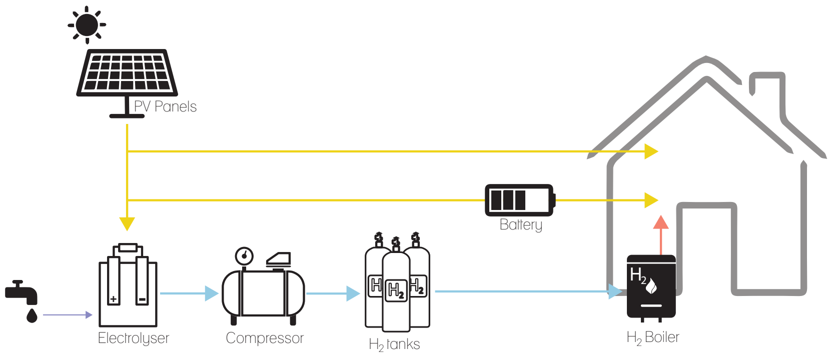


Figure 2.5: A simplified overview of a hydrogen-based hybrid energy system without fuel cells

A simplified control strategy is shown in fig. 2.6. From this figure, it can be seen that hydrogen is utterly responsible for the heat demand and does not interfere with the electricity demand. The electricity demand is met with PV generation or with the battery. In addtition, the PV panels are also responsible to supply electricity to generate hydrogen. In fig. 2.7, the electricity surplus from the PV generation is first used to produce hydrogen and subsequently to charge the battery. This is only the case in summer. During the winter, the battery is first charged. The reason is that during summer, the hydrogen storage must be filled, in order to have enough hydrogen to generate heat during winter, when the PV generation is lower, and the battery is more frequently needed to solve an electricity imbalance.

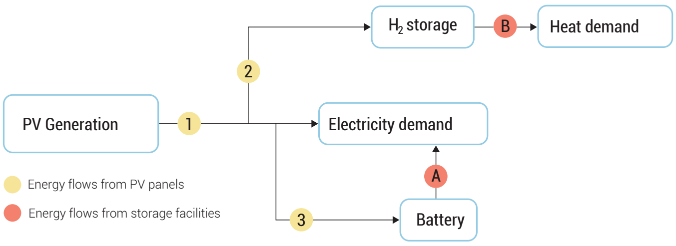


Figure 2.6: A simplified control strategy of a hydrogen-based hybrid energy system without fuel cells

The extensive control strategy for the $H_2$-HES is shown with a flowchart in fig. 2.7. There are two main flows; one for the heat demand and one for the electricity demand. The 'start' of the flowchart is found on the upper left side.

The left side of fig. 2.7 follows the heat flow. The heat demand is not directly dependent on the solar PV generation, but it relies on the amount of hydrogen stored in the tanks. Firstly, it checks if enough hydrogen is available in the storage tanks. If this is true, it checks if the hydrogen boiler can produce the heat demand.

The right side of this figure represents the electricity control strategy. Firstly, the electricity directly from the PV panels is used for the electricity demand. Subsequently, it checks if there is an energy surplus or an energy shortage based on the PV generation. If there is an energy surplus, one of the two middle flows in fig. 2.7 is followed, depending on the season. In summer, this strategy first checks if there is room for additional hydrogen storage, as it is essential to build a buffer for winter. Subsequently, the battery can be charged if there is electricity left and if the SoC is below the maximum SoC. During winter, this sequence is vice versa.

The flow on the right is followed when the electricity production from the PV panels is not sufficient to meet the electricity demand. If this occurs, the system checks if enough electricity is stored in the battery and if the SoC stays above the minimum SoC. Dumped energy or failed energy is monitored again at the end of each flow.

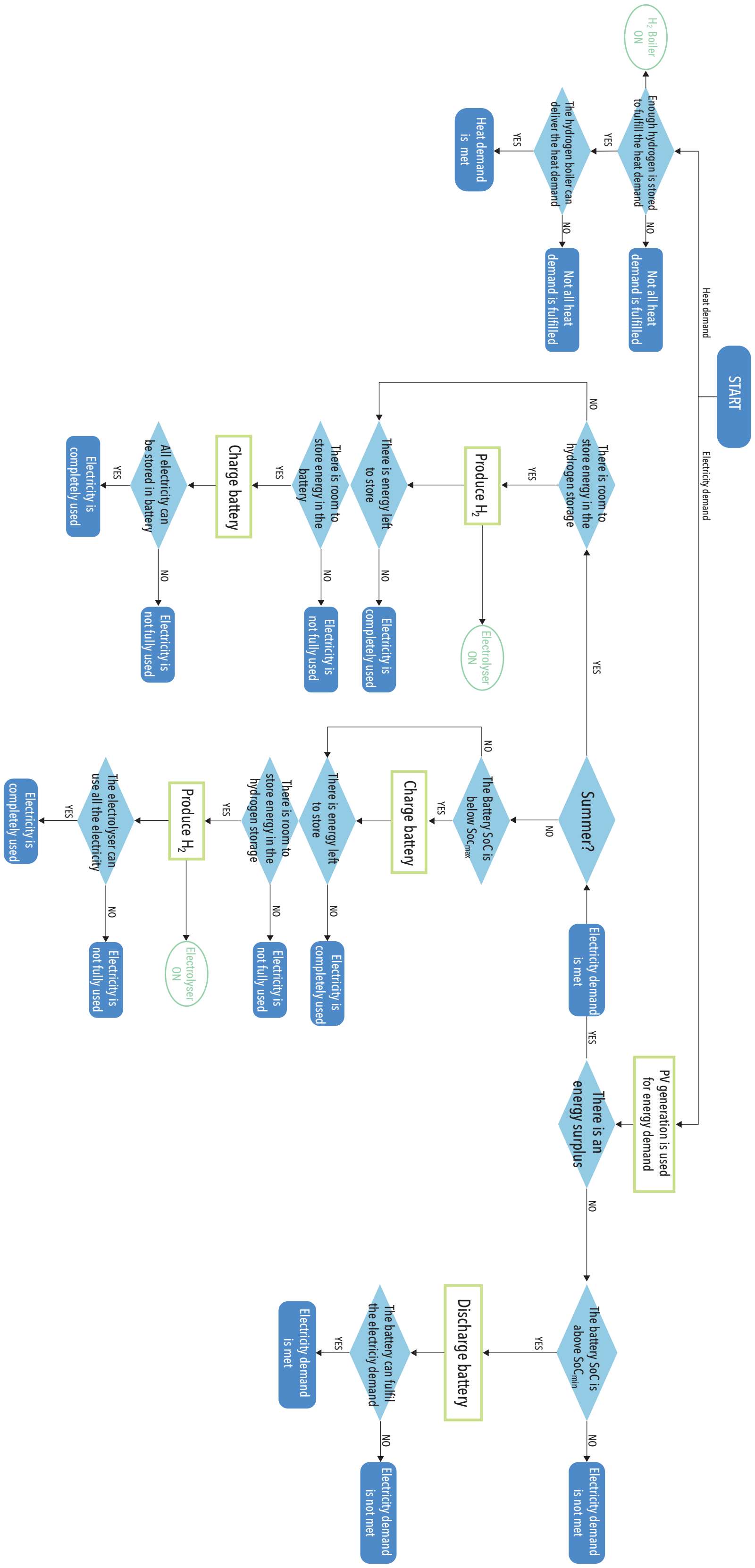


Figure 2.7: Extensive control strategy of a hydrogen-based hybrid energy system without fuel cells

## 2.4. A hydrogen-based hybrid energy system with fuel cells

Thirdly, the $H_2$-HES-FC design is a combination of the upper two configurations. In this design, the hydrogen is used for the heat demand and to charge the battery. A simplified overview is shown in fig. 2.8. The PV panels generate electricity directly for the electricity demand of the households, the battery and to the electrolyser. The hydrogen is primarily used as fuel for the hydrogen boiler to supply heat, and it can also used as fuel for the fuel cell that charges the battery.

In fig. 2.9 a simplified control strategy is shown. For this design, the hydrogen boiler is, just as in $H_2$-HES, used to generate the heat to satisfy the heat demand. The PV panels and the battery deliver the electricity demand, but the fuel cells are also installed to charge the battery if needed.

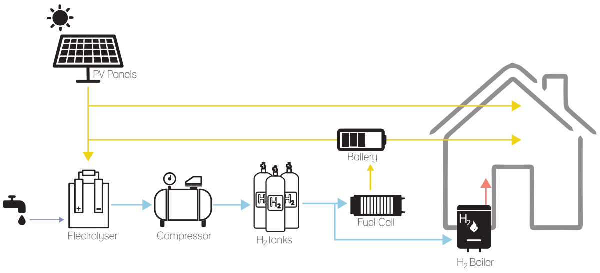


Figure 2.8: A simplified overview of a hydrogen-based hybrid energy system with fuel cells

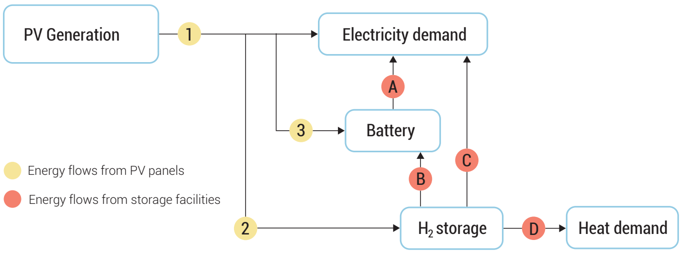


Figure 2.9: A simplified control strategy of a hydrogen-based hybrid energy system with fuel cells

An extensive control strategy for the $H_2$-HES-FC is shown in fig. 2.10. The flowchart has the heat demand flow on the left side. This flow is the same as the heat demand flow from the $H_2$-HES control strategy in fig. 2.7.

The electricity demand flow combines the $H_2$-HES control strategy and the $H_2$-FEES control strategy. Following the electricity flow, it first checks if the PV generation is sufficient to meet the electricity demand. If this is true, the same checking order is applied as for the $H_2$-HES control strategy. So, first, it checks if there is room to produce hydrogen, followed by checking if there is room in the battery and if there is electricity left to store. If the PV generation is insufficient, the same strategy is applied with the $H_2$-FEES control strategy. The fuel cell operates once the battery SoC is below a certain percentage. The battery is simultaneously discharged once it checks if enough electricity is left in the battery. Just as in the $H_2$-FEES control strategy, the fuel cells cannot deliver directly to the households as it takes time for the fuel cells to start operating.

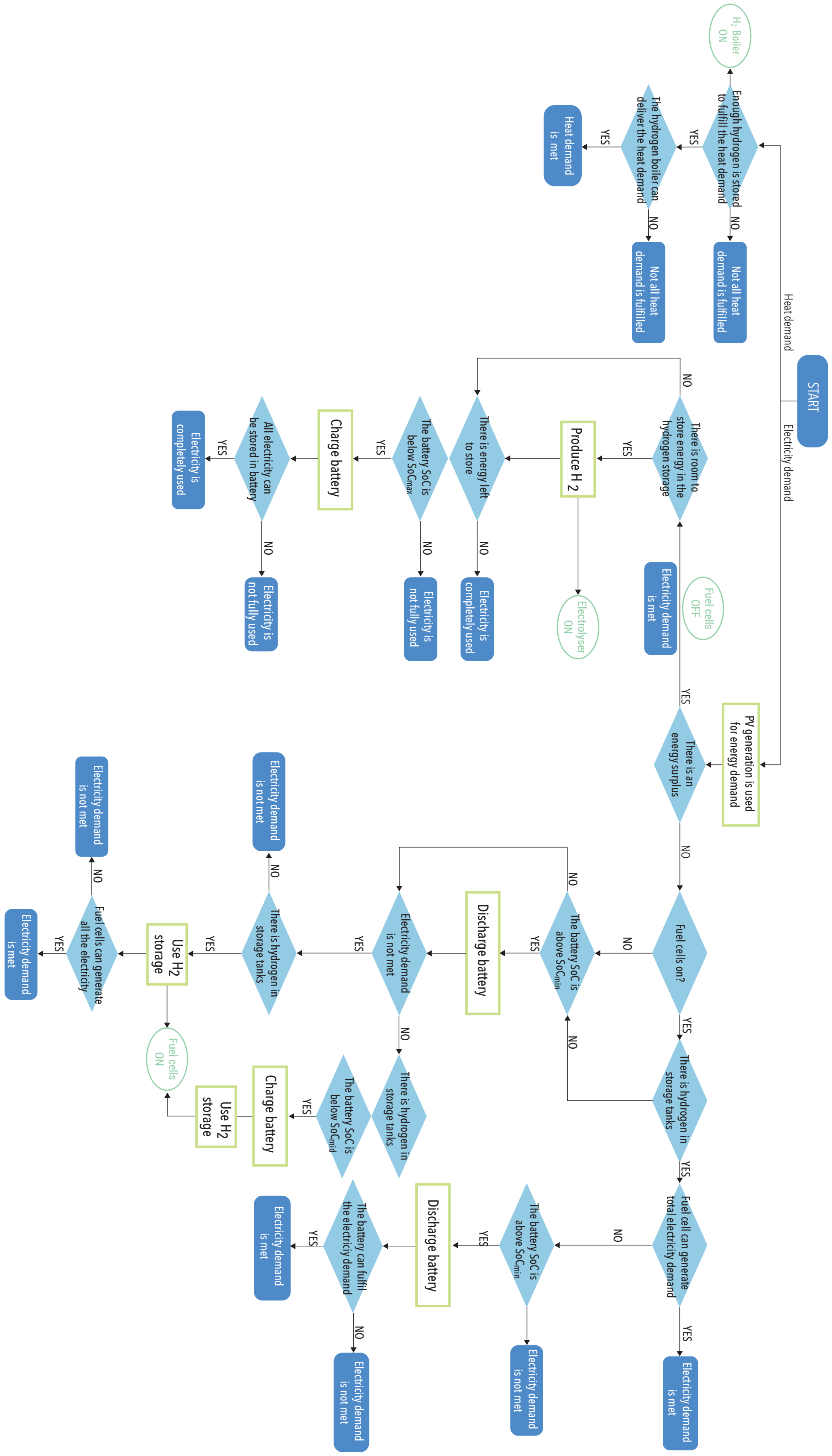


Figure 2.10: An extensive control strategy of a hydrogen-based hybrid energy system with fuel cells

## 2.5. Compressed air energy storage-based fully electrified energy system

The fourth configuration is the CAES-FEES. This system is similar to the $H_2$-FEES, but instead of hydrogen, compressed air is used to overcome the seasonal imbalance. This also results in other components operating with the CAES. Figure 2.11 is a simplified overview of the design, with all the components in the CAES-FEES. Instead of the electrolyser in the previous designs, a motor is needed, and the substitute for the fuel cells is the expander in combination with a generator.

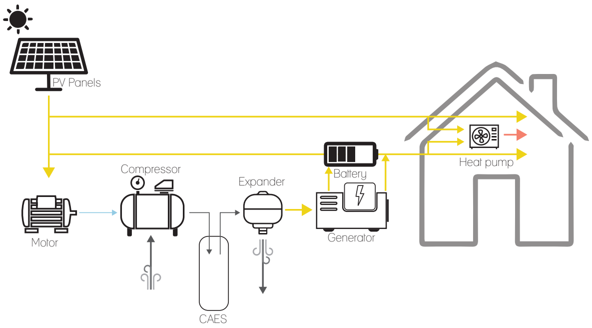


Figure 2.11: A simplified overview of a compressed air energy storage-based fully electrified energy system

A simplified control strategy is shown in fig. 2.12. This strategy is just as the configuration similar to the control strategy of $H_2$-FEES. The electricity and the heat demand are all generated with electricity. The energy is delivered by the PV panels directly, or indirectly by the battery or CAES flow. In addition, the electricity from the PV panels charge battery and the CAES, and the CAES can also charge the battery.

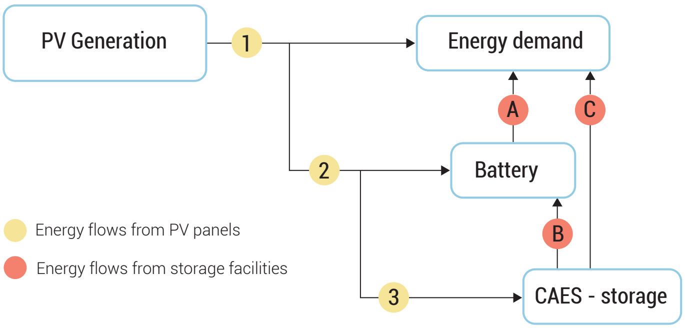


Figure 2.12: A simplified control strategy for compressed air energy storage-based fully electrified energy system

The extensive control strategy for the CAES-FEES is similar to the strategy of the $H_2$-FEES. In fig. 2.13 the flowchart of this control strategy can be found. The motor, generator and CAES are used instead of an electrolyser, fuel cells and hydrogen storage, respectively. The start is found on the left upper side. After the PV generation is used for the energy demand, it first checks if there is an energy surplus. If this is true, the left side of the control strategy is followed, checking first if it is possible to charge the battery with the surplus energy. Subsequently, if there is energy left, it is stored in the CAES if there is room.

The right side of the flowchart is followed when there is an energy shortage resulting from the PV generation. In that case, if the generator is o and there is energy stored in CAES, this energy is first used to solve the shortage. If this is not enough, the battery is discharged. If the generator is off, the battery is first used to supply energy, followed by the generator, using the CAES. If both the battery and the generator cannot fulfil the demand, there is failed energy. If the generator operates in the previous timestep but is not needed to fulfil the current timestep, the SoC is checked. Once this is below a certain percentage, the generator produces electricity to charge the battery using the stored energy in the CAES.

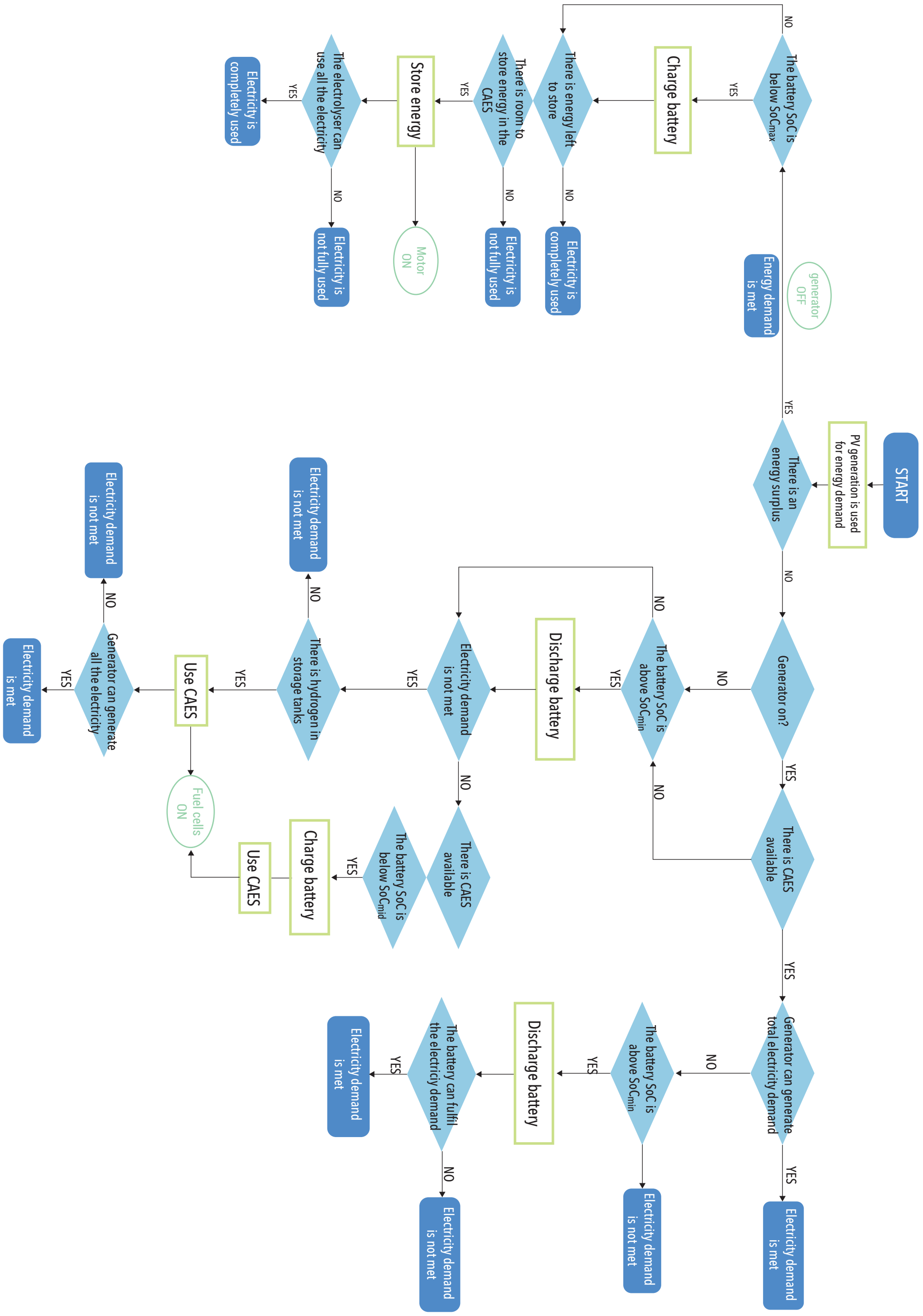


Figure 2.13: An extensive control strategy of a compressed air energy storage-based fully electrified energy system

These four energy systems are compared based on technical performance and financial outcome. In chapter 3, the method to determine the different sizes of the components for these four DES configurations, the technical simulation method based on the control strategies and the calculations for the financial outcome are described.

# 3

# Approach for modelling autonomous decentralised energy system

In this chapter, the path toward the cost calculation is described. There are three parts:

1. Sizing the components
2. Analysing the technical performance
3. Analysing the system costs

In section 3.1, the sizing of the components is discussed per DES configuration. The size of a component determines the investment costs for the whole system. For these designs, it is initially assumed that the energy system operates autonomously of the grid. The second part explains how the technical performance of the system is analysed. For the performance of the system, two objectives are essential. 1) Self-sufficiency of the system, and 2) minimising the costs of the system. In a self-sufficient energy system the energy demand is always met, resulting in a 100% reliable energy system. Minimising the costs from a technical performance point of view is analysed by looking at the efficiency of the system. If the generated energy with the PV panels is comparable with the energy demand the system is very efficient. In other words, the system has a high energetical value if the produced energy is used to satisfy the energy demand and not lost during the process. Therefore, the technical analyses look into the system's reliability and energetical performance. Five key performance indexes are established to analyse the system and explained in section 3.2. Section 3.3 look at the financial part. This section describes how to obtain energy prices [€/kWh] for the DES configurations that are used for the financial analyses.

## 3.1. Component sizing in Decentralized Energy Systems

A systematic design approach method to size the components is based on the method designed by Dr. N. Li for a research at TGV. This design approach follows nine steps to determine the sizes of different components, resulting in a realistic but not optimal determination of the component sizes. The sizes of the components are the capacities in kW, kWh, kg. The physical size of the components in not taken into account, so the sizing of the components only reflect the needed capacities, which are used for the cost calculation. The physical implementation on site is not taken into account. The size of each component is based on one or more formulae, resulting in a series of equations for the whole DES configuration.

The method of Dr. N. Li is applicable for DES configurations comparable with the $H_2$-FEES design. In the other three DES configurations, some of the components and control strategies differ. Therefore, new equations are established, based on the nine steps approach, expert knowledge and the book of Smets et al. (2016). The calculation method for the sizing of the components in the DES configurations is explained in the following sections.

### 3.1.1. A hydrogen-based fully electrified energy system

The $H_2$-FEES consists of 7 components; PV panels, a battery, a heat pump, an electrolyser, a compressor, $H_2$ storage tanks and fuel cells. The first step is to calculate the capacity of the PV panels and the battery. Subsequently, the capacities of the components of the hydrogen storage flow can be calculated.

**PV Panels**

The PV panels are responsible for the total energy generation. However, not all energy is directly used, as it is stored at first in a battery of as hydrogen. In addition, the heat pump reduces the energy demand, as it extract heat from the environment. As the solar irradiation is lower in winter, less electricity is generated with the PV panels and the energy must come from the long term storage facility. Therefore, the energy demand for winter is generated in summer with the PV panels and stored until needed in winter. In the case of this $H_2$-FEES, the energy is stored as hydrogen. With the conversion from electricity to hydrogen and vice versa, energy is lost, resulting in a higher PV generation to comply with the energy demand in winter. Therefore, the summer and winter demands are divided to calculate $\mathrm{E}_{\mathrm{PV,D}}$ [kWh], which results in

$$\mathrm{E}_{\mathrm{PV,D}} = (E_{\mathrm{w}}^{\mathrm{H_2}} + E_{\mathrm{w}}^{\mathrm{PV}} + \mathrm{E}_{\mathrm{s}}) \cdot \mathrm{SF}_{\mathrm{PV}}, \tag{3.1}$$

where $\mathrm{SF}_{\mathrm{PV}}$ [-] is the sizing factor for PV panels, $\mathrm{E}_{\mathrm{w}}^{\mathrm{H_2}}$ [kWh] and $\mathrm{E}_{\mathrm{w}}^{\mathrm{PV}}$ [kWh] together are the energy demand in the winter and $\mathrm{E}_{\mathrm{s}}$ [kWh] is the energy demand in the summer. The sizing factor for PV panels is needed as there are energy losses during the transport of electricity to the house and due to the inverter. Based on the research of Smets et al. (2016), the sizing factor is set to 1.1. For both of these energy demands the electricity and heat demand are separated as the heat demand is met with a heat pump and electricity demand is delivered directly from the PV panels. Multiple steps must be made to calculate $\mathrm{E}_{\mathrm{w}}^{\mathrm{H_2}}$ and $\mathrm{E}_{\mathrm{w}}^{\mathrm{PV}}$. The first step is to calculate the total energy demand in the winter with

$$\mathrm{E}_{\mathrm{winter}} = \mathrm{E}_{\mathrm{Q,w}} + \mathrm{E}_{\mathrm{el,w}}, \tag{3.2}$$

where $\mathrm{E}_{\mathrm{Q,w}}$ [kWh] is the heat demand in winter and $E_{\mathrm{el,\ w}}$ [kWh] the electricity demand in winter. The heat demand ($\mathrm{E}_{\mathrm{Q,w}}$) is calculated with

$$\mathrm{E}_{\mathrm{Q,w}} = \frac{\sum_{t=0}^{\mathrm{Tw}} \mathrm{P}_{\mathrm{Q}}(t)\, dt}{\mathrm{COP}_{\mathrm{HP}}}, \tag{3.3}$$

where $P_{\mathrm{Q}}(t)$ [kWh] is the heat demand per hour, $Tw$[h] indicates the time steps in winter from the

$4^{th}$ of November till the $6^{th}$ of May, where t=0 is January 1, 2020 at 00:00:00. The complete winter includes two time frames, from January 1 (t=0) till May 6 (t=2196) and from November 4 (t=6589) till December 31 (t = 8784). $\mathrm{COP_{HP}}$ [-] is the coefficient of performance (COP) of the heat pump.

The electricity demand in winter ($E_{\mathrm{el,\ w}}$) is calculated with

$$E_{\mathrm{el,w}} = \sum_{t=0}^{Tw} P_{el}(t)\,dt, \tag{3.4}$$

where $Tw$ is the same as in eq. (3.3) and $P_{\mathrm{el}}(t)$ [kW] is the electricity demand per hour.

During winter, not all electricity is delivered by hydrogen. Therefore a sizing factor is used. This sizing factor represents the ratio of energy that must be generated with hydrogen. In addition, for $\mathrm{E_w^{H_2}}$, the energy losses during the conversion from electricity to hydrogen and back are taken into account. The energy demand in the winter that is generated with hydrogen is calculated with

$$E_{\mathrm{w}}^{\mathrm{H_2}} = \frac{SF_{\mathrm{w}} \cdot E_{\mathrm{winter}}}{\eta_{\mathrm{Ele}}\eta_{\mathrm{FC}}}, \tag{3.5}$$

where $SF_w$ [-] is the sizing factor, $\mathrm{E_{winter}}$ [kWh] is obtained with eq. (3.2), and $\eta_{Ele}$ [kg/kWh] and $\eta_{FC}$ [kWh/kg] are the production rate of the electrolyser and the fuel cell respectively, based on the components installed at TGV. The electricity from the solar panels that directly goes to the households is subsequently calculate with

$$E_{\mathrm{w}}^{\mathrm{PV}} = (1 - \mathrm{SF_w}) \cdot E_{\mathrm{winter}}, \tag{3.6}$$

where $1 - \mathrm{SF_w}$ [-] equates to the electricity directly to the household and $\mathrm{E_{winter}}$ [kWh] is the total energy demand in the winter calculated with eq. (3.2).

The energy demand in summer ($\mathrm{E_{summer}}$) [kWh] is calculated similar to $\mathrm{E_{winter}}$. However, it is assumed that none of the electricity must be converted to hydrogen. To total energy demand during the summer is calculated with

$$\mathrm{E_{summer}} = \mathrm{E_{Q,s}} + \mathrm{E_{el,s}}, \tag{3.7}$$

where $E_{\mathrm{Q,s}}$ [kWh] is the heat demand in summer and $E_{\mathrm{el,s}}$ [kWh] the electricity demand. The heat demand in summer ($E_{\mathrm{Q,s}}$) is calculated with

$$\mathrm{E_{Q,s}} = \frac{\sum_{t=2197}^{\mathrm{Ts}} \mathrm{P_Q}(t)\,dt}{\mathrm{COP_{HP}}}, \tag{3.8}$$

where $Ts$ [h] indicates the time steps in summer, where t=2197 is the starting point of summer on May 7, 2020, at 00:00:00, and t = 6588 is the end of summer on November 3, 2020, at 23:00:00. $P_{\mathrm{Q}}(t)$ [kWh] is the hourly heat demand.

Comparable with eq. (3.8), $E_{\mathrm{el,s}}$ [kWh] is calculated with

$$\mathrm{E_{el,s}} = \sum_{\mathrm{t=2197}}^{\mathrm{Ts}} \mathrm{P_{el}}(t)\, dt, \tag{3.9}$$

where $Ts$[h] is the same as in eq. (3.8) and $P_{\mathrm{el}}$ [kWh] is the hourly electricity demand

Once the total energy demand is determined for a whole year with eq. (3.1), the needed installed PV capacity ($\mathrm{P_{PV}}$ [kW])is calculated with

$$\mathrm{P_{PV}} = \frac{\mathrm{E_{PV,D}}}{\mathrm{E_{PV,g}}}, \tag{3.10}$$

where $\mathrm{E_{PV,D}}$ [kWh] is the total energy demand calculated with eq. (3.1) and $\mathrm{E_{PV,g}}$ [kWh] is the yearly energy generation for 1 kW installed PV panels, calculated with

$$\mathrm{E_{PV,g}} = \sum_{t=0}^{\mathrm{T}} P_{\mathrm{PV,g}}(t)\, dt, \tag{3.11}$$

where $P_{\mathrm{PV,g}}$ [kWh] is based on the data from renewables.ninja, for a capacity of 1 kW and $\mathrm{T}$ is the hourly time step for one year, where $t$ = 0 is 2020-01-01 00:00:00.

**Battery**

During the night and on cloudy moments, solar energy is lacking. During hours with no or less PV generation, the battery needs to solve energy shortage. The night is, in general, the longest period without solar energy. Therefore the capacity of the battery is based on the average daily demand. The required capacity of the battery $\mathrm{P_{bat}}$ [kW] can be calculated with

$$\mathrm{P_{bat}} = \frac{\mathrm{E_{ave}^{day}} \cdot \mathrm{SF_{bat}}}{\mathrm{DoD}_{max}}, \tag{3.12}$$

where, $\mathrm{SF_{bat}}$ [-] is the sizing factor similar with the sizing factor used in eq. (3.1), $\mathrm{DoD}_{max}$ [%] is the maximal Depth of Discharge and $\Delta E_{ave}$ [kWh] is calculate with

$$\mathrm{E_{ave}^{day}} = \frac{\sum_{td=0}^{\mathrm{D}} \mathrm{E_d}(d)\, dt}{\mathrm{T}}, \tag{3.13}$$

where $\mathrm{E_d}$ [kWh] is the daily energy demand and T indicates a daily time step for one year, where $d$ = 0 is 2020-01-01 00:00:00.

### Electrolyser

The electrolyser produces hydrogen from electricity. The hydrogen is needed to supply energy in the winter. In addition, the hydrogen must be generated during summer when there is a lot of energy surplus from the PV panels. Therefore, the capacity of the electrolyser is based on the needed energy demand in the winter and the number of sun hours in summer. Because the total energy demand in winter is generated in summer. Therefore, the capacity of the electrolyser ($\mathrm{P_{Ele}}$)[kW] is calculated with

$$\mathrm{P_{Ele}} = \frac{\mathrm{E^{H_2}_{winter}}}{\mathrm{TSH_{summer}}}, \tag{3.14}$$

where $\mathrm{E_w}$ [kWh] is calculated with eq. (3.6) and $\mathrm{TSH_{summer}}$ [h] is the total amount of sun hours in the Netherlands from May till October retrieved from Weather and Climate (n.d.).

### Compressor

The compressor should be able to compress the hydrogen produced with the electrolyser. Therefore the capacity of the compressor [kg/day] is defined by both the capacity of the electrolyser and its production rate. The capacity of the compressor is calculated with

$$\mathrm{P_{com,H_2}} = \mathrm{P_{Ele}} \cdot \eta_{\mathrm{Ele}} \cdot 24, \tag{3.15}$$

where, $\mathrm{P_{Ele}}$ [kW] is calculated with eq. (3.14) and $\eta_{\mathrm{Ele}}$ [kg/kWh] based on the electrolyser used at TGV. Resulting in a capacity given in [kg/day]

### $H_2$ storage tanks

For the $H_2$-FEES, the hydrogen tanks [kg] store the energy demand needed in winter. Therefore the capacity is determined by

$$m_{\mathrm{H_2}} = \frac{\mathrm{SF_{winter}} \cdot \mathrm{E_{winter}}}{\eta_{\mathrm{FC}}}, \tag{3.16}$$

where $\mathrm{SF_{winter}}$ [-] is the sizing factor, $\mathrm{E_{winter}}$ [kWh] is the total energy demand for the winter defined with eq. (3.2) and $\eta_{\mathrm{FC}}$ [kWh/kg] is the production rate of a fuel cell.

### Fuel Cell

The fuel cell is responsible for the electricity generation during winter, when the PV panels and the battery are not sufficient. Therefore, the fuel cell should be able to deliver the peak demand for one hour either directly to the household or via a battery to ensure enough energy is stored in for the next hour. Therefore, the equation for the fuel cell capacity is similar to the equation for the battery capacity in eq. (3.12), as both components should be able to cover a part of the load demand for a certain period. The needed capacity of the fuel cell is calculated with

$$\mathrm{P_{FC}} = \mathrm{P_{max}} \cdot \mathrm{SF_{Bat}}, \tag{3.17}$$

where $SF_{\mathrm{Bat}}$ [-] is the sizing factor to account for the losses caused by charging the battery. Furthermore, the maximum demand load is defined with $\mathrm{P_{max}}$ [kWh].

### Heat pump

The heat pump generates the total heat demand in a year. Therefore, the needed capacity for the heat pump [kWh] is equal to the maximum heat demand, which can be determined with

$$P_{\mathrm{HP}} = P_{\mathrm{Peak,\,heat}} = \max(P_{\mathrm{Q}}(t)), \tag{3.18}$$

where $\mathrm{P_Q}(t)$ [kW] is the heat demand obtained from the data.

## 3.1.2. A hydrogen-based hybrid energy system

In contrast to the $H_2$-FEES, within this system, the total heat demand is delivered by the hydrogen boiler, which means that the total heat demand is converted to hydrogen. For the $H_2$-HES, seven components must be sized again: the PV panels, the battery, the electrolyser, the compressor, hydrogen storage, and the hydrogen boiler.

### PV panels

In this $H_2$-HES system the PV panels are responsible for the generation of the total energy demand. A division is made between heat demand and electricity demand. The heat demand must be corrected by the production rates of the electrolyser and the hydrogen boiler and the electricity demand must be corrected for the losses in the battery. This means that the needed PV generation [kWh] is calculated with

$$\mathrm{E_{PV,D}} = \mathrm{E_Q} + \mathrm{E_{el}}, \tag{3.19}$$

where the heat demand $\mathrm{E_Q}$ [kWh] is calculated with

$$\mathrm{E_Q} = \frac{\sum_{t=0}^{T} P_{\mathrm{Q}}(t)\, dt}{\eta_{\mathrm{Ele}} \cdot \frac{c_{\mathrm{H_2}}}{\rho_{\mathrm{H_2}}}}, \tag{3.20}$$

where $\mathrm{P_Q}$ [kWh] is the hourly heat demand, $\eta_{\mathrm{Ele}}$ [kg/kWh] is the production rate of the electrolyser, $c_{\mathrm{H_2}}$ [kWh/m$^3$] is the caloric value of hydrogen gas, which is equal to 33.32 KWh/m$^3$, and $\rho_{\mathrm{H_2}}$ [kg/m$^3$] the density of hydrogen gas at atmospheric pressure.

The electricity demand ($E_{\mathrm{el}}$) is calculated with

$$\mathrm{E_{el}} = \sum_{t=0}^{T} P_{el}(t)\, dt, \tag{3.21}$$

where $\mathrm{P_{el}}$ [kWh] is the hourly electricity demand.

Subsequently, the needed installed PV capacity follows from:

$$\mathrm{P_{PV}} = \frac{\mathrm{E_{PV,D}}}{\mathrm{E_{PV,g}}}. \tag{3.22}$$

where $\mathrm{E_{PV,g}}$ [kWh] is calculated with eq. (3.11), which equals the total solar generation a 1 kW solar panel, and $\mathrm{E_{PV,D}}$ is calculated with eq. (3.19)

### Battery

The battery in the $H_2$-HES is installed to solve the daily electrical imbalance and not the overall energy imbalance in the system. Following Smets et al. (2016, p. 324), the battery in a PV - battery system should be able to cover multiple days. The amount of days is based on the solar irradiation. The solar irradiation is different per location, and thus the amount of days depends on the location. For the location of TGV, the amount of days is set at five, following the example in Smets et al. (2016). Resulting in the following equation

$$\mathrm{P_{bat}} = \frac{\mathrm{E_{el_{ave(d)}}} \cdot \mathrm{SF_{bat}}}{\mathrm{DoD}_{max}}, \tag{3.23}$$

where $\mathrm{SF_{bat}}$ [-] and $\mathrm{DoD}_{max}$ [%] are equal to the values used in eq. (3.12) and the daily average energy demand($\mathrm{E_{el,ave}}$)[kWh] is calculated with

$$\Delta\mathrm{E_{el,ave(d)}} = \frac{(\sum_{d=0}^{\mathrm{d_{year}}} \mathrm{E_{el}}(d) \cdot \mathrm{days})}{\mathrm{d_{year}}}, \tag{3.24}$$

where $\mathrm{E}_{\mathrm{el,day}(d)}$ [kWh] is the average electricity demand of a single day, and $\mathrm{d_{year}}$ [days] the total amount of days in a year. For 2020 this amount is 366.

### Electrolyser

The electrolyser is needed to generate hydrogen gas to comply with the total heat demand. Therefore, the capacity calculation differs from the calculation used for the $H_2$-FEES system. Instead of sizing the electrolyser for the total needed stored energy to comply with the energy demand in winter, the electrolyser is also necessary to comply with the summer heat demand. The electrolyser is therefore sized to comply with the maximum heat demand. This means that during summer when heat demand is lower, the electrolyser produces hydrogen to satisfy the heat demand in summer and a surplus, which is stored for winter heat demand. For this system, the needed capacity [kW] is calculated with

$$\mathrm{P_{Ele}} = max(\mathrm{P_Q}(t)), \tag{3.25}$$

where $\mathrm{P_Q}(t)$ [kW] is the heat demand per time step.

### Compressor

The compressor is needed to compress the hydrogen generated with the electrolyser and is therefore depending on the capacity of the electrolyser. The calculation of the needed capacity for the compressor is equal to eq. (3.15).

### $H_2$ storage tanks

For the $H_2$-HES, the hydrogen tanks must be able to store the total heat demand for winter and also some additional space to comply with heat demand during the summer. The buffer for winter is needed, as the solar energy in winter is primarily needed to satisfy the electricity demand, resulting in less, or no hydrogen production in winter. The total hydrogen tank capacity [kg] for one year is determined by

$$m_{\mathrm{H_2}} = \frac{(\mathrm{E_Q^w} + \mathrm{E_Q^{s,ave}}(t))}{c_{\mathrm{H_2}}}, \tag{3.26}$$

The storage capacity is equal to $\mathrm{E_Q^w}$ [kWh] added with some space for daily heat demand in summer expressed with $\mathrm{E_Q^{s,ave}}$. The value for $c_{\mathrm{H_2}}$ [kWh/kg] is equal to the calorific value of hydrogen gas. There is no sizing factor as a hydrogen boiler must generate the total heat demand.

### Hydrogen boiler

The hydrogen boiler produces heat. To ensure there is enough heat, the boiler must be sized at the maximum heat demand. The capacity of the hydrogen boiler [kW] is therefore calculated with

$$\mathrm{P_{hb}} = max(\mathrm{E_Q(t)}), \tag{3.27}$$

where $max(\mathrm{E_Q(t)})$ [kW] is the highest heat demand that occurred during one year, as the hydrogen boiler provides only the heat demand.

## 3.1.3. A hydrogen-based hybrid energy system with fuel cell

The sizing of the components is equal to the sizing of the components in the $H_2$-HES without fuel cells, except for the battery and the additional fuel cell. The equations for the PV panels, the electrolyser, the compressor, the hydrogen tanks and hydrogen boiler are already explained above.

For the solar PV panels eq. (3.22) is used, with eq. (3.19) to calculate the total needed solar energy generation. The electrolyser capacity is calculated with eq. (3.25). The compressor size is determined with eq. (3.15), just as in the $H_2$-FEES system. The hydrogen storage tanks are sized with eq. (3.26), and the hydrogen boiler capacity is calculated with eq. (3.27).

### Battery

For the capacity calculation of the the battery, a combination between eq. (3.12) ($H_2$-FEES) and eq. (3.23) ($H_2$-HES) is needed. The battery is solely used for the electricity demand, but there is also a fuel cell that is used to charge the battery, instead of only PV panels. Therefore, it is not needed to size the battery for multiple days, resulting in

$$\mathrm{P_{bat}} = \frac{\mathrm{E^{day}_{El,ave}} \cdot \mathrm{SF_{bat}}}{\mathrm{DoD}_{max}}, \tag{3.28}$$

where, $\mathrm{SF_{bat}}$ [-] is the sizing factor similar to the sizing factor used in eq. (3.1), $\mathrm{DoD}_{max}$ [%] is the maximal Depth of Discharge (DoD) and $\Delta E_{El,ave}$ [kWh] is calculate with

$$\mathrm{E^{day}_{El,ave}} = \frac{\sum_{d=0}^{\mathrm{d_{year}}} \mathrm{E_{El,d}}(d)\, dt}{\mathrm{d_{year}}}, \tag{3.29}$$

where $\mathrm{E_{El,d}}$ [kWh] is the daily energy demand and $d$ indicates a daily time step for one year, where d = 0 is 2020-01-01 00:00:00. $\mathrm{d_{year}}$ is the total amount of days in one year, equal to 366.

### Fuel cell

The fuel cell is sized as in the $H_2$-FEES with eq. (3.17) and is only needed to meet the electricity demand. This means that the fuel cell capacity [kW] is calculated with

$$\mathrm{P_{FC}} = \mathrm{E^{hour}_{El,ave}} \cdot \mathrm{SF_{Bat}}, \tag{3.30}$$

where $\mathrm{SF_{Bat}}$[-] is the sizing factor due to losses caused by charging the battery. Furthermore, hourly average load demand is defined with $\mathrm{E^{hour}_{El,ave}}$ [kWh], where the electricity load demand data is used.

## 3.1.4. A compressed air energy storage - based fully electrified energy system

The sizing of the components in the CAES-FEES is similar to the $H_2$-FEES. However, there are some differences due to the different storage method. The steps and equations needed to calculate the capacities for the CAES-FEES are explained, where the equations equal to the equations in the $H_2$-FEES are only mentioned by referring to the equation number above.

### PV Panels

The PV panels in the CAES-FEES configuration are needed to comply with the total energy demand. The system is fully electrified, just as the $H_2$-FEES. So, the capacity of the solar panels is calculated with the same equation given in eq. (3.10), where $\mathrm{E_{PV,g}}$ [kWh] is obtained the same way as eq. (3.11). Only $\mathrm{E_{PV,D}}$ [kWh] is different, as the seasonal imbalance is stored in a CAES system and is therefore calculated with

$$\mathrm{E_{PV,D}} = (\mathrm{E_w^{CAES}} + \mathrm{E}_\mathrm{w}^{PV} + E_\mathrm{s}) \cdot \mathrm{SF_{PV}}, \tag{3.31}$$

Where $\mathrm{E_s}$ [kWh] is obtained with eq. (3.7), using both eq. (3.8) and eq. (3.9) as input values. $\mathrm{E}_\mathrm{w}^{PV}$ [kWh] is obtained with eq. (3.6), where $\mathrm{E_{winter}}$ [kWh] is calculated exactly the same as in eq. (3.2) with eq. (3.3) and eq. (3.4) for the heat and electricity demand during winter times and the same sizing factor is used as in eq. (3.1). In addition, $\mathrm{E_{w_{CAES}}}$ [kWh] is acquired similarly as eq. (3.5) with

$$\mathrm{E_{winter}^{CAES}} = \frac{\mathrm{SF_w} \cdot \mathrm{E_{winter}}}{\eta_\mathrm{motor}\eta_\mathrm{gen}}, \tag{3.32}$$

where, instead of the production rates of the electrolyser and fuel cell, the efficiencies [%] of the motor and the generator are used to calculate the winter demand obtained by long term storage.

### Battery

The reasoning behind the size of the battery in the CAES-FEES is the same as in the $H_2$-FEES. The generator in the CAES flow can also deliver electricity to the household and to the battery. Thus the capacity of the batteries are calculated with eq. (3.12) and eq. (3.13). ,

### Motor

The motor has the same function as the electrolyser in the hydrogen based system, except the motor is used to power the compressor instead of producing hydrogen. The calculation for thr motor capacity [kW] is therefore similar to the calculation for the capacity of the electrolyser in eq. (3.14) and is calculated with

$$\mathrm{P_{motor}} = \frac{\mathrm{E_{winter}^{CAES}}}{\mathrm{TSH_{summer}} \cdot \eta_\mathrm{motor}}, \tag{3.33}$$

where $\mathrm{E_{winter}^{CAES}}$ [kWh] is obtained with eq. (3.32) and TSH [h] is equal to the TSH used in eq. (3.14). $\eta_\mathrm{motor}$ [%] is the efficiency of the motor.

### Air compressor

The air compressor is used to compress air to a higher pressure, resulting in stored energy. The capacity of the air compressor [$m^3$/h] is similarly calculated as the capacity of the $H_2$ compressor in the $H_2$-FEES. The used equation is

$$\mathrm{P_{Com,air}} = \mathrm{P_{motor}} \cdot \eta_\mathrm{com,air}, \tag{3.34}$$

where $\mathrm{P_{motor}}$ [kW] is obtained with eq. (3.33) and $\eta_\mathrm{com,air}$ [$m^3$/kWh] is the production rate of the compressor.

### Compressed air energy storage

In the compressed air energy storage [kWh], all the energy is stored to solve the seasonal imbalance. For this storage facility the same rationale is used as for the hydrogen storage tanks in the $H_2$-FEES. There must be a buffer for the energy demand in winter. Thus, the calculation is similar to the $H_2$ tanks in eq. (3.16), resulting in:

$$\mathrm{E_{CAES}} = \frac{\mathrm{E^{CAES}_{winter}}}{\eta_{\mathrm{gen}}}, \tag{3.35}$$

where $\mathrm{E^{CAES}_{winter}}$ [kWh] is determined with eq. (3.32), this value is divided by $\eta_{\mathrm{gen}}$ [%], which is equal to the efficiency of the generator.

### Generator

The generator produces electricity from the compressed air for direct use of a household or to charge the battery. Just as the fuel cell in the $H_2$-FEES, the generator should be able to cover the demand of one hour. Therefore, the needed capacity of the generator is calculated with

$$\mathrm{P_{gen}} = max(\mathrm{E(t)}) \cdot \mathrm{SF_{Bat}}, \tag{3.36}$$

where $\mathrm{SF_{Bat}}$ [-] is the sizing factor, which takes into account the energy losses due to (dis)charging the battery and $max(\mathrm{E(t)})$ [kWh] is the average hourly demand retrieved from load demand data.

### Heat pump

The final component in the CAES-FEES is the heat pump. The capacity for the heat pump is the same as for the $H_2$-FEES and, therefore, is calculated with eq. (3.18).

## 3.2. Technical performance indicators

For the technical performance analysis, a simulation model is built. There are two objectives for the designed energy systems:

- The components should be sized so that the system is autonomous and can deliver all the needed energy. In other words, the system should be reliable;
- Secondly, the components should not be oversized, as costs depend on the size of the components, and the total objective of the energy systems is to minimise the expenses. Therefore, the system must be energetically optimal.

The first objective is analysed using the first two key performance indicators. In addition, the following three key performance indicators are used to analyse the second objective. This gives five Key Performance Indicators (KPIs):

- Loss of load probability (LLP)

- Failed energy ratio (FER)
- Dump ratio (DR)
- Storage ratio (SR)
- System efficiency (SE)

To make a conclusion about the performance of the design, multiple values are monitored in the simulation; power shortages, downtime, power dump, battery charge, battery discharge, long term storage produced, long term storage used. The simulation model follows the control strategies described in chapter 2. The following sections discuss the KPIs and how they are determined in the model.

**Loss of load probability**

The LLP expresses the potential downtime of an energy system in a percentage. In other words, how often the energy demand is not met. In this model, the LLP is calculated with (Narayan et al., 2019)

$$\mathrm{LLP} = \frac{\sum_{i=1}^{T} \mathrm{t}_{\mathrm{downtime}}(i)\, dt}{\mathrm{T}}, \tag{3.37}$$

where $\mathrm{t}_{\mathrm{downtime}}$ [h] is equal to 1 if the system fails to meet the energy demand, with a time interval of 1 hour, and T [h] is the total amount of hours in 1 year. The maximum value of the LLP depends on the application of the system. For residential applications, the LLP should be lower than 0.01%, based on the performance of TSO TenneT, where the grid operates 99.99% of the time (TenneT, n.d.).

**Failed energy ratio**

The FER measures the amount of energy that is not met. In order to compare the different cases, with different demand loads, the ratio is used. The FER is calculated with the following equation:

$$\mathrm{FER} = \frac{\sum_{t=0}^{T} \mathrm{E}_{\mathrm{fail}}(t)\, dt}{\sum_{t=0}^{T} \mathrm{E}_{\mathrm{d}}(t)\, dt}, \tag{3.38}$$

where, $\mathrm{E}_{\mathrm{fail}}$[kWh] is the failed energy per time step ”t”, summed for a whole year where T starts at t=0 and ends with t=8784, these values are an outcome from the control strategy. This value is divided by the sum of $\mathrm{E}_{\mathrm{d}}$, which is the energy demand per time step ”t” as given in the demand data, where t starts a t=0 and ends at t=8784. In the case of a 100% self-sufficient design, the FER is equal to zero.

**Dump ratio**

The DR is a system metric used by Narayan et al. (2019) to determine the amount of energy that is generated by the solar panels but cannot be used in the system. The potential energy, generated by PV panels, cannot be used if the load demand is met and the storage facilities are full. It is chosen to use a ratio to compare the different demand loads for the same DES. Due to this ratio, the dumped energy is levelised with the total energy load. The DR is calculated with

$$\mathrm{DR} = \frac{\sum_{t=0}^{T} \mathrm{E}_{\mathrm{dumped}}(t)\, dt}{\sum_{t=0}^{T} \mathrm{E}_{\mathrm{d}}(t)\, dt}, \tag{3.39}$$

where, $\mathrm{E}_{\mathrm{dumped}}$ [kWh] is dumped energy per timestep "t" and $\mathrm{E}_{\mathrm{d}}$ [kWh] the energy demand at timestep "t", both summed for a whole year where T starts at t=0 and ends with t=8784. An DR equal to zero is the best outcome concerning the energetical performance, as there is no dumped energy. If the DR is above zero, the potential energy is not generated. However, it can be concluded that either the storage facility is too small or the PV capacity is too large. This depends on the outcome of the SR.

### Storage ratio

The SR is used to analyse the performance of the storage facility. There are two types of storage; short-term and long-term. Both ratios [%] are calculated with

$$\mathrm{SR} = \frac{E_{\mathrm{output}}}{E_{\mathrm{input}}}, \tag{3.40}$$

where $E_{\mathrm{output}}$ [kWh] is the total energy output from the storage facility and $E_{\mathrm{input}}$ [kWh]is the energy stored in the storage facility. By using these two values, only the inflow and outflow are considered. For the battery, the minimum and maximum SoC are irrelevant to the outcome. For long term storage, this means that the initial storage capacity is also neglected. A storage ratio of 1 is optimal with respect to the energetical performance. In that case, all the stored energy is also used in the system.

In combination with the DR, statements can be made about the capacities of the PV panels and the storage facility. If the DR is above zero, and the SR is above one, the storage capacity is too small, because there is more stored energy needed to make sure the energy storage has enough stored energy for a longer period of time. If the DR is above zero and the SR is below one, the PV capacity is too large. If the DR is zero and the SR is above 1, the PV capacity is to small and if the DR is zero and the SR is below 1, the storage facility can be too big, depending on how much below 1.

### System efficiency

The total efficiency of the system is calculated to see how much of the generated energy is used to meet the energy demand. The system efficiency [%] is calculated with

$$\eta_{\mathrm{system}} = \frac{\sum_{t=0}^{T} \mathrm{E}_{\mathrm{d}}(t)\, dt}{E_{\mathrm{PV}} - \Delta\mathrm{H}_{2,\, storage} - \Delta\mathrm{Bat}}, \tag{3.41}$$

where $E_{\mathrm{d}}$ [kWh] is equal to energy demand at time step "t", and $E_{\mathrm{PV}}$ [kWh] is equal to the yearly energy generation calculated with eq. (3.1). $\Delta\mathrm{H}_{2,\, storage}$ [kWh] is the difference between the amount of stored hydrogen at the beginning of the run and the end of the run. The same definition is applied for $\Delta\mathrm{Bat}$ [kWh], but for the battery storage. By subtracting the storage differences, the amount of energy that is not generated by solar PV panels or not used to meet the demand is not considered for the system efficiency. Suppose the storage is increased at the end of the run compared to the start. In that case, the difference has a positive value, and the amount of additional stored energy is subtracted from the PV generation, as the energy is not used to comply with the energy demand. If the storage level is lower at the end of the run compared with the start, the value is negative and will be added to the PV generation, as more energy is needed to fulfil the energy demand. The system efficiency is optimal if the outcome is 100%. This means that all the generated energy is used to meet the energy demand.

## 3.3. Financial performance indicator

To answer the main research question and sub-question three, the financial impact of the DES cases on households must be determined. To do so, the costs for households in the current energy system are compared with the cost for households of DES. The reference case imports energy from the grid, and therefore the costs in the reference case are the energy market prices for electricity and gas, given in [€/kWh]. The DES cases operate entirely on solar energy, and therefore the generated energy is "free" once the system is installed. Therefore the costs for a DES are the investment costs, capital expenditures (CAPEX), and the operational and maintenance expenditures (OPEX), given in [€]. A conversion must be made to compare the reference case with the DES cases.

A commonly used method to compare energy systems in the renewable energy industry is the *Levelised Costs of Energy* (LCOE) (Branker et al., 2011). The definition of the LCOE is "the costs per kWh of electricity produced by a power generation facility" (Smets et al., 2016, p.354), resulting in a value given in [€/kWh], just as the energy prices in the reference case. Usually, the LCOE is calculated per power generation system, where $\mathrm{E}_t$ is equal to the energy output of the power generation system. However, storage facilities are included within these DES designs, as they also deliver energy to the households, but via a detour, resulting in energy losses during the charging or converting processes. So, to compare the "LCOE" of the total energy system with the reference case, the complete DES design is seen as one large power generation system that delivers energy to the household. All the efficiencies of the components and energy losses during the charge and discharge and conversion processes are incorporated within the power generation system. In other words, the DES is seen as a "*black box*" where the energy output is equal to the demand load of the household. As this method is not entirely similar to the LCOE calculation, it is defined as the consumer energy price (CEP), which is calculated with

$$\mathrm{CEP} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}. \tag{3.42}$$

The numerator is the sum of three costs components; 1) the total investment costs in year *t*, 2) the maintenance cost in year *t*, and 3) the fuel costs in year *t*, all given in [€], divided by the discount rate factor in year *t*, where *r* is the discount rate, over the total lifetime *n* of the energy system.

The investment costs are the sum of the CAPEX for all the different components. The maintenance costs are the OPEX for each of the components. The replacement costs for components that have a shorter lifetime than the total lifetime of the energy system are included in the CAPEX. The fuel costs are the costs for the fuel. In the case of these renewable DES designs, the only fuel costs that occur are during hydrogen production, as water is needed for this process. The discount rate factor is used to correct the total costs for the future value of money, the net present value (NPV) The denominator is the sum of total energy demand in year *t* given in [kWh], also divided by the discount rate factor in year *t*, over the entire lifetime *n* of the energy system.

# 4

# Case study: input data and assumptions

In this chapter, an explanation of the used data is given. The data can be divided into three subcategories; |1| the demand data, |2| PV generation data, and |3| component data. Section 4.1 describes the demand data, section 4.2 describes the PV generation data, and section 4.3 gives an overview of all the input data of the components.

## 4.1. Demand data

The demand data is retrieved from TGV. There are eight residential buildings at TGV. The demand data of these houses is collected in an Excel workbook, with a separate worksheet for each house. Within the buildings, sensors are installed that monitor demand data per 15 minutes, per hour, or per month. In addition, the demand data was given in different energy units. For the electricity demand, it was in either [Wh] or [kWh], and the natural gas use of the DreamHussen was given in [$m^3$]. Furthermore, the starting date when the sensors started to operate differs as well. In table 4.1 for each of the houses, the time step, the energy value unit and the starting date are stated.

Table 4.1: Demand data description overview of the Green Village

| House | Timestep | Energy value | Starting date |
|---|---|---|---|
| Woody 10 | 15 min | kWh | 01-01-2018 |
| Woody 10a | 15 min | kWh | 01-01-2018 |
| Sustainer Home 12 | 15 min | kWh | 01-01-2018 |
| Sustainer Home 14 | 15 min | kWh | 01-01-2018 |
| DreamHus 28 (electricity) | 15 min | Wh | 30-07-2019 |
| DreamHus 28 (gas) | 1 hour | $m^3$ | 30-07-2019 |
| DreamHus 30 (electricity) | 15 min | Wh | 30-07-2019 |
| DreamHus 30 (gas) | 1 hour | $m^3$ | 30-07-2019 |
| DreamHus 32 (electricity) | 15 min | Wh | 30-07-2019 |
| DreamHus 32 (gas) | 1 hour | $m^3$ | 30-07-2019 |
| Pret-a-Loger | 1 month | Wh | 01-06-2014 |

The first step is to unify the Excel workbook to use the data. After the demand preparation is for each building, the hourly demand in [kWh] is divided into heat demand and electricity demand for one year. It is decided to use the data from the year 2020. This year is for each of the houses almost wholly monitored. The steps to unify the data are described in appendix E.

For this study, the houses at TGV are classified into housing types. Five different types of houses are defined in the Dutch built environment and commonly used when looking into energy consumption in the built environment (ECW, Eneco, TNO):

- Detached house
- Semi-detached house
- Terraced house
- Corner house
- Apartment

A further specification of the different house types is given in appendix C.1. The classification of houses at TGV is shown in table 4.2.

Table 4.2: Houses at the Green Village ordered by housing type

| **Housing Type** | **House at TGV** |
|---|---|
| Apartments | Woody 10<br>Woody 10a<br>Sustainer Home 12<br>Sustainer Home 14 |
| Terraced House | DreamHus 30 |
| Corner House | DreamHus 28<br>DreamHus 32 |
| Detached House | Pret-a-Loger |

Not all the data from TGV could be used. The detached house only has monthly demand data available for the year 2020. This time step is considered too large to extrapolate to hourly demand data.

### 4.1.1. Data used in the model

In this research, two scales are considered, a single household and a community. A single household covers the energy demand of one household. A community is multiple households, assumed to have the same characteristics, as they are in the same geographic area resulting from the same building project. The available demand data from TGV made it possible to generate five different demand cases. These cases are presented in table 4.3 and are based on the types of houses defined in appendix C. Of the five cases, there are three single household cases and the two community scale cases.

Table 4.3: Model input

| **Model** | **Data** |
|---|---|
| Single apartment | Woody 10 |
| Terraced House | DreamHus 30 |
| Corner House | DreamHus 32 |
| Apartment community | 3 x (Woody 10 + Sustainer Home 12 + Sustainer Home 14) |
| Terraced House Community | DreamHus 28 + 7 x DreamHus 30 + DreamHus 32 |

For the single apartment, it is chosen to use Woody 10, as the Sustainer Homes have interconnected demand data. Therefore, it would result in more uncertainty around the demand data for a single household. In addition, for Woody 10a, there were gaps in energy use due to vacancy.

The only terraced house at TGV is DreamHus 30. Although there is one week where the data is affected by testing a PCM storage tank, this building is used in the model. The third single household case in the model is a corner house. DreamHus 32 is chosen for this case, as the other corner house, DreamHus 28, was used to test a heat exchanger, which had an impact on the demand curve.

The community scale cases are divided into an apartment community and a terraced house community. The communities are sized at nine households. It is chosen to size the community at nine household to have a significant difference between community and single household scale and because of the different available demand cases. The expected advantage of a community is based on the time variation when a peak demand occurs. By adding up the same demand curve multiple times, the additional benefit of scale effect is assumed to decrease.

Three different buildings are used in the apartment community to create variation in demand load data: both Sustainer Homes and Woody 10. As the demands are added up in the community, the interconnection between the Sustainer Homes is not a problem. In this case, all the demand curves are multiplied with three.

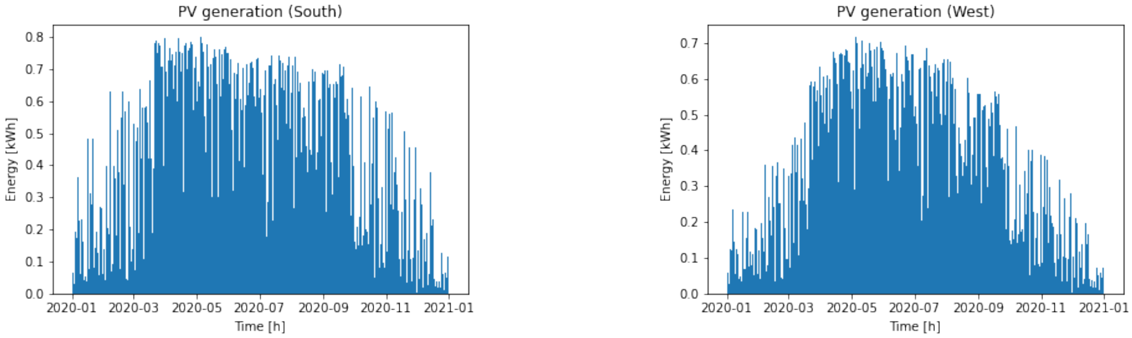
In the Terraced house community, this variation is obtained using multiple terraced houses, and at each end of the row, a corner house is placed. For this case, there are also three different demand loads used. Both DreamHus 28 and DreamHus 32 are used for the corner houses, and the terraced house is DreamHus 30. This community case is obtained by multiplying the terraced house with seven and the corner houses are both used once.

## 4.2. PV generation data

The generation of solar energy is non-dispatchable and unpredictable. When using historical data, it is possible to match demand data with PV generation data. In retrospect, we can calculate the capacity of the installed PV system. This resolves the unpredictable part of the model simulation. However, solar energy is still non-dispatchable. Therefore time series data is needed to determine the systems' capacity and subsequently simulate energy flows. For the year 2020, the PV data is derived from the website renewables.ninja developed by (Pfenninger & Staffell, 2016). For solar radiation at the TGV, the following input data is used:

- Longitude: 4.3776
- Latitude: 51.9975
- Data set: MERRA-2
- Year: 2020
- Capacity: 1000 W
- System loss: 0.1
- Tracking: None
- Tilt: 35 degree
- Azimuth: -

The last variable, the azimuth, is left blank as it depends on the facing direction of the solar panels. The azimuth is the angle between the North (0º) and the facing direction of the PV panels. The angle is measured clockwise, so when the PV panels face East, the azimuth is 90º. For South facing panels, the azimuth is 180º and 270º for panels facing West. In 4.1, the electricity generation of 2020 for South and West facing panels are shown, with the input set as shown above.



(a) PV generation (South) for the year 2020

(b) PV generation (West) for the year 2020

Figure 4.1: PV generation for three wind directions

The solar panels installed for the Sustainer homes at TGV are faced West. So, for the solar energy produced in 2020 for the Sustainer homes, an azimuth of 270º is used. The installed capacity is 6 kW. Therefore, the electricity output from renewables.ninja for West facing PV panels is multiplied by 6 to determine the amount of electricity consumed at Sustainer Home 12 in 2020.

The input data used as PV generation is facing south, as this results in the highest amount of solar energy yearly. Thus, an azimuth of 180º is used to obtain solar energy for 2020.

## 4.3. Component data

In this section, the input data for the different components are given. The input data are the technical specifications, investment costs (CAPEX), operation and management costs (OPEX), and lifetime.

For the components present at TGV, the input data is obtained by consulting the experts at TGV. For the other components, literature, manufacturer sites or governmental policy analysis are used. The components are discussed in alphabetical order.

### 4.3.1. Air compressor

The air compressor is part of the CAES-FEES design. The air compressor is used to compress air in the CAES and is driven by the electricity generated by the solar panels and the motor. A manufacture, airpress, site is consulted as a reference air compressor. In addition, a technical report carried out for the U.S Department of Energy is used to retrieve price indications, as the price difference at the manufacturing site is very high (Airpress, n.d.). According to the information of Airpress (n.d.) a reference air compressor can produce 41.88 m$^3$ per hour and has a capacity of 5.5 kW. This results in a production rate of 7.61 m$^3$/kWh.

For the costs Mongird et al. (2020) did a research to different CAES systems. Based on costs estimates made by Siemens and literature, this report gives price indicators for the different components in a CAES based energy system. This also includes the air compressor. With the use of initial capacity calculations for the CAES system, the power output of the total CAES flow in the CAES-FEES configuration is equal to the peak demand, as stated in chapter 3, eq. (3.36), because the power output is equal to the generator capacity. Therefore, the prices of the smallest case study are taken. In the technical report, the prices are given in $, so a currency rate is used to convert to euros. At this moment, the currency rate is 1.08966 $/€. So, the investment cost for the air compressor is $158.00/1.08966, resulting in a CAPEX of €145.00. The operation and management costs for the air compressor are set to zero. These costs are included in the generator costs, as only the OPEX of the total CAES system flow is available. For the lifetime of the air compressor, it is assumed that the air compressor has the same lifetime as the hydrogen compressor, which is equal to 10 years (Parks G et al., 2014)

Table 4.4: Input values: air compressor

| | Air Compressor | unit |
|---:|---:|:---|
| Production rate | 7.61 | [$m^3$/kWh] |
| CAPEX | 145.00 | [€/kW] |
| OPEX | - | [€/kWh year] |
| Life time | 10 | [year] |

### 4.3.2. Battery

The battery is one of the components installed at TGV. The battery they have is a $LiFePO_4$ accu. According to X. Wang et al. (2012) the efficiency of such a $LiFePO_4$ battery can be between 87% and 99%, depending on how fast the battery charges. As the battery is used as a flexible energy supply, it is assumed that the total charge/discharge time is around 10h, resulting in an efficiency of 95%. In addition, the review of X. Wang et al. (2012) shows that the DoD is also very high and could be above 90%. However, to increase the battery's lifetime, it is chosen to have a smaller DoD. The SoC minimum is 20%, and the SoC maximum is 95%, resulting in a DoD of 75%.

The price identification is based on the investment costs of TGV. The battery at TGV has a capacity of 15 kW, and the investment costs were €6000.- for the battery and €1500.00 additional costs for the inverter. This results in a CAPEX of €7000.00/15 = €500.00/kWh. The lifespan of a battery is often given in the number of cycles, where a cycle is from SoC min to SoC max and back to SoC min. For the $LiFePO_4$, the lifetime is approximately 2000 cycles, where it still operates at 80% of its capacity (X. Wang et al., 2012). It is difficult to determine the number of cycles per year within this control strategy, as the charging and discharging processes intersperse. So, based on expert knowledge, the lifetime is set at 12 years.

Table 4.5: Input values: battery

| | Battery | |
|:---|---:|:---|
| Efficiency [%] | 95 | % |
| SoC minimum [%] | 20 | % |
| SoC maximum [%] | 95 | % |
| CAPEX (variable) | 500.00 | [€/kW] |
| OPEX | 5.00 | [€/kWh year] |
| Lifetime | 12 | [year] |

### 4.3.3. CAES

The input data for the CAES system are based on the technical report of Mongird et al. (2020), just as the air compressor and the research of Nielsen and Leithner (2009). For the CAES, the storage capacity is in m$^3$. This metric is used to estimate how large the storage facility must be. The conversion factor is 3.07 kWh/m$^3$, based on the assumptions of Nielsen and Leithner (2009). However, this is based on the temperature and pressure in the storage facility. The rest of the calculations are all done in kWh.

Table 4.6: Input values: CAES

| CAES | | |
|---|---|---|
| Storage capacity | 3.07 | [kWh/m$^3$] |
| CAPEX | 3.67 | [€/kWh] |
| OPEX | 0.47 | [€/kWh year] |
| Life time | >25 | [year] |

The CAPEX and OPEX are retrieved from Mongird et al. (2020), where the prices are given in \$; therefore, the current currency rate of 1.08966 \$/€ is used. According to this technical report, a reasonable assumption of the investment costs for the CAES storage is between \$4.00 and \$3.50. This thesis uses the upper bound, resulting in a CAPEX of €3.67/kWh. For the OPEX, the value of \$0.5125/MWh is used. The MWh refers to the variable costs of the energy flow going through the storage. The fixed O&M costs are integrated with the OPEX of the generator. The lifetime of a CAES is expected to be a minimum of 20 years but could be up to 40 years (Rogers et al., 2014; J. Wang et al., 2017). In this case study, it is assumed the CAES has a lifetime longer than 25 years.

### 4.3.4. Electrolyser

The electrolyser is also acquired by TGV. Therefore, the input data, presented in table 4.7, is based on the Alkaline anion exchange membrane (AEM) electrolyser at TGV. The electrolyser is from Enapter. The product information can be found on the website of Enapter (2021). The electrolyser can produce 1.0785 kg/day, equal to 0.0449 kg/h. In addition, the electrolyser has a rated capacity of 2.4 kW. So, the production rate is 0.0187 kg/kWh. This value is needed to calculate how much hydrogen [kg] is produced.

Table 4.7: Input values: electrolyser

| Electrolyser | | |
|---|---|---|
| Production rate | 0.0187 | [kg/kWh] |
| CAPEX | 3750 | [€/kW] |
| OPEX | 37.50 | [€/kW year] |
| Life time | >20 | [year] |

The investment costs for the electrolyser are €9000.00 for a capacity of 2.4 kW, resulting in a price per kW of €3750.00. The operation and management costs of an electrolyser are assumed to be 10% of the CAPEX. This estimation is based on expert knowledge. Finally, according to Motealleh et al. (2021), the lifetime of an AEM electrolyser is more than 20 years.

### 4.3.5. Expander

The expander is part of the CAES energy system. In table 4.8 the input data is shown. As input data, only the efficiency is important to calculate the losses between the CAES and the power output. The CAPEX and OPEX are included in the CAPEX and OPEX of the generator, as the costs for the whole CAES energy system are calculated at once in Mongird et al. (2020). The efficiency of the generator is around 84%, according to the research of Deng et al. (2019).

Table 4.8: Input values: expander

| Expander | | |
|---|---|---|
| Efficiency | 84 | [%] |
| CAPEX | - | [€/kW] |
| OPEX | - | [€/kW year] |
| Life time [year] | - | [year] |

### 4.3.6. Fuel Cells

The fuel cells at TGV are PEM fuel cells from Nedstack. These fuel cells are used for the input data shown in table 4.9. The technical product information is obtained from Nedstack (2022). With this information, the production rate is calculated. The fuel cells consume 77 L/min, equal to 4.620 $m^3$/hour since 1L is equal to 1000 $m^3$ and 1 hour is equal to 60 minutes. Subsequently, the density of hydrogen is 0.089 kg/$m^3$, resulting in a consumption of 0.4158 kg/hour. The rated power of the fuel cells is 6.8 kWe. Therefore the production rate is 6.8 kWe/0.4158kg, equal to 16.354 kW/kg.

Table 4.9: Input values: fuel cells

| Fuel cells | | |
|---|---|---|
| Production rate | 16.354 | [kWh/kg] |
| CAPEX (variable) | 1029.41 | [€/kW] |
| CAPEX (fixed) | 6000 | [€] |
| OPEX | 10.29 | [€/kW year] |
| Life time | 8 | [year] |

The investment costs for these fuel cells are divided into capacity dependent costs and fixed costs. The fuel cells from Nedstack (2022) have a capacity of 6.8 kWe and costs around €7000.00, so the price per kW is €1029.41. The fixed costs are for the surrounding equipment and are equal to €6000.00. The lifetime of the fuel cell is 8 years. However, the fuel cells only operate during winter times. Therefore, it is assumed the fuel cells can run up to 16 years.

### 4.3.7. Generator

The input data of the generator is based on the technical report of Mongird et al. (2020) and the literature research of Deng et al. (2019). The efficiency of the generator is 84%, which is used to determine the power output of the CAES system.

Table 4.10: Input values: generator

| Generator | | |
|---|---|---|
| Efficiency | 84% | [%] |
| CAPEX | 477.21 | [€/kW] |
| OPEX | 14.96 | [€/year] |
| Life time | >25 | [year] |

The CAPEX and the OPEX in table 4.10 represents the total costs for the components of the CAES system, except for the storage facility. So, this includes the motor, the compressor, the expander and the generator. The CAPEX is based on a 110MW CAES power plant built in 1991, where the costs are corrected for the year 2020. The generator is part of the CAES system, which has a life expectancy of 20 to 40 years (Rogers et al., 2014; J. Wang et al., 2017). So it is assumed the generator will last longer than 25 years.

### 4.3.8. Heat pump

The heat pump is based on the heat pump at TGV. This heat pump is an electric heat pump from Panasonic. The COP value in table 4.11 are obtained via Aircon (n.d.). The COP is 5, which means that the heat pump is able to produce 5 kW of heat with 1 kW of electricity. In reality, this is not always the case, as it depends on the temperature difference between inside the building and the environment. However, for this thesis, the COP is constant, with a value of 5. The total investment cost for the 5 kW capacity heat pump is €3449.00, so the price per kW is €689.20. The OPEX is assumed at 5% of the CAPEX, as not much maintenance is needed. The lifetime of a heat pump is 10 years (Hepbasli & Kalinci, 2009; Willem et al., 2017).

Table 4.11: Input values: heat pump

| Heat pump | | |
|---|---|---|
| COP | 5 | [-] |
| CAPEX | 683.20 | [€/kW] |
| OPEX [€/year] | 3.42 | [€/year] |
| Life time | 10 | [year] |

### 4.3.9. Hydrogen boiler

A hydrogen boiler burns hydrogen gas a atmospheric pressure. Therefore the calorific value of hydrogen gas is used assuming a low heating volume. This is 3 kWh/m$^3$, and by using the density of hydrogen of 0.090 kg/m$^3$, the calorific value of 33.33 [kWh/kg] is obtained.

The technology of the hydrogen boiler is still at an early phase and not yet economically feasible, therefore, the price for a natural gas boiler is used. This boiler is currently commonly used in the Netherlands. An average natural gas boiler is used as reference (Feenstra, n.d.), resulting in a CAPEX of €97.50 per kW. The OPEX of the hydrogen is estimated at 5% of the CAPEX, as boilers are assumed to be low-maintenance. The lifetime of a hydrogen boiler is assumed to be similar to the lifetime of a natural gas boiler. According to the research of Consumentenbond (n.d.) the lifetime is around 15 years.

Table 4.12: Input values: hydrogen boiler

| $H_2$ Boiler | | |
|---|---|---|
| Calorific value | 33.33 | [kWh/kg] |
| CAPEX | 97.50 | [€/kW] |
| OPEX | 0.49 | [€/kW/year] |
| Life time | 15 | [year] |

### 4.3.10. Hydrogen compressor

At TGV, there is a hydrogen compressor from HyET. An overview of the input data is shown in table 4.13 and it retrieved from HyET (n.d.). The capacity of the compressor is 2 kg/day, which is equal to 0.0833 kg/hour. This value is used to determine the total CAPEX of the Hydrogen compressor. Using the electrolyser's hydrogen output, the compressor's needed capacity [kg/hour] is determined. The CAPEX of this hydrogen compressor is €300.00 per kg/day. As the capacity of the electrolyser is per hour, the needed capacity for the hydrogen compressor is multiplied by 24.

Table 4.13: Input values: hydrogen Compressor

| $H_2$ Compressor | | |
|---|---|---|
| Production rate | 0.0833 | [kg/h] |
| CAPEX | 300.00 | [€/kg/day] |
| OPEX | 0.5 | [€/kg/year] |
| Lifetime | 10 | [year] |

The OPEX in table 4.13 is the cost as a result of the kg that is produced per year. In a technical report for the U.S Department of Energy Hydrogen and Fuel Cells Program by Parks G et al. (2014) the lifetime of a hydrogen compressor is 10 years. This value is assumed in this case study.

### 4.3.11. Hydrogen storage

The hydrogen is stored at TGV in hydrogen tanks. These hydrogen tanks have a cylinder shape, and the total amount of cylinders can store 60 kg of hydrogen gas. The investment costs for these tanks were €12000.00, so to store 1 kg, €200.00 should be invested. The OPEX is assumed to be 10% of the CAPEX based on expert knowledge. The lifetime of these storage tanks is also based on expert knowledge and is assumed to be higher than 25 years. An overview of these values is shown in table 4.14.

Table 4.14: Input values: hydrogen storage

| $H_2$ storage | | |
|---|---|---|
| CAPEX (variable) | 200.00 | [€/kg] |
| CAPEX (fixed) | 12000.00 | [€] |
| OPEX | 2.00 | [€/kg/year] |
| Life time | 20 | [year] |

### 4.3.12. Motor

In table 4.15 the input values for the motor are depicted. The motor is an electrical motor, and the efficiency is assumed to be 96% based on the research of Courtois et al. (2021). The costs for the motor are included in the costs for the generator, as Mongird et al. (2020) includes all the costs in one value for the motor, expander, and generator.

Table 4.15: Input values: motor

| Motor | | |
|---|---|---|
| Efficiency | 96 | [%] |
| CAPEX | 0 | [€/kW] |
| OPEX | 0 | [€/year] |
| Life time | 25 | [year] |

### 4.3.13. PV panels

At TGV, there are PV panels, and the capacity of those panels is 260Wp per panel. However, there is no further information about the costs for these panels. According to the research of IRENA (2019) the price per kW capacity is $995.00. Converted to euros, the price is €913.12 per kW. The OPEX is assumed to be 5% of the CAPEX. The lifetime of solar panels is based on expert knowledge and set at 25 years.

Table 4.16: Input values: PV panels

| PV panels | | |
|---|---|---|
| CAPEX | 913.12 | [€/kW] |
| OPEX | 4.57 | [€/year] |
| Life time | 25 | [year] |

# 5

# Case study: Results analyses

In this chapter, the results of the case study are discussed. The results are two folded. First, in section 5.1, there is a technical analysis based on the operation of the energy system. Secondly, in section 5.2, there is a financial analysis, looking at the total costs, the consumer energy price of the system, and, in section 5.3, financial sensitivity analyses. These results are based on the capacities determined with the model. An overview of the capacities of all the components for each demand case and each DES design can be found in appendix G.1.

## 5.1. Technical analysis

In this heuristic design approach, assumptions are made about the size of the components in the system. Therefore, a technical analysis is carried out to reflect on the performance of the energy systems. For the technical performance, it is looked at the reliability of the system and the energetical performance of the system. From the five different KPIs, the LLP and the FER are used for the reliability analysis. The DR, SR and SE are used to examine the energetical performance.

### 5.1.1. Reliability analysis

In table 5.1 and table 5.3, the LLP and the DR are shown for the four DES configurations and the five demand cases. Two conclusions are made about the reliability.:

- The $H_2$-FEES, $H_2$-HES, and CAES-FEES have an LLP and DR of zero, i.e. the demand load per time step is always met for these three configurations. This also means that these DESs operate autonomously from the central grid.
- The $H_2$-HES-FC configuration is not 100% self-sufficient. An LLP between 0.2% and 0.4% is calculated. This means that the chance that the energy demand is not met during the year is equal to the LLP percentage. In the Dutch energy system, the goal of the TSO is a maximum LLP of 0.01%. However, the TSO measures their LLP with smaller time steps. In this LLP calculation, time steps of one hour are used. Thus, the LLP represents the percentage of hours where a black-out could occur for a few seconds or minutes. Therefore, the FER is relevant. The FER is between 0.0002 and 0.00195. This means that for each kWh, a maximum of 0.00195 kWh is not met.

Table 5.1: Loss of load probability per decentralised energy system and demand load in percentages [%]

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $H_2$-HES | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| $H_2$-HES-FC | 0.0 | 0.2 | 0.2 | 0.3 | 0.4 |
| CAES-FEES | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

Table 5.2: Failed energy ratio per decentralised energy system and demand load

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 0 | 0 | 0 | 0 | 0 |
| $H_2$-HES | 0 | 0 | 0 | 0 | 0 |
| $H_2$-HES-FC | 0 | 0.0002 | 0.0190 | 0.0009 | 0.0195 |
| CAES-FEES | 0 | 0 | 0 | 0 | 0 |

### 5.1.2. Energetical analysis

For the energetical performance analysis, three KPI's are used;

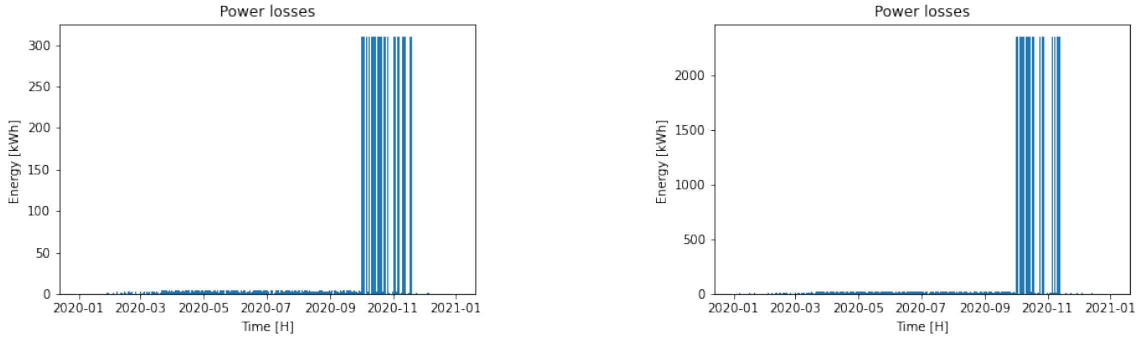
- First of all, the DR is used. According to Narayan et al. (2019) the DR should be below 1. This means that the dumped energy is lower or equal to the total demand load.
- Secondly, the SR. If the value is close to 1, the storage size is theoretically optimal because the stored energy is also used. If the value is close to zero, there is a lot of energy produced and stored that is not used. This means that the storage facility is oversized, as there is room for this unused energy. If the ratio value is above 1, more energy is used from the storage facility than stored. This is possible because the storage facilities start with an initial amount of stored energy for each of the different DES configurations.
- Thirdly, the SE. If the SEy is 100%, all the energy produced from the solar panels is used to meet the energy demand. However, some energy is lost due to the efficiencies of components or dumped energy. The SEy can be above 100% if additional energy is extracted from the environment using solar energy. This is the case when using a heat pump

From table 5.3, it can be concluded that for each of the designed energy systems, the DR is almost zero, or just above zero, except for the $H_2$-HES design. The DR is high for the $H_2$-HES configuration as the PV panel capacity is sized to comply with the electricity peak demand in winter. There is low solar irradiation during winter, and more PV panels are needed.

However, the long-term storage is sized for the heat demand, so the storage tank size equals the heat demand in the winter. Therefore, the hydrogen tanks are already full halfway through the year. In addition, during summer, there is a larger surplus. However, when there is no space to store the energy surplus, the potential energy cannot be used and is therefore dumped energy. Figure 5.1 shows the moments when the energy is dumped. This occurs already during summer, but the largest amounts of energy are dumped at the end of the summer. This is when the storage tanks are full for winter, but there is still an energy surplus.

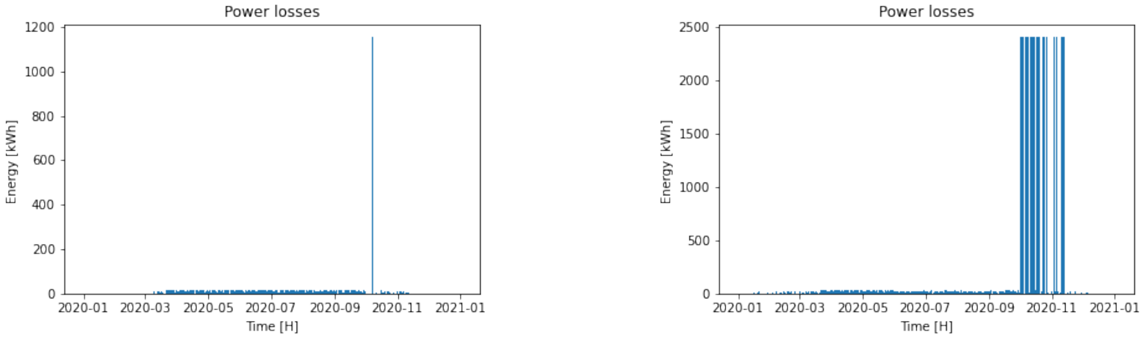
Table 5.3: Dump ratio per decentralised energy system and demand case

| | Single apartment | Corner house | Terraced house | Apartment community | Terraced house community |
|---|---|---|---|---|---|
| **$H_2$-FEES** | 0.000 25 | 0 | 0 | 0 | 0 |
| **$H_2$-HES** | 10.8 | 13.7 | 7.5 | 9.0 | 8.3 |
| **$H_2$-HES-FC** | 0 | 0 | 0 | 0 | 0 |
| **CAES-FEES** | 0.0038 | 0.0001 | 0.002 | 0.001 | 0.004 |



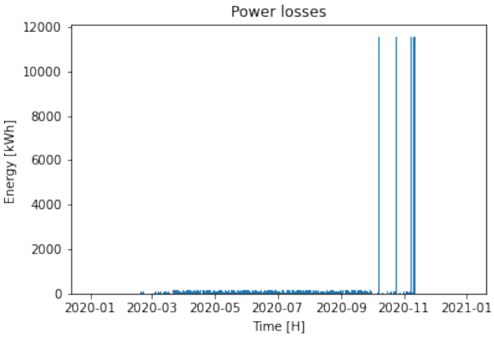
(a) Single apartment

(b) Corner house



(c) Terraced house

(d) Apartment community



(e) Terraced house community

Figure 5.1: Energy losses in the hydrogen-based hybrid energy system

The long term SRs are all above 1 except for the $H_2$-HES-FC configuration. Table 5.4 shows these values. So for the long term, this system operates best, followed by the $H_2$-HES design. As the hydrogen is needed for the heat demand, hydrogen production is based on the heat demand, resulting in lower SR values compared to the fully electrified energy systems.

Table 5.4: Storage ratio: long term storage facilities

| | Single apartment | Corner house | Terraced house | Apartment community | Terraced house community |
|---|---|---|---|---|---|
| $H_2$-FEES | 2.34 | 3.00 | 1.67 | 2.85 | 1.93 |
| $H_2$-HES | 1.24 | 1.23 | 1.28 | 1.31 | 1.19 |
| $H_2$-HES-FC | 0.75 | 2.25 | 0.72 | 0.75 | 0.85 |
| CAES-FEES | 2.35 | 4.03 | 1.63 | 5.34 | 1.76 |

For the short term storage in table 5.5, the fully electrified systems are better sized than the hybrid energy systems. The ratio values are relatively close to 1. The sizing of the battery for hybrid energy systems is less accurate. In the $H_2$-HES simulation, the outflow of the storage is higher than the inflow. The opposite accounts for the $H_2$-HES-FC. The inflow is higher than the outflow, resulting in unused stored energy.

Table 5.5: Storage ratio: short term storage facilities

| | Single apartment | Corner house | Terraced house | Apartment community | Terraced house community |
|---|---|---|---|---|---|
| $H_2$-FEES | 0.89 | 0.84 | 1.08 | 1.01 | 1.07 |
| $H_2$-HES | 1.31 | 1.70 | 1.28 | 1.31 | 1.30 |
| $H_2$-HES-FC | 0.44 | 0.94 | 0.81 | 0.15 | 0.56 |
| CAES-FEES | 0.82 | 0.89 | 0.99 | 0.93 | 1.00 |

The SE is shown in table 5.6. The SEs of the fully electrified energy systems are higher than the hybrid versions. This is due to the use of a heat pump in those systems. A heat pump extracts additional energy from the environment, and therefore, in this case, 1 kWh of electricity can supply 5 kWh of heat. This is also the reason why the corner house demand case is above 100% for the $H_2$-FEES configuration.

The SE values of the $H_2$-HES configuration are around 10%. The explanation for this low value is found within the DR. The DR is for this system configuration a value around 10. This means that per 1 kWh used as energy supply, 10 kWh could not be used. As explained in the DR section, this is due to the large capacity of solar panels. From an SE perspective, fully-electrified energy systems operate the most optimally.

Table 5.6: System efficiencies in percentages [%]

| | Single apartment | Corner house | Terraced house | Apartment community | Terraced house community |
|---|---|---|---|---|---|
| $H_2$-FEES | 93.3 | 121.2 | 67.8 | 97.8 | 72.5 |
| $H_2$-HES | 8.1 | 6.4 | 11.2 | 9.6 | 10.2 |
| $H_2$-HES-FC | 61.1 | 60.8 | 70.8 | 69.4 | 69.8 |
| CAES-FEES | 88.3 | 96.2 | 94.5 | 95 | 94.8 |

So, with respect to the energetical performance of the systems, the $H_2$-HES-FC design operates best. There is no dumped energy, the storage in and outflow make it possible to use the system for multiple years and for the SE, the fully electrified energy systems perform better, but this configuration has a efficiency above 60%, which is also a relatively high efficiency. However, improvements can be made to optimise the energetical performance. From both the DR and SR, two assumptions can be made about the correct sizing of the components.

- If the DR is above zero and the SR exceeds 1, the storage facility is full, and the energy cannot be stored. By increasing the storage capacity, the DR will go down.
- If the SR is above 1 and the DR is 0, the PV panel capacity can be increased. This will increase the costs of the system, although there is no failed energy.

**Conclusion: Technical analysis**

From the technical analysis, it can be concluded that:

- All the systems operate autonomous, except for the $H_2$-HES-FC system;
- The $H_2$-HES-FC performs best with respect to the energetical performance;
- All the systems could be improved with respect to sizing the storage and PV capacities.

## 5.2. Financial analysis

In this section, the financial analysis is discussed. The financial analysis looks at the financial impact on a household. A CEP is determined for each case to compare the price per kWh with the reference case. Therefore, the reference case is explained first, followed by the analysis of the CEP values. Afterwards, sensitivity analyses for the investment costs and the input demand data are included.

### 5.2.1. Reference energy system

The reference case represents the current centralised energy system. The national electricity grid supplies the electricity and the heat demand is generated by a natural gas boiler. The natural gas is delivered by pipelines. Figure 5.2 shows a simplified configuration. In this reference energy system, the sizing of the components does not matter as the TSOs of both the electricity network and the gas network make sure the demand is met.

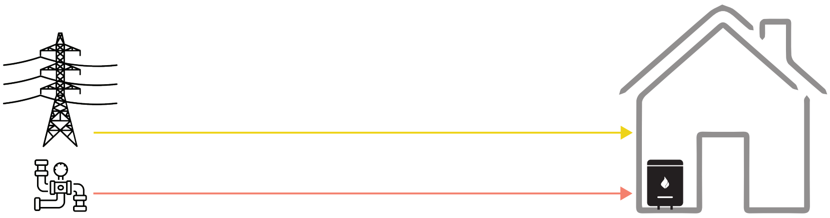


Figure 5.2: A simplified overview of the reference energy system

The energy demand for the reference case is equal to the demand used for the different demand cases. The cost input is based on the gas and electricity price in the Netherlands. Table 5.7 shows the energy prices used in this thesis.

Table 5.7: Input values: current energy price

| | Reference case | |
|---|---|---|
| Electricity price (variable) | 0.56 | €/kWh |
| Electricity price (fixed) | −485.10 | €/year |
| Gas price (variable) | 0.27 | €/kWh |
| Gas price (fixed) | 264.06 | €/year |
| CAPEX Boiler | 97.50 | €/kW |

The electricity price and gas price are the prices from March 2022 retrieved from (Centraal Bureau voor de Statistiek, 2022). Within these energy prices, the price for $CO_2$ compensation is included. In addition, there are fixed costs. These fixed costs are the delivery prices, transport prices and taxes.

Furthermore, during the life span of 25 years, a homeowner must replace a boiler for central heating at least twice, as the average lifetime of a boiler is 15 years. The calculation for the investment costs is similar to the calculation of the investment costs for the other systems, taking into account the discount rate and the investment year. The investment years are year 7 and year 22, assuming the boiler is already a few years old. The CAPEX for the boiler is from (Feenstra, n.d.).

### 5.2.2. Consumer energy price

The CEP reflects the price the consumer should pay for one kWh to have a return on investment in 25 years. This time span is set, as this is the expected life time of solar panels. This could either be the price a consumer has to pay to the system owner, or a virtual price per kWh for the prosumer, that does not pay per kWh but made the upfront costs. However, in this research, the system owner is out of scope, and it is assumed that the consumer pays the price per kWh, just as in the current energy system, neglecting to whom. In this research, the CEP is used to compare the different designs. In table 5.8, the CEP for the 20 different cases is presented, and the energy price for the current energy system per demand case. This current energy price is around €0.48, except for the corner house. Due to the different electricity:heat ratio, the energy price for the corner house demand case is €0.38.

Table 5.8: Consumer Energy Price in euros per kilowatt-hours [€/kWh]

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 1.86 | 1.37 | 1.43 | 1.06 | 1.35 |
| $H_2$-HES | 1.78 | 1.06 | 1.21 | 1.11 | 1.11 |
| $H_2$-HES-FC | 1.50 | 0.72 | 0.84 | 0.77 | 0.79 |
| CAES-FEES | 1.05 | 0.78 | 0.74 | 0.63 | 0.70 |
| Reference | 0.48 | 0.38 | 0.48 | 0.46 | 0.47 |

From table 5.8, four observations are made:

- Firstly, the DES configurations are not competitive with the current energy prices of reference case. So, with these input values, it is concluded that the financial impact for households is always negative compared with the current situation.

- Secondly, the prices of the single apartment case are substantively higher than the other demand cases for single households.
- Thirdly, the apartment community is the cheapest demand case, followed by the terraced house community, then the single household cases. Thus, the community cases are cheaper than the single household cases.
- Finally, the $H_2$-HES-FC and the CAES-FEES are the cheapest configurations.

To understand these observation, and thus the differences in CEP, the following two relations are identified:

- The ratio between the total investment costs and peak demand;
- The ratio between total energy demand and peak demand.

These two relations can be mathematically expressed with

$$\mathrm{CEP} = \frac{\text{Investment cost}}{\mathrm{P_{peak}}} \cdot \frac{\mathrm{P_{peak}}}{\mathrm{E_{demand}}}. \tag{5.1}$$

The first relation looks at a relation between the investment costs and the peak demand. This value is expressed in the capacity costs. The capacity costs are the costs that must be paid when increasing the capacity of the system (Hayes & Brown, 2022). In this thesis the expansion of capacity is not relevant, as the costs calculation is more complex as not all components are sized on peak capacity. Therefore, it is defined as the theoretical capacity costs and can be calculated with

$$\text{Theoretical capacity costs} = \frac{\text{Total costs}}{\mathrm{P_{peak}}}, \tag{5.2}$$

where the $\text{Total costs}$ [€] are equal to the investment costs and the operational costs and $\mathrm{P_{peak}}$ [kW] is the highest energy demand for a time step in the demand curve. The $\text{Theoretical capacity costs}$ [€/kW] are the theoretical costs for each additional kW of peak demand. In table 5.9, these theoretical capacity costs are shown.

Table 5.9: Theoretical capacity costs in euros per kilowatt [€/kW]

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 10 517.97 | 19 523.60 | 22 669.86 | 16 912.41 | 24 014.66 |
| $H_2$-HES | 14 255.50 | 28 910.43 | 27 322.08 | 27 548.00 | 30 053.22 |
| $H_2$-HES-FC | 8508.10 | 10 617.29 | 13 668.39 | 12 472.00 | 14 470.10 |
| CAES-FEES | 6263.55 | 11 822.57 | 12 555.36 | 10 675.44 | 13 386.02 |

From table 5.9, it can be seen that the theoretical capacity costs for the $H_2$-HES-FC and CAES-FEES configurations are almost half of the theoretical capacity costs for the $H_2$-FEES and $H_2$-HES configurations. This reflects the outcome of the CEP.

The second relation looks the ratio between peak demand and total energy demand. This ratio can be expressed as the capacity factor (CF). The CF is frequently calculated for renewable energy systems and it represents the percentage of time needed if a power plant operates at full capacity relative to the actual amount of energy that is produced over a certain time span. By dividing the actual energy output with the potential maximum output a value is obtained that represents this CF. In this thesis, the time span to calculate the CF is set at one year. This means that the actual energy output is equal to the yearly total energy demand. The potential maximum output is defined as the peak demand times the amount of hours per year, as the system is sized to comply with peak demand. The CF of the system can be seen as the percentage of a year that the system should operate to comply with the total energy demand. A higher CF means that the peak capacity of the system is in theory more frequently needed to fulfill the total energy demand, resulting in a lower price per kWh. The other way around, if the percentage is lower, the peak capacity of the system is not often used, resulting in a higher price per kWh. The CF of the system can be calculated with

$$\mathrm{CF} = \frac{\mathrm{E}_{\mathrm{demand}}}{\mathrm{P}_{\mathrm{peak}} \cdot \mathrm{time}}. \tag{5.3}$$

In table 5.10, the results of this calculation can be found. $\mathrm{E}_{\mathrm{demand}}$[kWh] and $\mathrm{P}_{\mathrm{peak}}$[kW] are obtained from TGV data, where $\mathrm{E}_{\mathrm{demand}}$ is the yearly total energy demand and $\mathrm{P}_{\mathrm{peak}}$ is the highest energy demand found in the demand curve. For $\mathrm{time}$[h] the total amount of hours in a certain time span is used. For this thesis the amount of hours is equal to 366 ×24 = 8784. The bottom row represents the capacity factor.

Table 5.10: Capacity factor of the system

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| Total demand [kWh] | 4306.3 | 23 782.6 | 22 083.3 | 43 241.2 | 199 688.0 |
| Peak demand [kW] | 8.4 | 18.3 | 15.3 | 29.7 | 122.5 |
| Capacity factor [-] | 6 % | 15 % | 16 % | 17 % | 19 % |

### difference between household types

Both relations explain the difference between households. From table 5.8, it can be seen that the CEPs of the corner house and the terraced house are cheaper than the single apartment demand case. A price difference between 10% and 25% is calculated, respectively. On community scale, the difference is much smaller between apartments and terraced houses.

The second relation and table 5.10 help with understanding this difference. At the single household scale, the single apartment CF is around two to three times smaller than the CF of the corner house and the terraced house respectively. For the community scale the difference between the apartment community and the terraced house community less apparent. So, the CF of the system and the CEP are inversely proportional; a higher CF results in a lower CEP. This relation partly explains the difference between demand cases.

The first relation explains why the CEP difference is not the same as the CF difference. The CF of the system only looks at peak demand related to the total demand. However, the capacity of the different components in the system is not entirely sized on the peak demand. The impact of the peak demand related to the costs depends on the demand case. The costs per kW of the peak demand is lower for the single apartment than for the corner house and terraced house. Therefore, the difference between the household types is not as high as the CF ratio.

### Differences between scale

Two scales are considered, a single household scale and a community scale. From table 5.8, it is observed that the community scale demand cases are cheaper than the single household cases. The same reasoning accounts as for the difference between housing types account for the community scale. The CF of the system is for the community demand cases higher than for the single household demand cases, resulting in lower prices. In addition, the investment costs divided by the peak demand explains why the difference is not equal to only the CF difference. Looking at table 5.8, it can be seen that the difference between the single apartment and apartment community is bigger than between the terraced house community and the corner and terraced house. This large difference is also seen in table 5.10. This differene can be explained by the composition of the community scales. The terraced house community is based on seven times a terraced house and only two corner houses, as the community is assumed to be one row of 9 houses. Thus, the sizing of the components in the community is for almost 80% determined by the demand of the terraced house case from TGV. Therefore, the benefit of community sizing is less significant, as the peak hours coincide instead of the advantage of the distribution of peak hours.

### Difference between configurations

From table 5.9 and table 5.8 it is seen that the lowest investment costs related to the peak demand result in the lowest CEP as well. However, the influence of the peak demand on the investment costs is more complicated as not all components are sized on the peak demand. This can be explained by diving deeper into the investment costs per component.

Table 5.11 gives an overview of the investment costs per component per unit. From this table, it can be concluded that the components in the CAES system that are different from the components in the $H_2$-based energy systems are cheaper. This partly explains why the CAES-FEES is cheaper than the $H_2$-FEES system. The size of the components determines the other part.

Table 5.11: Investment costs per component

| | CAPEX | unit |
|---|---|---|
| Air Compressor | 145.00 | €/m^3 |
| Battery | 500.00 | €/kW |
| CAES | 3.67 | €/m^3 |
| Compressor | 12.50 | €/(kg/day) |
| Electrolyser | 3750.00 | €/kW |
| Fuel Cell | 1029.41 | €/kW |
| Generator | 477.21 | €/kW |
| Heat Pump | 683.20 | €/kW |
| Hydrogen Boiler | 97.50 | €/kW |
| Hydrogen Storage | 200.00 | €/kg |
| Motor | 176.54 | €/kW |
| PV panels | 913.13 | €/kW |

In fig. 5.3 four columns are included that show the CAPEX, including the costs per component, of the single apartment demand case.

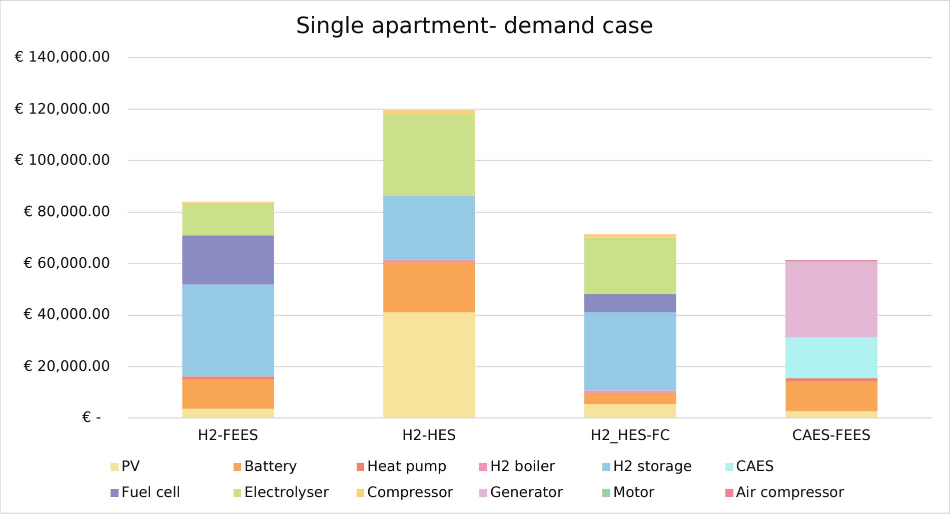


Figure 5.3: CAPEX division for each of the energy system configurations - single apartment demand case

The costs are elaborated per system:

- In the $H_2$-FEES, the cost for the hydrogen storage tanks is 54% of the total investment costs. In this system, hydrogen storage is responsible for both the heat demand and electricity demand. In addition, the capacity is sized to store 70% of the total energy demand in winter. This results in a high capacity, and thus, high investment costs as the costs per kg are €200.00.
- The division for the $H_2$-HES is quite different. The PV panels contribute most to the CAPEX. Within this configuration, the electricity demand is completely generated with the PV panels and a battery. This means that there must be enough PV panels installed to fulfil the electricity demand during winter when there are not many solar hours. In addition, hydrogen is only needed for the heat demand, resulting in smaller capacities for the electrolyser and hydrogen storage. The high share of investment costs for the PV panels was expected as the DR of this $H_2$-HES is very high, as seen in table 5.3. From this, it can be concluded that the size of the PV panels and the storage facility should be reconsidered. Because a larger battery results in less needed installed PV capacity, and the battery is cheaper per kW than the PV panels. However, the energy losses with charging and discharging may result in higher costs.
- For the $H_2$-HES-FC, the contribution of the costs for the hydrogen storage is higher than for the $H_2$-FEES; 59% of the total costs. In this system hydrogen is also used for both heat and electricity. The share is higher, due to the hydrogen boiler. The hydrogen boiler is used to generate heat, and therefore hydrogen is used for the total heat demand. This is different than the $H_2$-FEES, where solar energy can be used as well to comply with the heat demand.
- In the CAES-FEES configuration, the generator contributes most to the total investment costs for the single apartment demand case. However, in the other demand cases the CAES contributes most to the total costs, as can be seen in appendix G.1. Although the CAES component is the cheapest per unit, the total capacity needed is similar to the hydrogen storage in the $H_2$-FEES configuration. The cost share of long-term storage is the biggest because the other components in the CAES-based energy system are relatively cheaper than the components in the $H_2$-based energy system responsible for converting the long-term storage back to electricity.

### 5.2.3. Conclusion: Financial analysis

Based on this case study, four conclusions can be made with the demand data from TGV and the chosen configurations.

- First, these DES configurations are not competitive with the current energy system prices.
- Secondly, systems sized for community scale demand are cheaper than single household scale. This is due to the higher CF of the system, cause by a distribution of peak demands of different households. Moreover, the difference for apartments is larger than between the terraced house community and corner and terraced house.
- Thirdly, the $H_2$-HES-FC and CAES-FEES configurations are the cheapest DES designs. For the $H_2$-HES-FC, this is due to the smaller components in the hydrogen flow due to the hydrogen boiler compared to the other hydrogen-based energy systems. For the CAES-FEES design, this is due to the cheaper components related to long term storage compared to the components for the hydrogen flow.
- Finally, the costs for the long term storage facilities contribute most to the total investment costs for all the energy systems, except for the $H_2$-HES. For that design, the costs are mostly based on the costs for the PV panels.

## 5.3. Financial sensitivity analyses

A sensitivity analysis looks at the effect of input values on the outcome. For this study, two sensitivity analyses are carried out to see the effect of different variables on the CEP. The first analysis is into the investment costs per component, and a second one into demand date input.

### 5.3.1. Sensitivity of the investment costs

The influence per component on the total investment costs is analysed by varying the input value one at a time. This method eliminates the ambiguity of which input variable caused the change. The input variables are changed with respect to the base case, which is defined in chapter 4.

The input value is varied with 10%, resulting in a 90% price scenario and a 110% price scenario. In this section, for the four different DES configurations, the sensitivity analysis for the single apartment demand case is included. The other demand cases can be found in appendix H.

In fig. 5.4, the result of the sensitivity analysis is shown for the $H_2$-FEES. The sensitivity analysis shows that the costs for hydrogen storage have the most significant impact on the total investment cost, followed by the battery, electrolyser, PV panels, fuel cell, heat pump, and compressor. Although the fuel cell and electrolyser are the most expensive components in the system, a 10% reduction or rise results in a price difference of less than 1%. This is due to the relatively small capacity needed compared to the PV panels, battery and hydrogen storage. However, it should be noted that the maximum difference is 3.6% if the price increases or decreases by 10%. Therefore, the outcome is non-sensitive to the cost input variables.

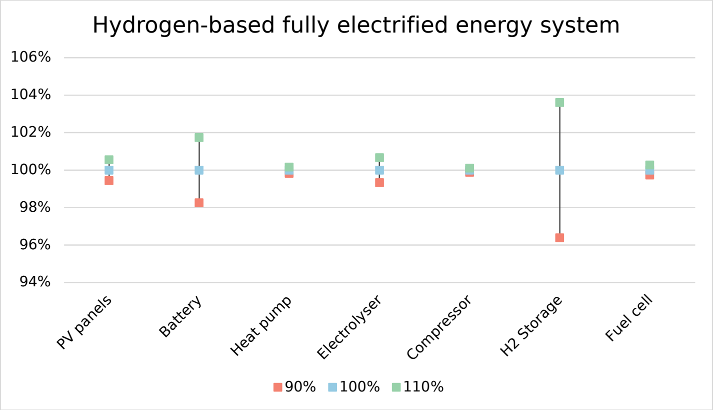


Figure 5.4: Sensitivity analysis: single apartment, a hydrogen-based fully electrified energy system

Figure 5.5 shows the result of the sensitivity analysis for the $H_2$-HES. In this configuration, the price of PV panels has the largest influence on the investment costs. With a price change of 10%, the total investment costs vary by 4.2%. The solar panels have the largest impact because the capacity is oversized, as was seen with the DR analysis. In addition, the solar panels' capacity is larger than in the $H_2$ system as it must produce more electricity during winter, as long term storage only contributes to satisfying the heat demand. The influence of the electrolyser is in this configuration greater than for the $H_2$-FEES design. In this case, the capacity of the electrolyser is higher, as it generates the total amount of hydrogen needed to comply with the heat demand. The maximum result difference for this configuration is 4.2%, and therefore, the outcome is insensitive to a variety of input values.

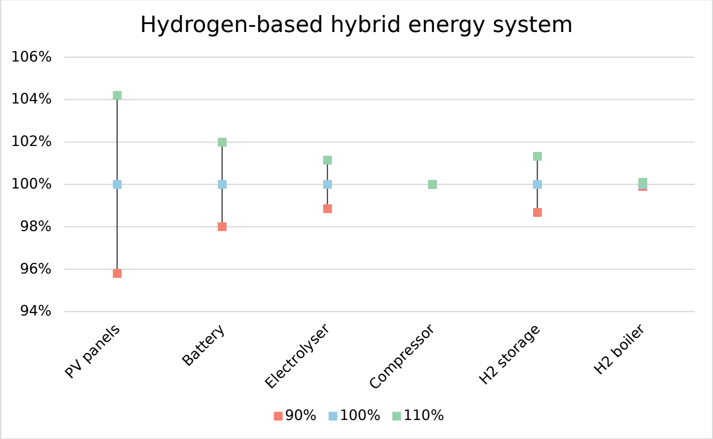


Figure 5.5: Sensitivity analysis: single apartment, a hydrogen-based hybrid energy system

From fig. 5.6, it can be concluded that the price for the hydrogen storage has the biggest impact on the $H_2$-HES-FC configuration. In this system, hydrogen is used for heat and electricity, just as in the $H_2$-FEES system. Therefore, the hydrogen storage capacity is more significant, resulting in a bigger influence than in the $H_2$-HES. In addition, the costs for the fuel cell have the second largest impact. This is different from the $H_2$-FEES configuration. The smaller capacity of the battery partly explains this. Moreover, the influence of the electrolyser is comparable with the PV panels and the battery. This is due to the smaller difference between the capacities in the system. The biggest impact is a change of 3.6%, which means that the outcome is not sensitive to a change of the input values.

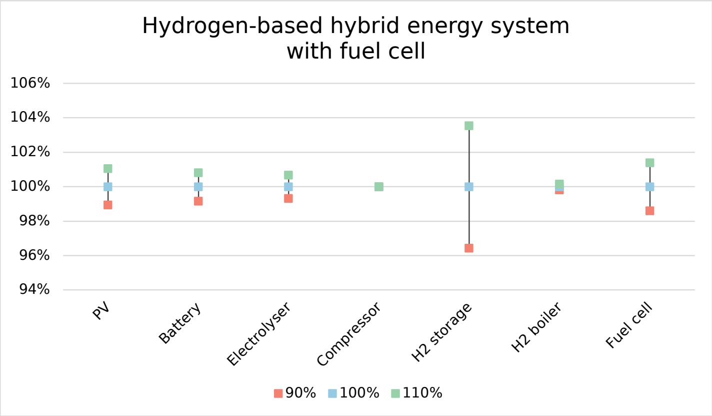


Figure 5.6: Sensitivity analysis: single apartment, a hydrogen-based hybrid energy system with fuel cell

The result of the sensitivity analysis for the CAES-FEES configuration is shown in fig. 5.7. For this DES design, the change in costs for the CAES results in the biggest change in the total investment costs, followed by the battery. In this case, it should be noted again that a 10% reduction of the CAES costs results in a 3.2% difference in the total costs, and therefore the outcome is not sensitive to the changes in input values. The most negligible impact is by the motor and compressor.

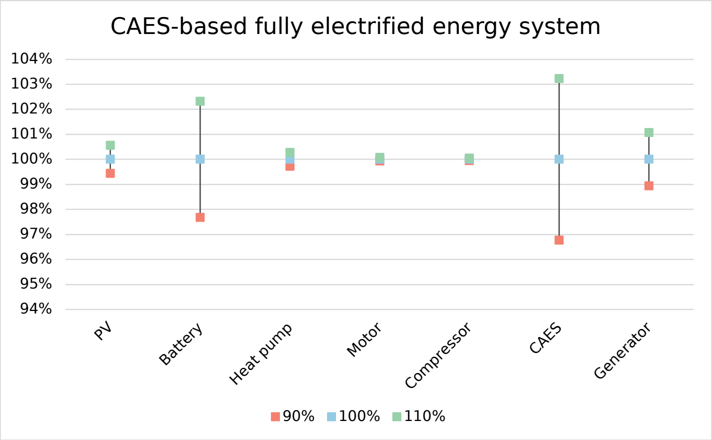


Figure 5.7: Sensitivity analysis: single apartment, a compressed air energy storage-based fully electrified energy system

Thus, based on this sensitivity analysis, it can be concluded that the results are non-sensitive to the changes in the input values as a change from 10% results in a maximum change of 4.2%. However, conclusions can be made about the impact of the different components. In most configurations, the long-term storage facility price has the most impact on the total investment costs, except for the $H_2$-HES system. In that case, the price of PV panels has the biggest influence on the costs. The other demand cases are similar to these figures, resulting in the same components per DES configuration with the most significant impact on the total investment cost.

### 5.3.2. Sensitivity of component sizes

Thus far, the designs of the energy systems are all based on 100% autonomy, assuming they are not connected to the main grid. The FER and LLP are zero, so a grid connection is unnecessary to fulfil the energy demand. In the case of occurring dumped energy, this energy is wasted, as it cannot be used or stored in the system.

If there is a grid connection, there is a possibility of selling and importing energy to and from other users outside this designed community. In this part of the research, a sensitivity analysis is performed into the technical performance and financial outcome. The energy system is designed for an autonomy of 80%. This is done by lowering the hourly demand input for the sizing part of the model to 80%. The outcome of the component sizes is included in appendix G.1. The total energy demand declines by reducing the autonomy level. In addition, the peak demands will also be lower. After the sizing, the simulation is done with the 100% demand data. For this sensitivity analysis, the LLP, FER and DR are looked at. From these values, it can be concluded how often and how large the share of energy is that must be imported from the grid. In addition, with the DR it can be seen if electricity can be sold to the grid. Finally, the average CEP is calculated, including the power bought from the grid and energy sold to the grid.

$$\mathrm{CEP_{corrected}} = \frac{\mathrm{CEP_{\%}} \cdot (\mathrm{E_d} - \mathrm{E_{fail}}) + \mathrm{import} - \mathrm{export}}{\mathrm{E_d}}, \tag{5.4}$$

where CEP is determined with eq. (3.42), $\mathrm{E}_{d}$ is the total energy demand and the import and export are equal to:

$$\mathrm{import} = \mathrm{E_{fail}} \cdot p_{\mathrm{energy}}, \tag{5.5}$$

$$\mathrm{export} = \mathrm{E_{dump}} \cdot \mathrm{p_{LCOE}}, \tag{5.6}$$

where $\mathrm{E}_{fail}$[kWh] and $\mathrm{E}_{dump}$ [kWh] are the total amount of failed energy and dumped energy, respectively. $\mathrm{p}_{electricity}$ is equal to the electricity price as defined in table 5.7. $\mathrm{p}_{LCOE}$ is the LCOE of the solar panels. This LCOE is assumed to be the minimum price for which the generated energy is sold to the grid.

### Technical performance analysis

For the technical performance analysis a autonomy level of 80% is chosen. This means that the capacities of the components are sized based on 80% of the total demand. However, for the performance simulation, the 100% demand data is used. For this sensitivity analysis the LLP, the FER and the DR are analysed.

In table 5.12 the LPP is shown, in table 5.13 the FER is presented and in table 5.14 the DR is depicted. From these KPIs two conclusions are made.

- The LLP stays the same for the all the configurations, except for the $H_2$-HES-FC. For this design, the LLP increases. However, looking at the FER, the amount of energy that should be bought from the grid is 3% or lower, so the system is still 97% self-sufficient. Thus the smaller size of the components does not result in a significant change in technical performance.
- The DR decreases for the $H_2$-HES and CAES-FEES configuration. The smaller capacities of solar PV result in less dumped energy.

Table 5.12: Loss of load probability for 80% autonomy design in percentages [%]

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 0.0002 | 0 | 0 | 0 | 0 |
| $H_2$-HES | 0.001 | 0 | 0 | 0 | 0.002 |
| $H_2$-HES-FC | 0.034 | 0.300 | 0.307 | 0.338 | 0.482 |
| CAES-FEES | 0.15 | 0.11 | 0.00 | 0.14 | 0.00 |

Table 5.13: Failed energy ratio for 80% autonomy design

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 0.0019 | 0.0 | 0.0 | 0.0 | 0.0 |
| $H_2$-HES | 0.0015 | 0 | 0 | 0 | 0.0018 |
| $H_2$-HES-FC | 0.0014 | 0.0005 | 0.027 | 0.0011 | 0.030 |
| CAES-FEES | 0.24 | 0.16 | 0 | 0.16 | 0 |

Table 5.14: Dump ratio for 80% autonomy design

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 0.000 27 | 0 | 0 | 0 | 0 |
| $H_2$-HES | 8.4 | 10.7 | 5.8 | 7.0 | 6.4 |
| $H_2$-HES-FC | 0 | 0 | 0 | 0 | 0 |
| CAES-FEES | 0.008 | 0 | 0.001 | 0 | 0.002 |

**Investment costs analysis**

In table 5.15 the new CEPs are shown. Comparing this table and table 5.8, table 5.16 is generated with the differences in price. From these tables, four observations are made;

- The CEP decreases for all the demand cases;
- The CAES-FEES and $H_2$-HES-FC configuration become competitive with the current energy system prices for the apartment community;
- The CEP for the corner house has the higher reduction;
- The CEP for $H_2$-HES declines the most.

The first observation can be explained by the CF of the system and the change in component sizes. In table 5.18, the new CF percentage are presented. For the four configurations, the CF of the system changes. The largest difference in CF is for the terraced house community. In addition, per system, some components change in size:

- For the $H_2$-FEES, the decrease in the costs arises in the first place from the reduction of $H_2$ storage capacity. This component changes the most. Secondly, the most expensive components per kW, the fuel cell and electrolyser decrease as well. However, the total financial impact is lower as is concluded from the product of investment costs and capacity reduction.

- In the case of the $H_2$-HES configuration, the highest reduction is for the solar panels. This component contributed the most to the total investment costs. In addition, the capacities of the other components are lower as well.
- For the $H_2$-HES-FC design, the storage decreases the most. This has the highest influence on the CEP. The financial impact for the lower capacities of the more expensive components is smaller, as the product of the investment costs and the capacity change is lower than for the hydrogen storage.
- In the CAES-FEES, the cost reduction is mainly caused by the difference in CAES size. The same reasoning goes for this system as for the hydrogen-based systems, as the CAES is the cheapest component in the system.

The second observation can be explained by the difference between the price reduction between the components. In the 100% self-sufficient system, the CAES-FEES and $H_2$-HES-FC configurations are the cheapest designs. From table 5.16, it can be seen that the CAES-FEES design declines a bit more than the $H_2$-HES-FC configuration. As a result, the CAES-FEES becomes the cheapest option, except for the corner house. However, The CEP difference is still close.

The third observation can be explained by the combination of the CF and the theoretical capacity costs. The theoretical capacity costs are one of the most expensive for the corner house demand case. In addition, the CF increases more than the other CFs. Together, this resulted in the largest decline.

The fourth observation is because of the decline in the total costs for solar panels. But also the benefits from selling the dumped energy to the grid. As seen in table 5.14, the DR ratio is between 5.4 and 10.7. This means that perused kWh, 5.4 kWh - 10.7 kWh is sold to the grid. The LCOE of solar panels is €0.07. This results in a price reduction of €0.38 - €0.75 per kWh. This has a significant impact on the final outcome.

Table 5.15: Consumer energy price for 80% autonomy design in euros per kilowatt-hours [€/kWh]

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 1.62 | 1.12 | 1.19 | 0.87 | 1.12 |
| $H_2$-HES | 1.49 | 0.88 | 0.99 | 0.90 | 0.90 |
| $H_2$-HES-FC | 1.27 | 0.59 | 0.69 | 0.63 | 0.64 |
| CAES-FEES | 0.79 | 0.62 | 0.61 | 0.52 | 0.56 |
| Reference | 0.48 | 0.38 | 0.48 | 0.46 | 0.47 |

Table 5.16: Percentage of consumer energy price change between the 100% and 80% demand input in percentages [%]

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | −23 | −29 | −28 | −29 | −29 |
| $H_2$-HES | −45 | −60 | −45 | −50 | −49 |
| $H_2$-HES-FC | −12 | −18 | −16 | −18 | −18 |
| CAES-FEES | −25 | −20 | −18 | −18 | −19 |

From the percentages in table 5.16, conclusion about the sensitivity of the demand input data are made as well. For the $H_2$-FEES the reduction of 20% causes a cost reduction between 11% and 13%. Therefore, the CEP is not sensitive to the input data in case of the $H_2$-FEES configuration. The same accounts for the $H_2$-HES-FC configuration, except in the Apartment community case. For the $H_2$-HES and CAES-FEES the input data is sensitive. A reduction of 20% results in a CEP reduction of more than 36%.

Table 5.17: Theoretical capacity costs - 80% autonomy in euros [€/kW]

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| $H_2$-FEES | 10 900.39 | 20 580.48 | 23 103.10 | 17 897.68 | 24 487.78 |
| $H_2$-HES | 13 710.44 | 29 158.35 | 29 782.67 | 29 542.15 | 32 605.44 |
| $H_2$-HES-FC | 7467.08 | 11 031.71 | 13 758.32 | 11 121.05 | 13 975.85 |
| CAES-FEES | 7164.11 | 13 151.13 | 14 018.05 | 12 053.93 | 14 780.08 |

Table 5.18: Capacity factor of the system - 80% autonomy

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| Total demand [kWh] | 4306.3 | 23 782.6 | 22 083.3 | 43 241.2 | 199 688.0 |
| Peak demand [kW] | 6.7 | 14.7 | 12.2 | 23.7 | 98.0 |
| Capacity factor [-] | 7 % | 18 % | 21 % | 21 % | 23 % |

## 5.4. Discussion of results

From this analysis, the conclusion can be made that staying connected to the grid is beneficial for the financial competitiveness with the current energy system. By determining the sizes of the components based on a lower demand, the performance of the system does not change much; however, the price does. In this thesis, only the 80% scenario is looked into, and a significant price reduction is already observed. This result is fruitful for further research on the autonomy of the system. In addition, with these sensitivity analyses the CEP differs, resulting in a smaller or larger difference with the current energy price. The current energy prices are assumed to be constant in this study, but in real life this price is fluctuating over time. Therefore, the smallest differences between the CEP and current energy prices are interpreted as competitive.

# 6

# Conclusions and recommendations

The goal for a sustainable future is set; however, this comes with many changes in different sectors. One of the sectors that has a significant impact on life is the built environment, as changes in the built environment change the residents where people live in and most likely also the way people live. A more active role is predicted in the future for residents due to a switch to DESs. This research aimed to gain insight into the financial impact on households concerning this change. In this chapter, the answer to the main research question is given. Afterwards, recommendations for further research and real-life applications are presented.

## 6.1. Conclusions

In this section, only the main findings are stated, as the sub-questions are answered throughout the report already. Firstly, the technical performance conclusions are listed, followed by the financial conclusions and the conclusions arising from the sensitivity analyses. In the end, these separate conclusions are combined into one final conclusion and the answer to the main research question.

### Technical conclusions

Based on five KPIs, the reliability of the system and the energetically of the system is analysed for the four different autonomous decentralised energy systems.

- The reliability of the system is analysed with the loss of load probability and the failed energy ratio. From this analysis, it can be concluded that the $H_2$-FEES, the $H_2$-HES and the CAES-FEES configurations are 100% reliable. Only the $H_2$-HES-FC operates not 100% self-sufficient. For that design, the amount of energy that is not met by the system is only 0.2% of the total energy demand.
- For the energetical analysis of the system, three KPIs are used. A dump ratio, the storage ratio and the system efficiency. Based on these outcomes, the $H_2$-FEES operates best. However, not optimal, as there is still dumped energy for one of the demand cases, and the storage ratio could also be improved.

### Financial conclusions

For the financial outcome, three conclusions can be made.

- First, 100% autonomous decentralised energy systems are not competitive with the current energy prices. The difference between the cheapest DES design case and the reference case is €0.16.
- When looking only at the three single households cases, the corner house has the lowest CEP. This difference can be explained by the CF and the theoretical capacity costs. The CF has the most impact on the CEP difference. A higher CF, results in a lower CEP. In addition, lower theoretical capacity costs results in a lower CEP, however this relation has less impact than the CF.
- The CEPes for community scale DES are lower than the DES designed for a single household. This is due to the higher CF. With the community scale, the peak demands of different households are distributed over time. This means that the components sized at peak demand are more often used at a higher capacity.
- Thirdly, the $H_2$-HES-FC and the CAES-FEES configurations are the cheapest configurations. For the hydrogen based energy system, using a hydrogen boiler results in a lower hydrogen storage capacity. In addition, using a fuel cell is beneficial, as it reduces the need for PV panels, and the fuel cell is sized for the electricity demand only. The CAES-FEES configuration is relatively cheap because the generator, motor and expander have lower investment costs than the fuel cell and the electrolyser. For the long term storage capacity, the price for the CAES is per unit much lower. However, the needed capacity for the CAES is higher than for the hydrogen storage.

### Conclusions based on the sensitivity analyses

From the sensitivity analyses, two conclusions can be made.

- Firstly, a reduction in investment costs does not influence the price enormously. A reduction of 10% for a component leads to only a maximum decrease of 4%. This maximum reduction is seen with the long term storage facilities, except for the H2-HES system. In that case, the most profit is gained from reducing the price of PV panels.
- Secondly, a design based on a lower demand input makes the energy system competitive with the current energy system. The lower capacities of components result in lower investment costs and thus a lower CEP. In this thesis, a demand input of 80% is studied. The technical performance of the system changes not much. Only small fractions must be imported from the grid. In addition, the dumped energy for the hybrid energy system without fuel cells is reduced. Financially, a reduced level of autonomy is attractive. The CEP is for the CAES-FEES, and the $H_2$ are similar to the current energy price. Moreover, for the community scale and terraced house demand cases, the CAES-FEES is cheaper, and for the corner house demand case, the price is equal to the current energy price. This result shows that sizing the components to a reduced self-sufficiency level makes a DES competitive with the current energy prices.

The financial impact is determined by the energy price per kWh, which is based on the costs for the installation and operation of the components in the system. These costs are determined by the used components in the configuration and the needed size. There are many different configurations possible. In this thesis a selection of four different DES designs is researched, resulting in different outcomes. The needed sizes for the components is based on the total demand curve, which is, in turn, determined by the community size, the autonomy level, the housing type, the energy label, and the households it self. All resulting in different demand curves. The financial impact is thus affected by many variables, and therefore, the answer to the question *"What is the financial impact of a small scale decentralised energy system on households?"* is not unambiguous. However, based on the input values and model in this thesis, the cheapest case would result a negative financial impact of €0.17 per kWh for the CAES-FEES system in the apartment community case and a 100% self-sufficiency. All the other cases have a larger negative financial impact. If the self-sufficiency level is declined to 80%, the negative impact is €0.06 per kWh for the cheapest case.

Based on all these conclusions, it is advised to design a decentralised energy system on a community scale that is not 100% self-sufficient. Furthermore, the CAES-FEES is the cheapest configuration in the apartment community case, and it becomes competitive with the current energy system, within the error margin. Therefore, it is advised to start adapting apartment communities.

In addition, the hydrogen energy system with a hydrogen boiler and the fuel cell is also competitive. So, if a hydrogen configuration is preferred, the hydrogen should be used for electricity, and the heat demand should be generated with a hydrogen boiler.

However, there are limitation with respect to this conclusion. In section 6.2 these limitations are discussed.

## 6.2. Reflections

In this thesis research is done into DES configurations to gain insight into the financial impact on households. Four different DES configurations are analysed, and conclusions are made based on a heuristic design approach to define the sizing of the components in the DES. However, this research has its limitations. These limitations are essential to consider when reading the conclusions of the research. In this section, the limitations are discussed.

The study is looks into four DES configurations. Many assumptions are being made within these DES designs about the components. First of all, there are various other components applicable for DES. In appendix B, some of these other components are mentioned. In this thesis, it is decided to look into hydrogen based systems and neglect CHP systems. However, it could be possible that CHP systems result in lower energy prices, as the efficiencies are higher.

Secondly, there are also different technologies available on the market for the chosen subsystems. As mentioned in appendix B, this accounts for batteries, electrolysers, fuel cells and CAES systems. These design decisions also influence the sizing outcome due to different performance levels, and subsequently, the financial outcome is also influenced by these design choices. Thirdly, within the technologies, there are different performance levels as well. Some newer, more recent developments could result in better performance of the components. So the assumed characteristics of the components have an effect as well.

Furthermore, the assumed costs of the components do have an impact on the outcome as well. Most of the costs are based on actual investments made by TGV. However, these investments were made already in 2020 or earlier. Within the energy sector, the prices of components are developing together with the technology. So, the costs used for this research could be changed already. An example is the price of solar panels. In the report of IRENA (2019) the price of PV panels, a cost reduction of more than 20% occurred between the years 2018 and 2019. For the $H_2$-HES configuration, this has a considerable influence on the final outcome as shown in the sensitivity analysis. The sensitivity analysis gained insight into how big the impact is when costs differ. Although the effect of a 10% cost reduction or increment is not exceeding 5% for one single component, if multiple components have different actual prices, the result will be different.

Beside the costs for the components, the current energy market price does also differ. At the moment, due to the global developments in Ukraine, the energy prices became sky high during this research. This change has an effect on the financial impact, as the difference declines when the energy prices increase. In addition, this also influences the priority within the political environment to be energy independent. As a result the Dutch government is already reducing the negative financial impact by introducing subsidies for hybrid heat pumps (Rijksoverheid, 2022).

For this thesis, the demand data from TGV is used. But, TGV is a testing site, resulting in multiple energy systems that are being tested. This influenced the demand curve. For example, at the end of 2020, a company tested a PCM storage. This flattened out the expected demand curve. Furthermore, the people living in the residential building at TGV are not regular. One of the Woody's is inhabited by a student with a 3D printer. This results in other energy demands than is expected. Moreover, there were some complications with the sensors of the Sustainer Homes. As these sensors only measured the energy input from the grid and the output, the solar panels' energy was assumed to be the value from renewables.ninja. However, it is not 100% sure if this was the actual energy production by the solar panels, as there could be clouds, or technical issues. Finally, a division between heat and electricity demand was needed for this research. This division was given only for the DreamHussen, as the other buildings at TGV are fully electrified. Therefore, assumptions are made about the ratio between heat and electricity demand.

In addition, there are no communities at TGV with the same housing type of more than three houses. Therefore the communities are composed from the available demand data by using one load curve multiple times in a community. As a result, the effect of community size systems is smaller than in case of nine different demand curves, due to the division of the peak load over the year.

Finally, there are geographical consideration. First of all, the performed case study was located in Delft at TGV. The solar irradiation from that location is used. However, the solar irradiation is site specific. The results obtained with this case study only account for TGV. In addition, for some locations other energy sources could be more beneficial. For example, to satisfy the heat demand in some areas district heating is also an option and could be preferred over a heat pump or a hydrogen boiler and the DESs is only needed to satisfy the electricity demand. In that case the configuration design must be dominated by the electricity demand.

## 6.3. Recommendations

Further research into DESs is relevant to gaining insights into a potential future energy system. In this thesis, a model is built to define the sizing of the components for four different autonomous DES configurations. With this model, many insights are already acquired. However, there are also matters left for further investigations. In addition, from this research, there are also recommendations for real life. The recommendations are divided into four categories: recommendations for model improvements, recommendations for input improvements, recommendations for real life applications and recommendations for stakeholders.

### Recommendations for model improvements

This model is built within the time and the decisions made for this thesis. However, the model can be improved. The most relevant improvements for the model :

- Firstly, the model can be improved by making it possible to compare more configurations and control strategies. This thesis considers four configurations: two fully electrified energy systems and two hybrid energy systems. The used calculation method works for these configurations. However, there are more configurations and control strategies possible. Further research is therefore advised into other configurations.
- Secondly, for the reference case, there are energy prices assumed. However, these energy prices are not constant over a whole year. Therefore, it is relevant to look into the price sensitivity of the reference case, as this is the price used to compare if a DES is competitive with the current energy system. Moreover, the model can be improved by making the energy price variable per time step.
- In addition, the sizing method worked for the five demand cases used as a case study. However, between these demand cases, there were differences in the financial outcome and the technical performance. Testing more demand cases can improve the sizing method, making it a more robust design method, and widely applicable.
- Finally, the model can be improved by implementing subsidies. Currently, there are already subsidies available for households to invest in sustainable improvements to their homes. This is also not taken into account, but it is interesting to see if a policy measurement has an significant effect on the outcome. Also new policy measurements can be tested, to see if the desired effect is achieved.

### Recommendations for input improvements

The input of the model has a significant impact on the outcome. The input of the model was the demand data, the PV data and the cost data. Those three can be improved.

- First, the model can be improved by expanding the time span of the demand cases. In the current model, the DES is designed and analysed for energy demands of one year. The storage ratios show that the amount of long-term stored energy at the end of the year is lower than at the beginning of the year. When following this energy demand curve for multiple years, the stored energy will not be sufficient. However, the energy demand and energy generation are different per year, as this depends on the available solar energy and household behaviour. Therefore it is advised to expand the run time to multiple years.
- In addition, the used demand data is from TGV. As mentioned in the reflection part, this demand data has some limitations. Therefore the demand data can be improved by using demand data that is not influenced by different technologies that are tested for a few weeks or months. In addition, for the community size demand data, it is advised to use demand curves from different households, instead using a demand curve multiple times to see a better effect of the community case. Finally, it should be considered how the demand is expected to change over the years. Due to technical developments and consumer behaviour changes.
- The PV data is based on the solar irradiation for solar panels facing south, as this results in the highest total energy generation over a year. However, it could be more beneficial to place the solar panels East and West, because this distributes the energy generation over the day, which could result in a lower storage capacity as this means that energy generation and energy consumption are more aligned.

- For the costs data, investment costs are assumed based on available data. As mentioned by the limitations, some of these costs are from a few years back. In addition, there are developments with respect to the investment costs. It could be interesting to look into realistic price developments to improve the input data.

### Recommendations for real life applications

This thesis is mainly desk research. A model is used to calculate the sizes and the technical performance of different configurations. Therefore, practical experience can give more insights. In real life, the following studies are interesting:

- First of all, the outcome of this research is a virtually designed energy system. The actual sizes of the components are not taken into account for the feasibility of the systems. A study into the actual area needed to install a DES is necessary, as that could be a limitation for implementing a DES. In addition, the physical house adaptations are not taken into account. For example, the research with respect to hydrogen pipelines in houses is lacking.
- Secondly, this model should be used in a real design case. By putting this model into practice, the model can be improved based on experiences and feedback. In addition, this sizing method aims to design a suitable initial decentralised energy system configurations and should be helpful in practice.
- Finally, this thesis touches upon the autonomy level of the system and significant price reduction is seen. However, the assumed 80% self-sufficiency level is not necessarily the optimal level. Therefore, a more extensive research into the autonomy level can be performed to look for an optimum. This could be either a research to find a generic optimum, to see at which percentage the reduction of autonomy and the price decline is not significant any more.

### Recommendations for stakeholders

This research is relevant for multiple stakeholders. First and foremost, the households, but this research is also relevant for policy makers and companies in the energy sector. For each of the stakeholders the most important recommendations are stated below:

- For households it has been found that the heat demand contributes most to the total energy demand. The heat demand is influenced by the insulation level of a house. Therefore it is advised to look for insulation possibilities to reduce the total costs of a DES. This research makes this recommendation more apparent, as the division between electricity demand and heat demand is made explicitly. In addition, for households it is recommended to look into their demand profile and reduce their peak demands. The peak demand is for multiple components the guideline for the capacity and thus determines the investment costs. So, reducing the peak demand will reduce costs.
- For policymakers it is necessary to make sure to achieve the climate goals. DESs can contribute to these goals. However, it is concluded from this research that at the moment these options are financially not attractive. Therefore, it is advised to compose policy measures to reduces the investment costs. This can be done with either subsidies to stimulate households to buy these installations. Another option is to look for economies of scale, by stimulating mass production for certain technologies. Furthermore, policymakers should steer the direction of the DES solution. From this research it is concluded that the hydrogen-based configurations are more expensive than the CAES-based DES design. So, for the residential sector this

- For energy system operators the need to adapt to DESs is already clear. In the Netherlands, the TSO, responsible for the electricity grid, does not make new grid connections in multiple provinces (TenneT, 2022). In this case, this measurement does not affect the residential sector, however, the solution could be in the residential sector. The TSO of the Netherlands is currently working on research into grid congestion. As follow up, it is recommended to advise municipalities and provinces and about the DESs options and do research into the locations where the need to adapt is pressing. Furthermore, from this research is it concluded that DESs should not completely autonomous. Thus the households should stay connected to the main grid. This gives additional challenges for the system operators. These challenges include the trading between DESs and how to deal with an overall surplus in multiple DES configurations. With these insights it is recommended for the system operators to find solutions on how to deal with these changes and do research into other, less obvious, challenges.

# A

# Appendix: Literature Overview

In this appendix an overview of the literature used for the literature review is included. This overview is obtained by a systematic research using the search engine ”Scopus”. The keywords used to find the suitable articles are ”decentralised energy system”, ”Integrated Community Energy System”, and ”self-sufficient energy communities”.

For the selection of relevant articles, a few criteria were set.

- Only articles published is the past 10 years is included;
- Specific case studies are excluded.

Based on this initial set of articles, the last step is to include articles by forwards and backwards snowballing. This is respectively looking at articles that have cited the initial article or looking at articles that are cited by the initial article. This process resulted in 46 articles that represent the current research into DESs. This overview is presented in table A.1 and table A.2

Table A.1: Literature overview (1)

| Authors | Year |
|---|---|
| Adams S, et al. | 2021 |
| Arsalis A, Gearghiou G | 2018 |
| Bahret C , Eltrop L | 2021 |
| Bögel P, et al. | 2021 |
| Calver P, Simcock N | 2021 |
| Chen Y, et al | 2020 |
| Davarzani S, et al. | 2021 |
| de São José D, Faria P, Vale Z | 2021 |
| Eriksson E, Gray E | 2017 |
| Fonseca J, et al | 2019 |
| Gassar A, Cha S | 2021 |
| Ghaem Sigarchian S, Malmquist A, Martin V | 2018 |
| Gstöhl U, Pfenninger S | 2020 |
| Gui E, MacGill I | 2018 |
| Kalinci Y, Hepbasli A, Dincer I | 2014 |
| Karunathilake H, et al. | 2019 |
| Khalid F, Dincer I, Rosen M | 2016 |
| Kolahan A, et al. | 2021 |
| Li N, Hakvoort R, Lukszo Z | 2021 |
| Li N, Hakvoort R, Lukszo Z | 2021 |
| Little M, Thomson M, Inflied D | 2007 |

Table A.2: Literature overview (2)

| Authors | Year |
|---|---|
| Majeed Butt O, Zulqarnain M, Majeed Butt T | 2021 |
| Maroufmashat A, et al | 2016 |
| McKenna R, Merkel E, Fichtner W | 2017 |
| Milan C, Bojesen C, Nielsen M | 2012 |
| Murray P, et al. | 2018 |
| Natarajan S, et al | 2019 |
| Parag Y, Sovacool B | 2016 |
| Peláez-Pelsáez S, et al | 2021 |
| Perger T, et al. | 2021 |
| Rafea K, et al. | 2017 |
| Roberts M, Sharma A, MacGill I | 2022 |
| Scheller F, et al | 2018 |
| Schwarz H, et al | 2019 |
| Schwarz H, et al | 2018 |
| Schwarz H, et al | 2017 |
| Sidki Uyar T, Ikci B | 2016 |
| Singh S, et al | 2020 |
| Song Y et al. | 2021 |
| Zakeri B, et al. | 2021 |
| Zoulias Ã, E I, Lymberopoulos, N | 2007 |
| Bauwens T, et al. | 2022 |
| Weinand J, Scheller F, McKenna R | 2020 |

# B

# Appendix: components applicable in decentralised energy systems

In this section different components are discussed that are suitable in small scale DESs. A division is made between subsystems that supply heat, subsystems that supply electricity, subsystems that supply heat and electricity, and subsystems that can store energy. The subsystems, explained in this thesis, are a selection of many more subsystems. The selection is based on two criteria.

- The scale of the system.

The subsystem should be able to meet the total energy demand for a particular area. This means that the energy system must generate electricity and heat that complies with that energy demand. For a small scale DES it is assumed that the subsystem must generate for multiple houses.

- The readiness of the system.

Only technologies that are already deployed for residential use are taken into account. Technologies that have not reached the deployment phase are not considered, as those technologies have too many uncertainties about operability and costs.

## B.1. Heat subsystems

**Solar thermal collectors**

A mature technology to fulfil the heat demand of a household is solar thermal collectors. Solar collectors are placed on top of a roof and use solar radiation to produce heat. The solar collectors are applicable on single-household, multi-household and district scale, respectively studied by Rahaman and Iqbal (2019), Monsalvete Álvarez de Uribarri et al. (2017) and Huang et al. (2019). The heat generated with solar thermal collectors can solve the intraday imbalance.

**Boilers**

A boiler is a central heating system that needs an energy source to heat water (Martinopoulos et al., 2018). The boiler is frequently used in multiple residential buildings for space heating and DHW in the

Dutch built environment. However, most of them operate on natural gas, resulting in $CO_2$ emissions. RES-based boilers also exist. Two sorts of boilers are considered; a full electric boiler and a hydrogen boiler

The electrical boiler needs electricity to generate heat. The needed electricity to heat the tank can come from PV panels, wind turbines or another RES power plant. Such a full electric boiler can be applied on a household scale, just as the current gas-fired boilers. On the other hand, electric boilers can also be upscaled to district-scale (Sinha et al., 2019).

The hydrogen boiler needs hydrogen to produce heat. This hydrogen boiler operates the same as a natural gas boiler. A hydrogen boiler can be applied at a single household level but also at multiple household level as Ozturk and Dincer (2021) explain their research. With the use of direct combustion, the hydrogen gas is incinerated, resulting in a flame that heats the water tank (Dodds et al., 2015).

Comparing both boilers, the electric boiler is more mature than a hydrogen boiler. The electric boiler is already commercially available for single households, whereas the hydrogen boilers are not yet commercially available, also because of safety reasons (Gigler et al., n.d.).

**Heat pumps**

A heat pump can be used to develop a DES without $CO_2$ emissions. A heat pump pumps heat from a low-temperature source to a source with a higher temperature (Sarbu & Sebarchievici, 2014). During summer, the heat pump can provide cooling to a building, and during winter, vice versa. The needed temperature difference can be found within the ground, air, or water.

The air-source heat pump (ASHP) . extracts heat from the open air. The efficiency is therefore dependent on surrounding climate (Zhao et al., n.d.). The ASHP is suitable for single households but also applicable in larger scales (Zhang et al., 2017) Guo and Goumba (2018) compares the heat pump on both scales. They conclude that ASHP should be applied at an individual level. In addition, the ASHPs are a proven technology Cho and Yun (2011) and De Swardt and Meyer (2001). This also results in a configuration that is easy to instal and has low installation costs Bertsch and Groll (2008). A disadvantage of an ASHP is that the system stops operating when the outside temperature is below 0 ºC Zhang et al. (2017) therefore, the ASHP is not always a suitable solution.

The ground-source heat pumps (GSHP) extract heat from the ground. Either horizontal or vertical pipelines are installed underground to a maximum of 100 meters. The pipelines form a closed loop filled with water or another antifreeze liquid. The ground temperature does not differ much, and therefore the ground is perceived as a better heat source than air Sarbu and Sebarchievici (2014). The GSHP operates on an electro-compressor and relies on electrical energy to pump the heat through the pipelines. The GSHP can be installed at a single household level, and multiple household scale as Schibuola and Scarpa (2016) describes. A major disadvantage of GSHP is the high installation costs associated with it due to the digging for the pipelines in the ground (Kang et al., 2017).

Thirdly, there are water-source heat pumps (WSHP) . Some literature scale the ground water heat source under GSHP. However, the heat source is water. Besides groundwater, the WSHP can also use surface water, e.g. a lake or the sea, as a heat source. A WSHP can be either a closed-loop system or an open-loop system. In the closed-loop system, the pipelines are filled with water or another antifreeze liquid. In an open-loop system, the water from the source is extracted, pumped through the pipelines and restored in the source Sarbu and Sebarchievici (2014). Compared to the ASHP, WSHP performs better in low-temperature environments, as water temperature varies less, just like GSHPs (Baik et al., 2014). The technology is already functional in the natural environment on both single household scale and multiple household scale. Still, there are also a lot of developments to make sure the efficiency is improved, and the costs per kW are declined.

All the different sorts of heat pumps can be applied at single and multiple household scale (Sarbu & Sebarchievici, 2014; Schibuola & Scarpa, 2016; Zhang et al., 2017). According to (Bernier, 2006) the closed-loop GSHP system, including its cooling function, is the most popular heat pump configuration. In addition, Sarbu and Sebarchievici (2014) argues that the GSHP also has a higher efficiency and is more environmentally friendly.

### Concluding remarks about heating subsystems

The heating demand in the residential sector is higher on cold days, during the winter season when there is less solar radiation. This means that solar thermal collectors help fulfil the DHW demand, but there is a mismatch for space heating. Because the demand for space heating is much higher during winter periods than during the summer, therefore, it can be concluded that for the heating systems, either boilers or heat pumps are most suitable for the Dutch built environment. The electric boiler is more mature for a boiler, but using a hydrogen boiler can lead to higher efficiencies in the whole energy system as hydrogen gas can be used instead of first being converted back to electricity, with associated energy losses. It is argued that the GSHP is the most favourable heat pump system for the heat pump. Important to notice is that both the boilers and heat pumps need electricity to function.

## B.2. Electricity subsystems

### PV panels

PV panels are used to convert sunlight into electricity. PV panels are a mature technology in the Dutch energy system. Due to technological developments and governmental support, the costs were reduced, and the solar panels became more economically feasible (Nabi Mughal et al., 2018). 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. Due to this weather dependency, solar energy is defined as a variable energy source. Solar panels can be used on 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. For small and district-scale, there are so-called solar farms. Solar panels are already used at the Green Village to supply electricity to completely electrified houses.

### Wind turbines

Wind turbines use wind velocity to generate electricity. Like solar PV panels, wind turbines are weather-dependent and an unpredictable and variable energy source. In a DES, the wind turbine can be placed onshore near the houses. This technology is currently the most efficient and also cheapest solution (Rijksdienst, n.d.). The only setback is the lack of social acceptance when a wind turbine is planned near someone's home, the so-called *Not In My BackYard* (NIMBY) argument (Petrova, 2015). In addition, the economic feasibility of a wind turbine depends on the scale. Therefore wind turbines are most suitable for large scale projects.

### Concluding remarks about electricity subsystems

There are two technologies based on RES that can provide electricity. Both technologies have the disadvantage of weather dependency and require storage in the system. Comparing both systems, it can be concluded that solar PV panels are more eligible for small scale applications. This conclusion is also recognised by various researchers Loganathan et al. (2019) and Sunderland et al. (2016) and experts in the field.

## B.2.1. Combined Heat and Power systems

### Internal Combustion Engines

Internal Combustion Engine (ICE) is a mature and well-known technology. Therefore, ICE could be considered. The Spark Ignition is a type of ICE that can be attractive for a climate neutral DES. Karim (2003) and Al-Baghdadi and Al-Janabi (2003) both discuss the potential of hydrogen as fuel for a SI engine. When using hydrogen as fuel instead of natural gas, there are no $CO_2$ emissions. SI engines are applicable at single-household scale as well as on multiple household scale Onovwiona and Ugursal (2006).

### External Combustion Engines

Stirling Engine (SE) is an External Combustion (EC) suitable for residential use (Onovwiona & Ugursal, 2006) and (U. R. Singh & Kumar, 2018). In a renewable energy system the heat source for the SE is concentrated solar energy instead of natural gas or coal (Ferreira et al., 2016). Although most research is done to SE with natural gas as fuel (Alanne et al., 2010; Balcombe et al., 2015; Ferreira et al., 2016), according to U. R. Singh and Kumar (2018) the solar SE is already successfully tested in several countries.

### Fuel cells

Fuel cells used as CHP have a high potential in the residential sector due to increased efficiencies (Onovwiona & Ugursal, 2006). Fuel cells convert hydrogen into electricity and heat. Three types of fuel cells: Proton-Exchange Membrane fuel cell (PEMFC) , Molten Carbonate Fuel Cell (MOFC) , and Solid Oxide Fuel Cell (SOFC) . All of them are applicable on a single household scale as well as multiple-households scale and even larger scaleDodds et al. (2015). However, according to (Staffell et al., 2019), the MOFC is the most suitable in the industry sector. Comparing the PEMFC and the SOFC, the PEMFC is perceived as superior based o the flexibility of the fuel cell Dodds et al. (2015). In addition, the PEMFC is also the most mature. TGV also uses this type of fuel cell to generate electricity.

### Solar PVT collectors

Solar PVT collectors are CHP systems that only use solar radiation as an energy source. This subsystem combines solar PV panels and solar collectors and therefore has a higher efficiency.

### Concluding remarks about CHP systems

Looking at the different CHP systems, the combustion engines are technically more mature than fuel cells and, therefore, more economically feasible. On the other hand, fuel cells make less noise and have the potential to be more efficient than combustion engines so that they could be more beneficial in the future (Alanne et al., 2010). Solar is not the optimal energy source in the Netherlands. Therefore the Solar PVT is not considered, as their efficiency is not entirely benefited.

## B.3. Energy Storage Systems

As mentioned above, the RES are variable and unpredictable, but the grid must be balanced. Therefore an energy vector is needed to store energy over time. Within a DES, the storage time is essential because wind and solar imbalance occur intraday but also interseasonal. Therefore the storage system must be able to store for multiple months. Flywheels, superconducting magnetic energy storage (SMES) , and certain types of batteries are therefore not suitable (Luo et al., 2014). Another objective is that the storage system must be applied in the Netherlands. This means that, e.g. Pumped Hydrogen Storage (PHS) is not yet feasible, as there is an altitude difference needed (Luo et al., 2014).

### Batteries

Batteries can store electricity produced by power plants and, later on, deliver the power to the grid. This characteristic makes batteries suitable as an energy vector in DES based on renewable energy. According to Dhundhara et al. (2018) electrochemical batteries are most promising in an energy system with many variable energy sources. There are various types of batteries, and not all are suitable for a DES. In a review made by Hoppmann et al. (2014), those multiple types of batteries are discussed. The *lead-acid battery* is most frequently mentioned in literature research of Hoppmann et al. (2014). This also makes sense as the lead-acid battery is a mature technology and also suitable for long term storage (Díaz-González et al., 2012). Another suitable battery is the *Sodium-Sulphur (NaS) battery*. This battery is compared to the Lead-acid battery relatively new, but in the U.S. NaS batteries are already installed to store electricity surplus generated by wind turbines (B. P. Roberts, 2008). Furthermore, at TGV, a Lithium-Iron-Phosphate ($LiFePO_4$) battery is installed. This $LiFePO_4$ battery is perceived as a safe, efficient, and environmentally friendly battery that can be used in residential energy systems with PV panels (X. Wang et al., 2012). *Redox Flow Batteries* (RFB) are also a technology with high potential in the residential sector. The RFB makes use of redox reactions which are reversible (W. Wang et al., 2013). Therefore, this battery has a low self-discharge and a long lifetime. Furthermore, it is easily scalable, and it has low investment costs (Díaz-González et al., 2012). RFB is perceived safe in operations (W. Wang et al., 2013).

### Compressed Air Energy Storage (CAES)

CAES is a technology where the air is stored in the form of high pressure and later on released when the power is needed. The air is compressed using a compressor, which is powered by a motor. The compressed air is stored in a storage space and when electricity is needed, the air is release. The generator starts running due to the pressure flow through the turbines. An expander is used to let the air out of the system.

The compressed air can be stored long term as the system's self-discharge is almost zero (Olabi et al., 2021). Therefore, CAES is suitable for seasonal storage. At first, the CAES technology depended on a combustion fuel and was not entirely climate neutral, however, currently, a CAES can be powered by RESs (Olabi et al., 2021). Furthermore, the CAES needs underground storage space. Therefore the large scale CAES is geographically dependent, just as the PHS mentioned above. However, there are developments in the technology. In a review from Luo et al. (2014), the Advanced Adiabatic CAES (AA-CAES) is mentioned. As a result, combustion is generated by a renewable energy source. Those AA-CAES systems are being developed already in Germany and the US. In addition, CAES is currently also available on a small scale, resulting in overground systems (Proczka et al., 2012).

### Hydrogen storage

Some of the subsystems mentioned above depend on hydrogen gas as fuel. Unfortunately, pure hydrogen gas does not occur in our atmosphere. Therefore, hydrogen must be created in the first place. This can be done with an electrolyser. An electrolyser splits water [$H_2O$] in oxygen [$O_2$] and hydrogen [$H_2$]. This hydrogen gas can be either directly used or stored. The stored hydrogen is a good solution for seasonal storage as the hydrogen is stored in tanks without any leak potential. Due to the high energy density of hydrogen, the storage space needed is relatively small compared to CAES systems or GSHP. For small scale residential purposes, this characteristic of hydrogen is a big advantage concerning the design space. Overall, it can be concluded that hydrogen is a promising solution in the energy system (Sorgulu & Dincer, 2018). At the Green Village, they acknowledge this as well. Currently, they are installing a hydrogen storage facility in combination with an electrolyser and fuel cell.

### Concluding remarks about storage systems

One of the main problems in self-sufficient climate neutral DES is storage as those systems operate on variable RES. To be more specific, a solution for seasonal storage is crucial. Therefore long term storage is a prerequisite. This can be either fulfilled with RFB, CAES or hydrogen storage. Looking at policy documents, the Dutch government is redirecting towards hydrogen usage (Rijksoverheid, n.d.).

# C

# Appendix: Housing types and energy demand

In the Dutch built environment, different types of houses can be identified. In addition, those types of houses have different characteristics, which determine the energy consumption of a house. In this chapter sub-question 2 is treated. The division of housing types in the Dutch built environment is explained and the different characteristics are elaborated. To finalise this chapter the residential buildings of TGV are classified into housing types according to those characteristics. This classification is used in chapter 4, in order to use the demand date of those building for a case study.

## C.1. Housing types

The housing types are based on how the building is constructed. There are five different types of houses defined in the Dutch built environment and commonly used when looking into energy consumption in the built environment (ECW, Eneco, TNO). Besides the fact that those different types of houses are commonly used, the division can also be explained. The division goes from least embedded to most embedded. The inclusion of a house is relevant when looking at the energy consumption as it influences the heat loss of a building. The five different housing types are: detached, semi-detached, corner house, terraced house, and apartment.

*Detached house*

The dwelling that is the least embedded is a detached house. This home is only connected to the ground, all exterior walls and the roof are connected to the air.

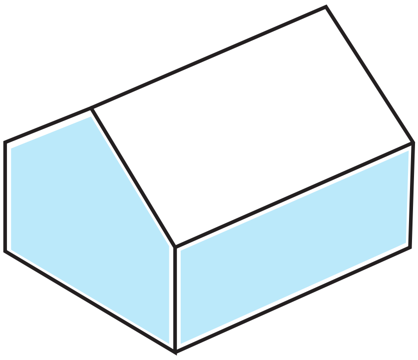


Figure C.1: Housing type: detached

*Semi-detached house*

Secondly, a semi-detached house is attached with one outer wall to another house, also semi-detached. This results in two sides of the house that are connected with either the ground or another house and all other sides are connected with the air.

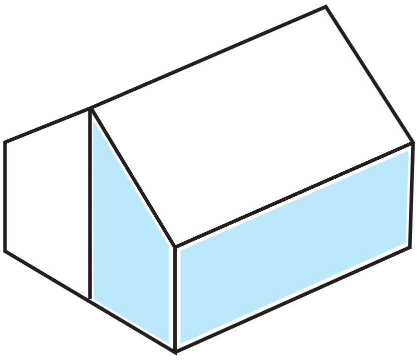


Figure C.2: Housing type: semi-detached

*Terraced house*

A terraced house is a house that is embedded between a row of other houses on both sides. So, per definition, it has three sides connected to the ground of with other houses.

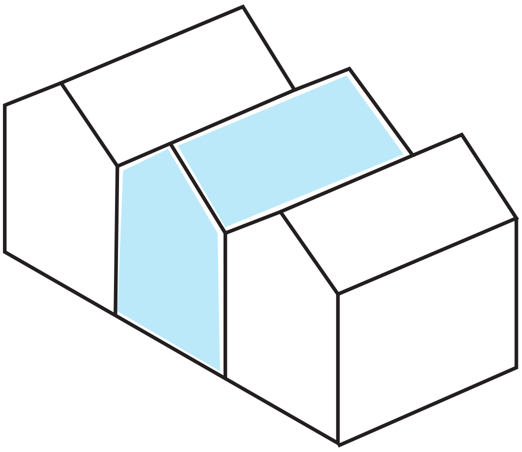


Figure C.3: Housing type: terraced house

*Corner house*

A house 'corner' is a house that is placed at the end of a row of terraced houses. This will result in two (or three) sides connected with either the ground or another house.

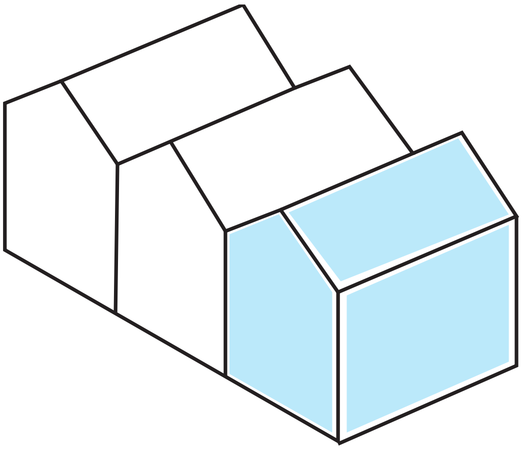


Figure C.4: Housing type: corner house

*Apartment*

An apartment is defined as a single home in a multi-story, multi-family building. The apartment itself can have multiple stories, but it is not necessary.

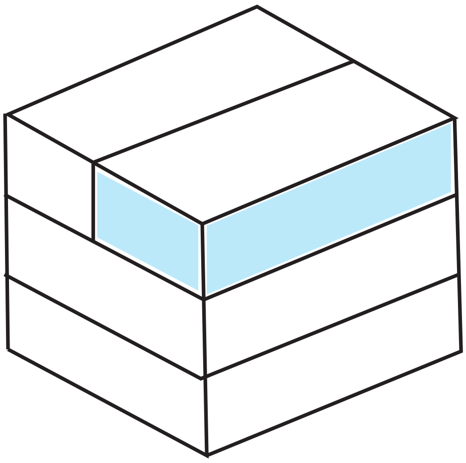


Figure C.5: Housing type: apartment

## C.2. Energy label

The Energy Performance of Buildings Directive (EPBD) is a European directive that makes it mandatory for buildings to have a performance certificate with respect to energy (The European Parliament & The Council, 2010; Visscher et al., 2014).

Since 2015, the Dutch government satisfy this Directive by assigning energy labels to residential buildings. The energy label is determined by the energy efficiency of a building. This energy efficiency is subsequently based on the insulation level and the installed energy supply devices, resulting in a value expressed in kilowatt hour per squared meter per year [kWh/m$^2$a]. The scale of the energy label goes from *G* to *A++++*, where *G* is the worst label and *A++++* the best (Rijksdienst, 2021). To further specify the energy labels, fig. C.6 is placed below. From this figure it can be concluded that the energy labels from *A++* and better are residential buildings that are almost energy neutral and the energy label *A++++* is energy neutral or energy positive.
This thesis only looks into dwellings that need to adapt to a new energy system. Therefore, every house that has an energy label of *A+* or higher is not taken into account, as it is assumed that those building are already sufficient to connect to a DES.
So, with respect to the energy label, a seven scale division from G to A is taken into account based on the energy efficiency of a residential building.

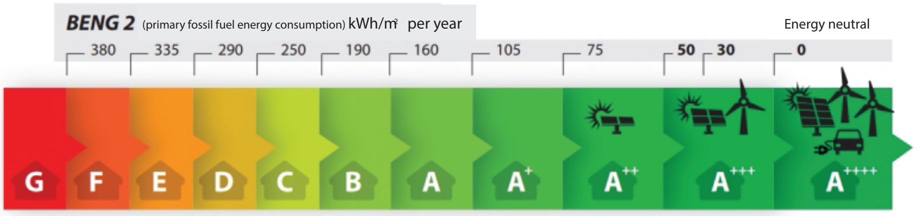


Figure C.6: Energy labels

The energy level can by altered by increasing the insulation level. To do this, upfront investments must be made. However, a better insulation level, results in lower energy consumption. In table C.1 an overview is shown with the costs to increase the insulation level and alter the energy label (Niessink, 2021a, 2021b, 2021c).

Table C.1: Costs for increasing the energy label

| **Energy label** | A+ | A | B | DC |
|---|---|---|---|---|
| A-label | € 10,034.00 | / | / | / |
| B-label | / | N/A | / | / |
| C-label | / | € 31,442.00 | € 16,829.00 | / |
| D-label | / | € 31,442.00 | € 16,829.00 | / |
| E-label | / | / | € 35,085.00 | € 15,353.00 |
| F-label | / | / | € 35,085.00 | € 15,353.00 |
| G-label | / | / | € 35,085.00 | € 15,353.00 |

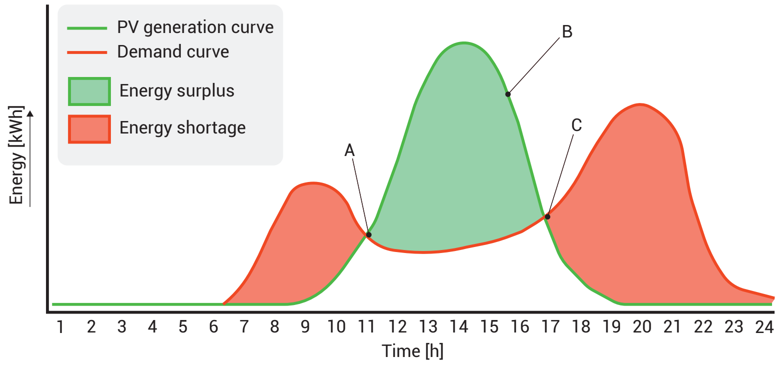
## C.3. Energy consumption level

Besides the design of the building itself that determines the energy label, the people who live in a home have also a role in how much energy is consumed. Depending on their habits and jobs the energy demand curve differs per household.

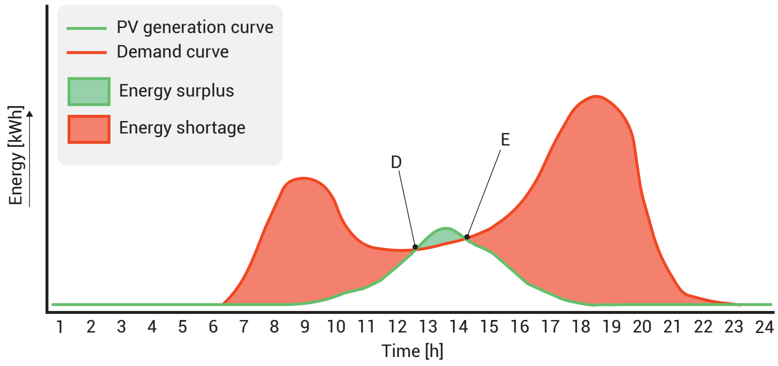
# D

# Appendix: Reasoning behind control strategy

The control strategy determines whether an energy surplus is stored in the battery or used for the long term storage facility and vice versa if the energy shortage is solved with the battery or the long term storage facility. The load demand and the PV generation curves are plotted to understand the logic behind the control strategy. In fig. D.1 the demand and generation curves are shown for the summer (fig. D.1a) and winter (fig. D.1b). The difference between winter and summer is a lower amount of solar energy during winter for the PV generation. For the energy demand, the energy consumption in winter increases due to the heat demand.



(a) Summer



(b) Winter

Figure D.1: Daily energy curves

During summer, there is overgeneration from the solar panels. This overproduction is needed during the winter when less solar energy is available. This means that a part of the energy produced in the summer needs to be stored in a long term storage facility. In addition, there is a daily imbalance. For this daily shortage, the battery is used. These observations result in the following conclusions about the control strategy. In summer, there are multiple hours in a sequence of energy surplus. The battery is charged in the first hours, as the battery was discharged in the evening and the morning. Once the battery is full again, the long term storage will be charged by turning on the electrolyser or motor. In winter, the overgeneration is minimal. Therefore, the battery and long-term storage are used most of the time. The little bit of overgeneration is first stored in the battery, as the long term storage is charged during summer. For each of the DES cases, a more extensive control strategy is used to write a code for the model is described and shown in the following section.

Important to notice is that the fuel cell is not a flexible energy source. It takes time before the fuel cell operates at a rated power level. Therefore, the battery is used to solve the daily imbalance. However, once the fuel cell is running, the fuel cell is used to supply the energy demand.

# E

# Appendix: Data preparation

In this part of the report an extensive description on how the data, obtained from TGV, is modified to use it for the calculations. First, the data is selected, subsequently the missing data is filled in, followed by a conversion of the data to the same entity [kWh/h]. Afterwards a division is made between heat and electricity demand. In the end all the data is reviewed and corrected if mistakes are found, so in the end the data is applicable in the model.

## E.1. Data selection

It was chosen to only use the data for 2020, as this year is most complete. The year 2020 was a leap year and therefore it had 366 days instead of 365. This means that for the buildings with a 15 min time step, 35.136 energy values should be available, the buildings with a 1 hour time step should have 8784 values, and the buildings with a monthly time step should have 12 values. This first filter step was done in excel with the filter function. For the Woody's, the Sustainer Homes, and Pret-a-Loger, the amount of measurements were correct, as shown in table E.1.

Table E.1: The number of measurements per building, including the amount of missing data.

| House | Amount of values | Needed amount | Difference |
|---|---:|---:|---:|
| Woody 10 | 35136 | 35136 | 0 |
| Woody 10a | 35136 | 35136 | 0 |
| Sustainer Home 12 | 35136 | 35136 | 0 |
| Sustainer Home 14 | 35136 | 35136 | 0 |
| DreamHus 28 (electricity) | 227059 | 35136 | -191923 |
| DreamHus 28 (gas) | 5454 | 8784 | 3330 |
| DreamHus 30 (electricity) | 245066 | 35136 | -209930 |
| DreamHus 30 (gas) | 4401 | 8784 | 4383 |
| DreamHus 32 (electricity) | 245187 | 35136 | -210051 |
| DreamHus 32 (gas) | 6242 | 8784 | 2542 |
| Pret-a-Loger | 12 | 12 | 0 |

#### Pret-a-Loger

For the residential building Pret-a-Loger only monthly data is available. This time step is too big to interpolate to hourly data. Therefore the Pret-a-Loger building is not included in the the rest of the case study.

## E.2. Data completion

At the DreamHussen there are missing values for the gas demand and there are too much values for the electricity load. In addition, although the Sustainer Home 12 has enough values, the sheet has two rows that define the energy consumption, therefore some recalculation must be done.

### Electricity demand DreamHussen

For the electricity demand data in the DreamHussen 28, 30 and 32 there were respectively 227.059, 245.066 and 245.187 energy values, which is around seven times the needed amount of 35.136. This can be explained by the fact that three electricity wires are connected to each of the DreamHussen and within the DreamHussen there are four electricity groups. So in the electrical fuse boxes of the DreamHussen, there are three wires that come from the gird outside the house, called the ”main connection” and from the electrical fuse box there are four wires that are distributed around the four electricity groups in the house, referred to as the ”groups”. Each of those wires have their own sensor, therefore, for each time step there are 7 measurements resulting in much more values. In addition, it also results in a duplication of the total energy demand, as the main connection is equal to the electricity going into the house to the electrical fuse box and the groups are equal to the total used electricity within the house measured from the fuse box. So, to calculate the total energy demand either the main connection values or the groups must be summed up. By first deleting the group values with the filter function in excel and subsequently using the ”SUMIF” function. In order to use the SUMIF function, first a new column is made with all the timestamps from 2020-01-01 00:00:00 to 2020-12-31 23:45:00. Then, in a new column the SUMIF function is used. The first input is the range, these are the columns with the timestamps from the initial measurements resulting from the main connection. Secondly, the criteria is formulated. In this case the value in the range column is equal to the value in the new timestamp column. Lastly, the column with the electricity values is the column that is summed. The end result is the total electricity demand per time step resulting from the three main connection wires.

### Gas demand DreamHussen

In order to fill in the missing data, python is used. With a re-sample function to identify the missing time steps and subsequently, to obtain a gas demand value for this missing values, a interpolation is done with

$$\mathrm{E(t)} = \frac{\mathrm{E(t-1)} + \mathrm{E(t+1)}}{2}, \tag{E.1}$$

where $E(t)$ is the energy demand for time step t, $E(t-1)$ is the energy demand of the previous time step and $E(t+1)$ is the energy demand of the next time step

The next step in the data preparation process is unifying the data. This is also done with Python. A script is written to end up with hourly demand data and energy values given in [kWh] for each building. This meant a re-sampling to hourly data for all the data that was given per 15 minutes, by summing the four 15 minutes data with

$$\mathrm{E}_{\mathrm{hour}}(t) = \mathrm{E}(t)_{1^{st}\ 15\,min} + \mathrm{E}(t)_{2^{nd}\ 15\,min} + \mathrm{E}(t)_{3^{rd}\ 15\,min} + \mathrm{E}(t)_{4^{th}\ 15\,min}, \tag{E.2}$$

where $\mathrm{E}_{\mathrm{hour}}(t)$ is equal to the energy demand of one hour,

### Energy demand Sustainer Home 12

Sustainer Home 12 is connected to Solar PV panels. So, a part of the electricity demand is delivered by those panels. However, the sensors only measured the electricity retrieved from the grid or send back to the grid. This means that the total energy demand is calculated with

$$\mathrm{E}_{\mathrm{total}}(t) = \mathrm{E}_{\mathrm{PV}}(t) + \mathrm{E}_{\mathrm{grid}}(t) - \mathrm{E}_{\mathrm{retour}}(t), \tag{E.3}$$

where $\mathrm{E}_{\mathrm{PV}}(t)$ is the total energy supply from the installed PV panels, $E_{\mathrm{grid}}(t)$ is the energy supply from the electricity grid and $\mathrm{E}_{\mathrm{retour}}(t)$ is the energy supply generated by the PV panels that is returned to the electricity grid, all on time step t. As stated before, there are two columns defined in the worksheet. The first column represents $\mathrm{E}_{\mathrm{grid}}$ and the second column represents $\mathrm{E}_{\mathrm{retour}}$. The column representing $\mathrm{E}_{\mathrm{PV}}$ is missing. In order to fill this column, PV generation data from renewables.ninja is used. The following values are used:

- Longitude: 4.3776
- Latitude: 51.9975
- Data set: MERRA-2
- Year: 2020
- Capacity: 1000 W
- System loss: 0.1
- Tracking: None
- Tilt: 35 degree
- Azimuth: 270°

By applying eq. (E.3) a new column is created that represents the corrected energy demand.

## E.3. Data conversion

Once all the missing data and incorrect data is corrected, all energy values are converted to [kWh]. So, the energy values given in [Wh] are divided by a factor 1000. The values measured in [m$^3$] for natural gas use, were multiplied by the calorific value of Groningen gas, which is 8.9 [kWh/m$^3$]. This conversion is done as well in Python

## E.4. Data division

The next step is divide the energy consumption between heat demand and electricity demand. As this is needed for the energy system configuration *with hydrogen boiler*. For the DreamHussen this differentiation is already known, as the heat demand is reflected in the natural gas use. For the full electric buildings, an assumption is made for the ratio heat: electricity demand per day based on the ratio seen at DreamHus 32. The ratio 84:16 for respectively, the heat and electricity demand was mentioned based on research from International Energy Agency (2020) into the Dutch energy consumption. However, this ratio accounts for a yearly basis. On daily basis, this ratio differs depending on the outdoor temperature. Therefore, during summer times the electricity demand is much higher compared to the heat demand and during the winter vice versa. So, in order to come up with a reasonable ratio per time step the ratio from DreamHus 32 is used. The heat fraction (HF) is calculated with:

$$\mathrm{HF}(t) = \frac{\mathrm{Q_{DH32}}(t)}{\mathrm{E_{DH32}}(t) + \mathrm{Q_{DH32}}(t)}, \tag{E.4}$$

where $\mathrm{Q_{DH32}}$ is the heat demand for DreamHus 32 for time step t and $\mathrm{E)_{DH32}}$ is the electricity demand for DreamHus 32 for time step t.

The electricity fraction (EF) per time step is similarly calculated with:

$$\mathrm{EF}(t) = \frac{\mathrm{E_{DH32}}(t)}{\mathrm{E_{DH32}}(t) + \mathrm{Q_{DH32}}(t)}, \tag{E.5}$$

These fractions are applied to the full electric buildings Woody 10, Woody 10a, Sustainer Home 12, and Sustainer Home 14. The heat demand is obtained with:

$$\mathrm{Q_D}(t) = \mathrm{HF}(t) * \mathrm{E_D}(t), \tag{E.6}$$

where $\mathrm{HF}(t)$ is the result of eq. (E.4) and $\mathrm{E_D}(t)$ is the energy demand on timestamp t for one of the buildings. The electricity demand is calculated with:

$$\mathrm{E_D}(t) = \mathrm{EF}(t) * \mathrm{E_D}(t), \tag{E.7}$$

where $\mathrm{EF}(t)$ is obtained with eq. (E.5) and $\mathrm{E_D}(t)$ is again the energy demand on timestamp t for one of the buildings. The end result of all these steps is a workbook including a worksheet for each building with the energy demand data given in [kWh] per hour time step specified into heat demand and electricity demand.

### E.4.1. Demand per building

With the modified data, table E.2 is generated. It shows an overview of the total yearly demand per house at TGV after going through all the steps described above. In this subsection the demand curve plots are shown for each house at TGV.

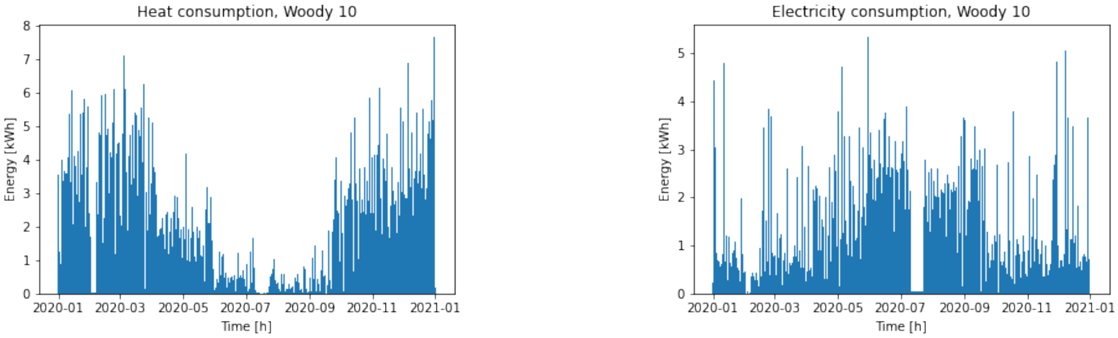
Table E.2: Energy demand, buildings TGV

| House | Yearly E$_{heat}$ [kWh] | Yearly E$_{Electricity}$ [kWh] |
|---|---:|---:|
| Woody 10 | 2628 | 1678 |
| Woody 10a | 1607 | 689 |
| Sustainer Home 12 | 2932 | 4423 |
| Sustainer Home 14 | 1667 | 1085 |
| DreamHus 28 | 9345 | 11978 |
| DreamHus 30 | 9294 | 12788 |
| DreamHus 32 | 18584 | 5198 |

**Woody's**

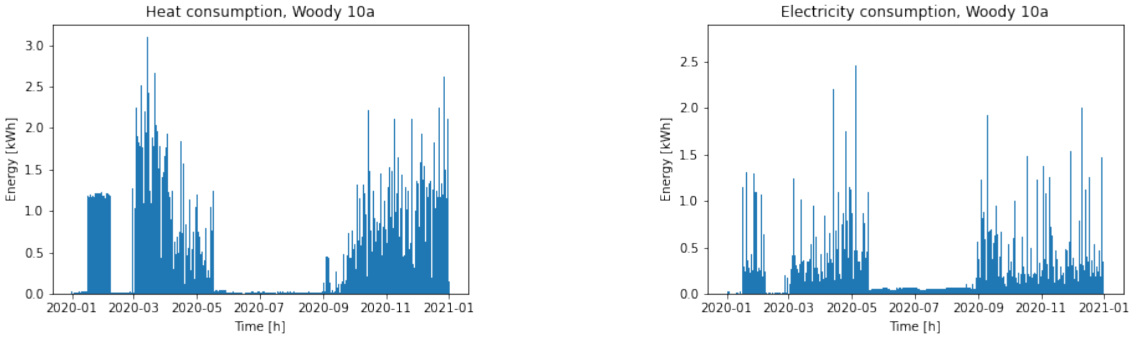
For the Woody houses the energy demand curves are shown in fig. E.1. The heating demand for the two Woody's is being fulfilled with infrared panel heaters, both the apartments have two panels installed. Those infrared heater have a capacity of around 300 Watt, depending on the size. The needed electricity for both the infrared heaters and other equipment is derived from the grid.

The demand curves for Woody 10 shown in fig. E.1a and fig. E.1b follow an expected demand curve with a higher heat demand during the winter. There are a few weeks where the energy demand is very low. These troughs are during the holiday periods. The first one is the first week of February and the second trough is during the summer break in July. In the demand curves of Woody 10a shown in fig. E.1c and fig. E.1c there are bigger gaps. The first gap can be explained by the fact that the house was uninhabited, only from August onward someone rented the house. The energy demand in March, April and May can be explained by experiments that were performed by people from TGV. Due to this unusual demand curve, it is decided that the demand of Woody 10a is not taken into account, as the building is quite similar to Woody 10.



(a) Heat consumption of Woody 10 for the year 2020

(b) Electricity consumption of Woody 10 for the year 2020



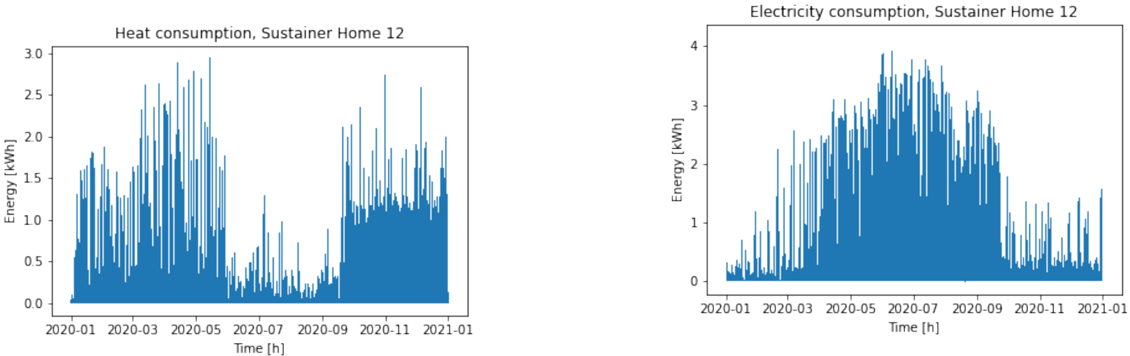
(c) Heat consumption of Woody 10a for the year 2020

(d) Electricity consumption of Woody 10a for the year 2020

Figure E.1: Energy consumption of Woody's in the year 2020

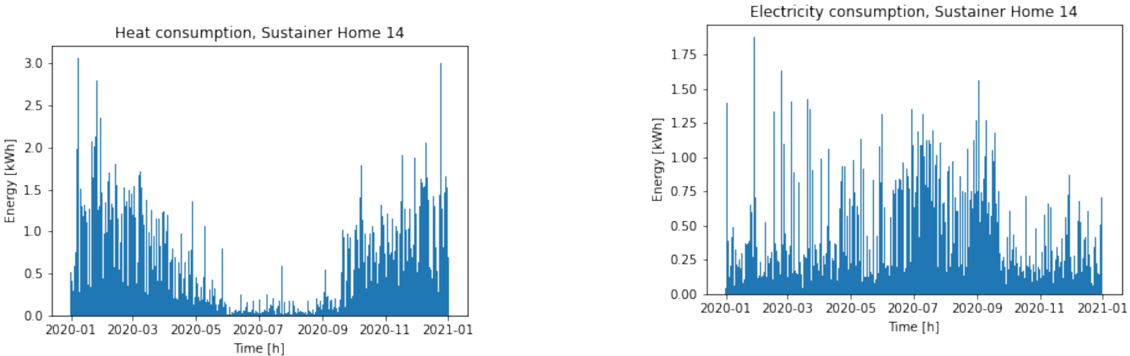
### Sustainer Homes

The energy demand curves of the Sustainer Homes are presented in fig. E.2. For the Sustainer Homes a heat pump is installed. This heat pump is an ASHP placed on the roof of the Sustainer Homes. In addition, there are PV panels delivering a part of the electricity. The other part is from the grid connection.



(a) Heat consumption of Sustainer Home 12 for the year 2020

(b) Electricity consumption of Sustainer Home 12 for the year 2020



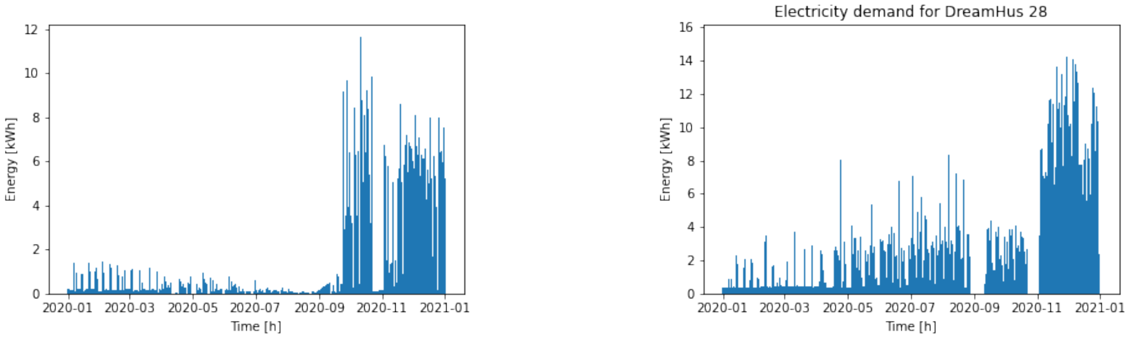
(c) Heat consumption of Sustainer Home 14 for the year 2020

(d) Electricity consumption for Sustainer Home 14 for the year 2020

Figure E.2: Energy consumption of the Sustainer Homes the in the year 2020

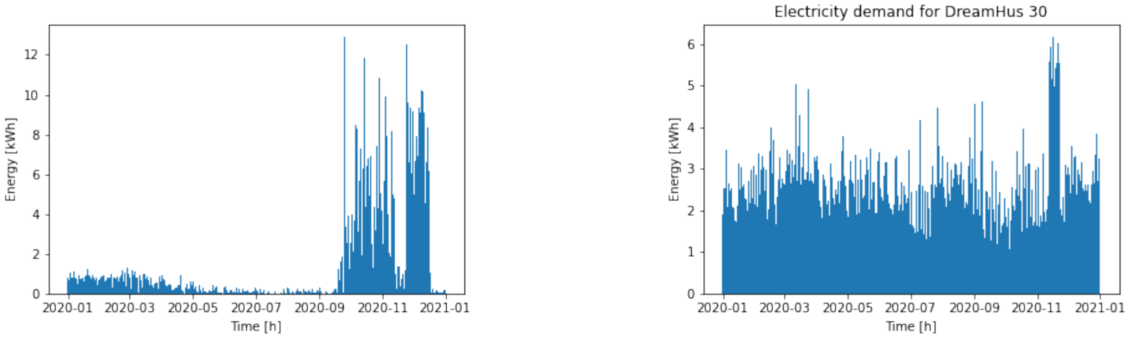
### DreamHussen

For the DreamHussen the yearly energy consumption is shown in figure E.3. These three dwellings are replica's of a 1970s house and have a natural gas boiler installed to comply with the heat demand. Furthermore, there are some installations tested during the year 2020. This can also be seen in the demand data. However, the first thing to notice, when looking at the heat demand curves in fig. E.3a, fig. E.3c, and fig. E.3e, is the low demand load at the beginning of the year. This demand load is around a factor 10 smaller than in the end of the year, whereas it is expected to be similar, as the outside temperatures are similar as well.



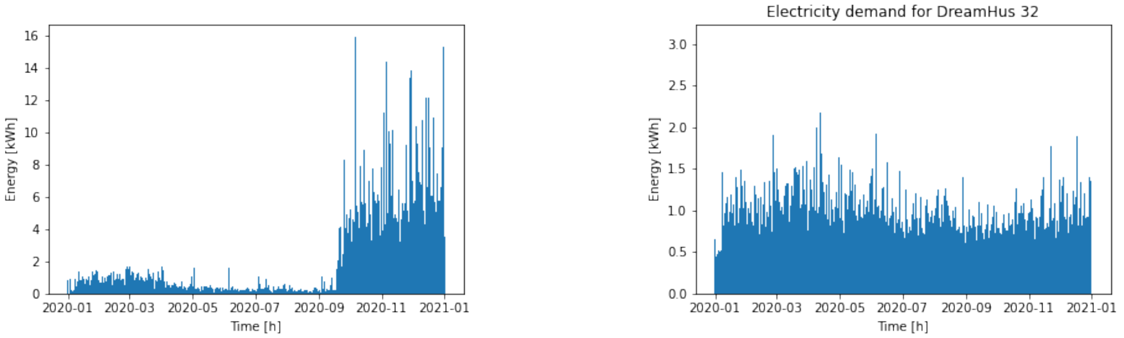
(a) Heat consumption of DreamHus 28 for the year 2020

(b) Electricity consumption of DreamHus 28 for the year 2020



(c) Heat consumption of DreamHus 30 for the year 2020

(d) Electricity consumption of DreamHus 30 for the year 2020



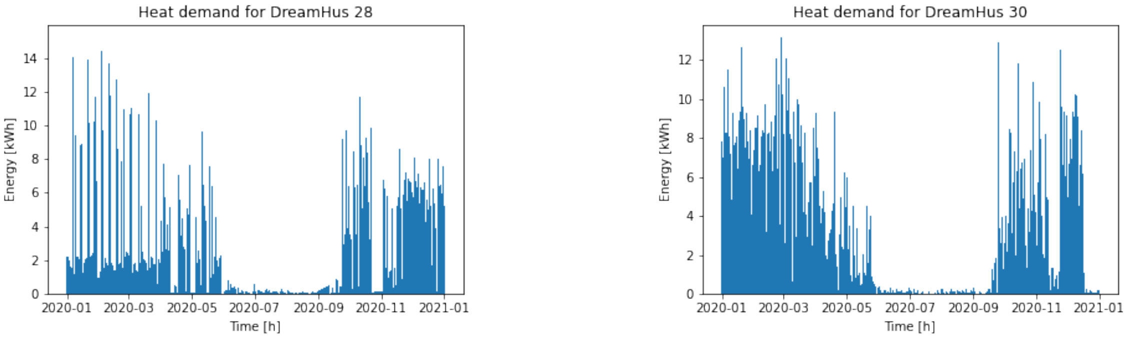
(e) Heat consumption of DreamHus 32 for the year 2020

(f) Electricity consumption of DreamHus 32 for the year 2020

Figure E.3: Energy consumption of DreamHussen in the year 2020

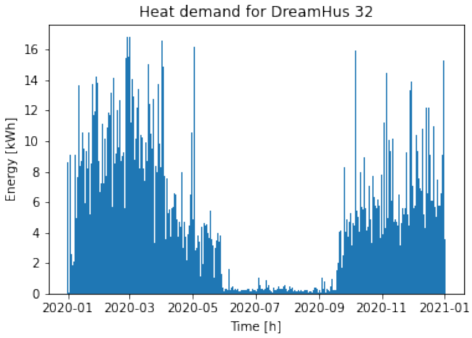
After discussing this intern at TGV, it turned out to be a fault in the system. Therefore, all the values from 2020-01-01 till 2020-05-01 are multiplied with 10 in order to get more realistic data. These results are shown in fig. E.4.

Considering the tested subsystems, in fig. E.3a there is a through around week 44. This can be explained by a project that extracts heat for DHW from the sewage system. Furthermore, in fig. E.3d there is a peak in week 46, where in fig. E.4b a through. This is because a PCM storage tank was tested. This resulted in a lower natural gas demand, but a higher electricity demand.



(a) Heat consumption of DreamHus 28 for the year 2020

(b) Heat consumption of DreamHus 30 for the year 2020



(c) Heat consumption of DreamHus 32 for the year 2020

Figure E.4: Corrected heat consumption in DreamHussen

# F

# Appendix: Model verification and validation

Model verification and validation is required to make sure the computer model operates as expected and correctly and resulting in an outcome that is reliable. Below, both the model verification and validation are described. During this process of verification and validation the work of Thacker et al. (2004) is consulted.

## F.1. Model verification

"Verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model." (Thacker et al., 2004, p.2). There are two types of verification; code verification and calculation verification. For this model a code verification is performed. Code verification is focused on two aspects. First of all, gives the code the same results on different computers, to make sure the code can be used by others as well, this check is done during the writing process. Secondly, code verification looks at the correct operation of numerical algorithms, also referred to as numerical algorithm verification. A simplified method is alternating input values and parameters. By changing the input values and parameters systematically, it is checked if the outcome changes as expected. The model follows the three parts explained in chapter 3.

In the first part the sizes of the components are calculated. For the code verification, the capacity of the single apartment is manually calculated following the equations for each DES configuration. These capacities are compared with the outcome of the model. At the end of the verification the outcomes are the same.

In the second part of the model, the technical performance of the design is modelled. This part of the model contains many "*if*"-statements. Per statement a verification is done to see if the outcome is as expected. By assigning a predefined input value for the "*if*"-statement, the path is known beforehand. This way all the paths are tested and verified. After the verification, all the "*if*"-statements work as expected.

In the last part of the model the financial calculations are stated. A part of the verification of this part is done with an proven excel to calculate the LCOE, as the CEP is similar to the LCOE. The outcomes of the model are the same as the outcomes in the excel. The CAPEX outcomes are manually checked for the single apartment case. By multiplying the investment costs per unit with the capacity for each component the same total investment costs are acquired.

In addition, if an unexpected value was obtained, this was checked manually as well. As a result the model is verified with respect to the code verification.

## F.2. Model validation

”Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model” (Thacker et al., 2004, p.2).

The average daily demand curves shown in fig. F.1. Based on these demand curves it is expected that during the summer the electrolyser operates most of the time, as there is a high energy surplus due to solar generation. If the battery is full, the electrolyser starts to operate. During the winter there is en solar generation shortage, therefore the fuel cell will operate most of the time. The model is validated by looking at the operational times of the fuel cell and the electrolyser.

(a) Summer

(b) Winter

Figure F.1: Daily energy curves

In fig. F.2 two figures are shown. In fig. F.2a the operation times of the fuel cell is presented. It can be seen that the fuel cell operates during the winter as expected. Figure F.2b shows the operation times of the electrolyser. The electrolyser is turned on during the summer, this is also as expected.

(a) Operation times of the fuel cell in a hydrogen-based fully electrified energy system

(b) Operation times of the electrolyser in a hydrogen-based fully electrified energy system

Figure F.2: Operation times of the fuel cell and electrolyser in a hydrogen-based fully electrified energy system

# G

# Appendix: Results

In this chapter a complete overview of the results is given. Starting with the capacities for the four different autonomous DES configurations for the five different demand cases. Subsequently the component sizing for 80% autonomous systems are added, that is used for the sensitivity analysis. After the component sizes, the CAPEX build-up for all the different DES configurations and demand cases are attached.

## G.1. Component sizing

### G.1.1. 100% autonomous decentralized energy systems

Hydrogen-based Fully Electrified Energy System component sizing

Table G.1: Capacities of a hydrogen-based fully electrified energy system

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| PV capacity [kW] | 4 | 17 | 27 | 37 | 228 |
| Battery capacity [kW] | 18.7 | 99 | 91.3 | 179.3 | 826.1 |
| Electrolyzer capacity [kW] | 3 | 15 | 21 | 22 | 183 |
| Compressor capacity [kW] | 0.06 | 0.28 | 0.39 | 0.41 | 3.42 |
| H2 storage tank [kW] | 119 | 807 | 634 | 941 | 5951 |
| Fuel Cell capacity [kW] | 10 | 21 | 17 | 33 | 135 |
| Heat pump size [kW] | 1.5 | 3.4 | 2.6 | 5.0 | 21.0 |

#### Hydrogen-based hybrid energy system

Table G.2: Capacities of a hydrogen-based hybrid energy system

| | Single apartment | Corner house | Terraced house | Apartment community | Terraced house community |
|---|---|---|---|---|---|
| PV capacity [kW] | 45 | 313 | 166 | 380 | 1644 |
| Battery capacity [kW] | 32 | 98 | 241 | 405 | 2005 |
| Electrolyser capacity [kW]] | 8 | 17 | 13 | 25 | 105 |
| Compressor capacity [kW] | 4 | 20 | 11 | 24 | 100 |
| H2 storage tank [kg] | 65 | 489 | 240 | 500 | 2401 |
| H2 boiler [kW] | 8 | 17 | 14 | 26 | 106 |

#### Hydrogen-based hybrid energy system with fuel cell

Table G.3: Capacities of a hydrogen-based hybrid energy system with fuel cell

| | Single apartment | Corner house | Terraced house | Apartment community | Terraced house community |
|---|---|---|---|---|---|
| PV capacity [kW] | 6 | 33 | 26 | 53 | 239 |
| Battery capacity [kW]] | 7 | 20 | 49 | 81 | 401 |
| Electrolyser capacity [kW] | 6 | 42 | 21 | 49 | 209 |
| Compressor capacity[kW] | 2 | 2 | 2 | 2 | 2 |
| H2 storage tank[kg] | 92 | 600 | 532 | 728 | 4928 |
| Fuel cell capacity [kW] | 6 | 4 | 7 | 22 | 59 |
| $H_2$ boiler [kW] | 8 | 17 | 13 | 25 | 105 |

#### Capacities of a compressed air energy storage-based fully electrified energy system

Table G.4: Capacities of a compressed air energy storage-based fully electrified energy system

| | Single apartment | Corner house | Terraced house | Apartment community | Terraced house community |
|---|---|---|---|---|---|
| PV capacity [kW] | 3 | 10 | 16 | 27 | 138 |
| Battery capacity [kWh] | 18.7 | 99 | 91.3 | 179.3 | 826.1 |
| Generator capacity [kW] | 11 | 24 | 20 | 39 | 160 |
| CAES [$m^3$] | 4330 | 29 409 | 23 074 | 34 263 | 216 739 |
| Motor capacity [kW] | 2 | 7 | 10 | 10 | 83 |
| Compressor capacity [kW] | 16 | 54 | 77 | 77 | 633 |
| Heat pump size [kW] | 2 | 4 | 3 | 6 | 22 |

### G.1.2. 80% autonomous decentralized energy systems

## Capacities of a hydrogen-based fully electrified energy system

Table G.5: Capacities of a hydrogen-based fully electrified energy system - 80%

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| PV capacity [kW] | 4 | 15 | 23 | 31 | 198 |
| Battery capacity [kW] | 14 | 79 | 74 | 143 | 661 |
| Electrolyzer capacity [kW] | 3 | 12 | 18 | 19 | 162 |
| Compressor capacity [kW] | 2 | 6 | 9 | 9 | 73 |
| H2 storage tank [kg] | 95.10 | 645.95 | 506.80 | 752.58 | 4760.64 |
| Fuel Cell capacity [kW] | 8 | 17 | 14 | 27 | 108 |
| Heat pump size [kW] | 1.2 | 2.6 | 2.1 | 4.0 | 16.8 |

## Capacities of a hydrogen-based hybrid energy system

Table G.6: Capacities of a hydrogen-based hybrid energy system - 80%

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| PV capacity [kW] | 36 | 250 | 133 | 304 | 1315 |
| Battery capacity [kW] | 26 | 79 | 193 | 324 | 1604 |
| Electrolyser capacity[kW] | 6 | 13 | 10 | 20 | 84 |
| Compressor capacity[kW] | 3 | 7 | 5 | 10 | 38 |
| H2 storage tank[kg] | 52 | 391 | 192 | 400 | 1921 |
| H2 boiler[kWh] | 7 | 14 | 11 | 21 | 85 |

## Capacities of a hydrogen-based hybrid energy system with fuel cell

Table G.7: Capacities of a hydrogen-based hybrid energy system with fuel cell - 80%

| | **Single apartment** | **Corner house** | **Terraced house** | **Apartment community** | **Terraced house community** |
|---|---|---|---|---|---|
| PV capacity | 5 | 27 | 21 | 43 | 191 |
| Battery capacity | 6 | 16 | 39 | 65 | 321 |
| Electrolyser capacity | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 |
| Compressor capacity | 2 | 2 | 2 | 2 | 2 |
| H2 storage tank | 74 | 480 | 426 | 5883 | 3943 |
| Fuel cell capacity | 5 | 3 | 6 | 18 | 47 |
| H2 boiler | 6 | 13 | 11 | 20 | 84 |

## Capacities of a CAES-based fully electrified energy system

Table G.8: Capacities of a CAES-based fully electrified energy system - 80%

| | Single apartment | Corner house | Terraced house | Apartment community | Terraced house community |
|---|---|---|---|---|---|
| PV capacity [kW] | 2 | 8 | 13 | 22 | 110 |
| Battery capacity [kWh] | 14 | 79 | 73 | 143 | 661 |
| Generator capacity [kW] | 8 | 19 | 16 | 31 | 128 |
| CAES [m^3] | 3464 | 23 527 | 18 459 | 27 411 | 173 391 |
| Motor capacity [kW] | 1 | 6 | 8 | 8 | 66 |
| Compressor capacity [kW] | 8 | 46 | 61 | 61 | 503 |
| Heat pump size [kW] | 2 | 3 | 3 | 5 | 17 |

## G.2. CAPEX analysis

For all the five demand cases the CAPEX division of the four different DES configurations is included.

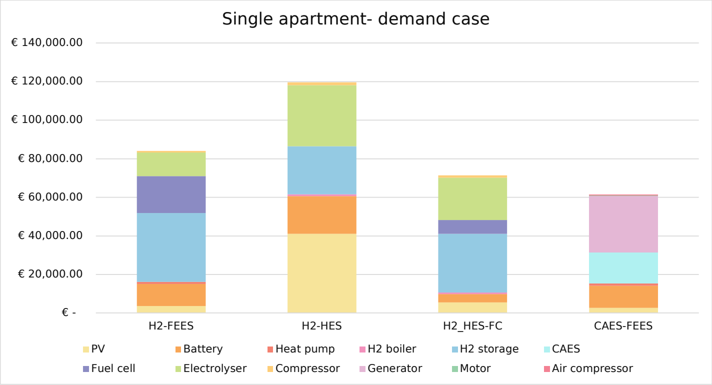


Figure G.1: CAPEX division for the single apartment demand case

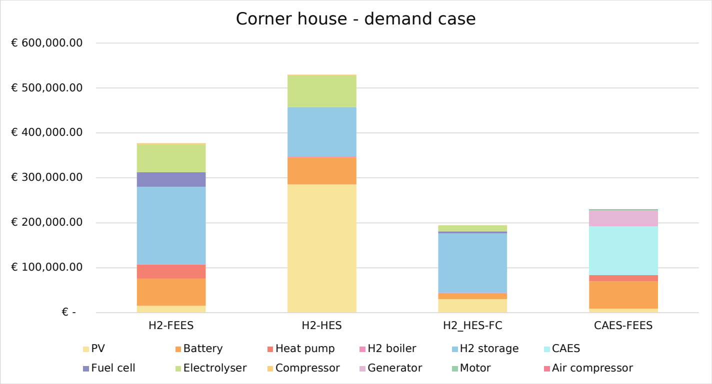


Figure G.2: CAPEX division for the corner house demand case

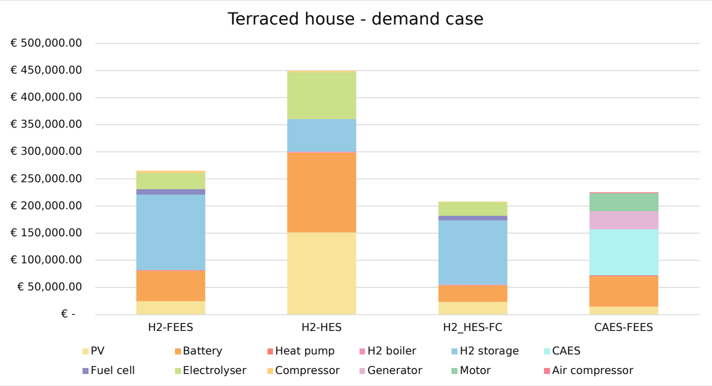


Figure G.3: CAPEX division for the terraced house demand case

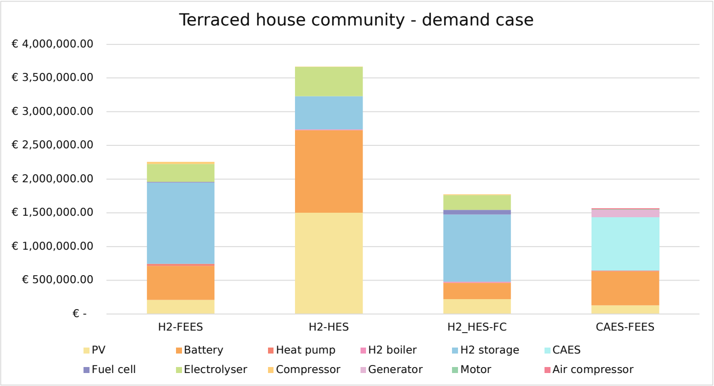


Figure G.5: CAPEX division for the terraced house demand case

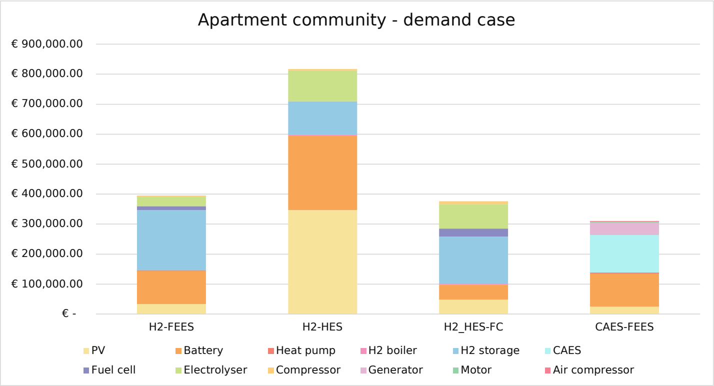
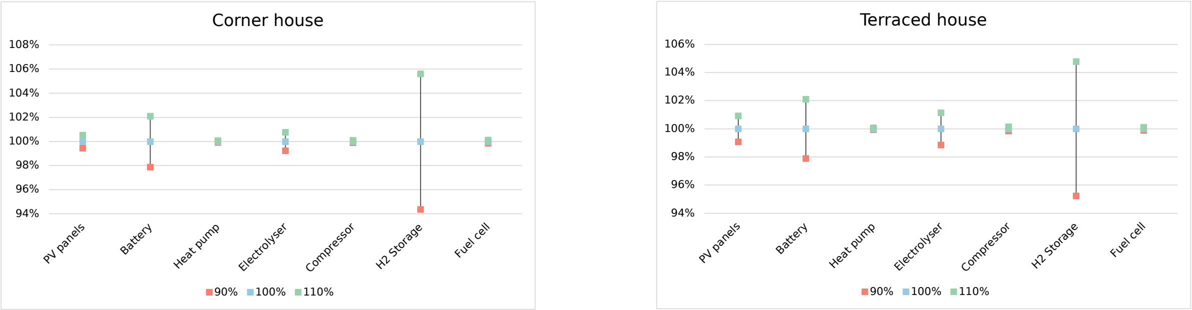


Figure G.4: CAPEX division for the apartment community demand case

# H

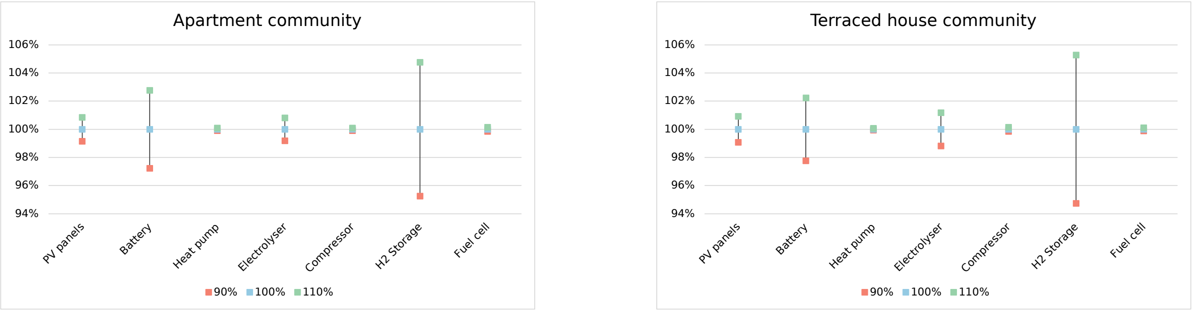
# Appendix: Sensitivity Analyses

In this appendix, all the graphs for the sensitivity analysis can be found.



(a) Corner house

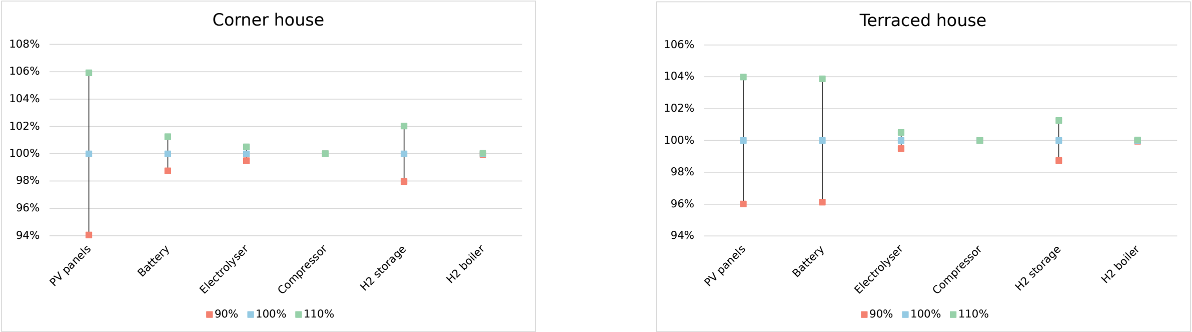
(b) Terraced house



(c) Apartment community

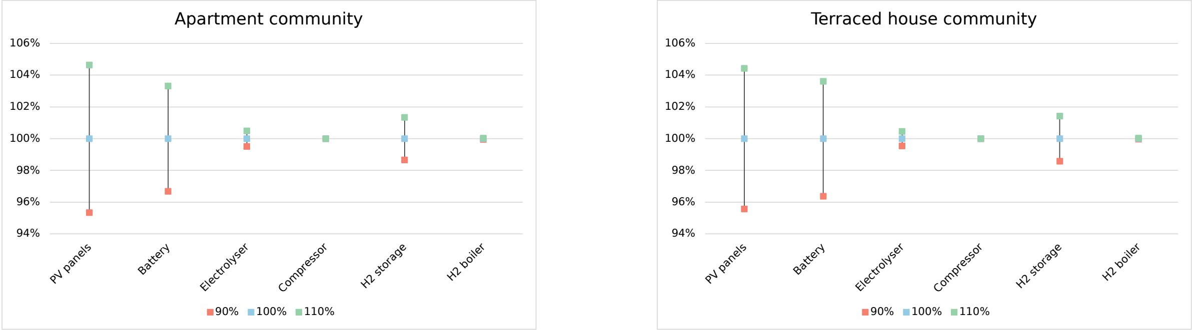
(d) Terraced house community

Figure H.1: Sensitivity analyses: hydrogen-based fully electrified energy system



(a) Corner house

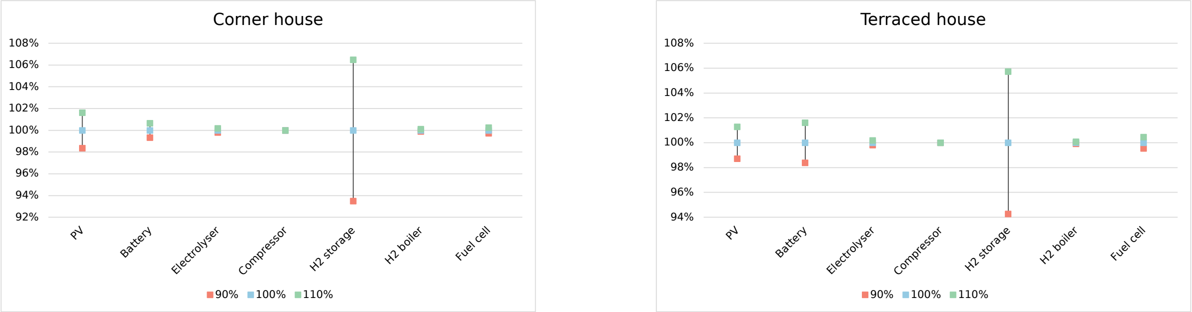
(b) Terraced house



(c) Apartment community

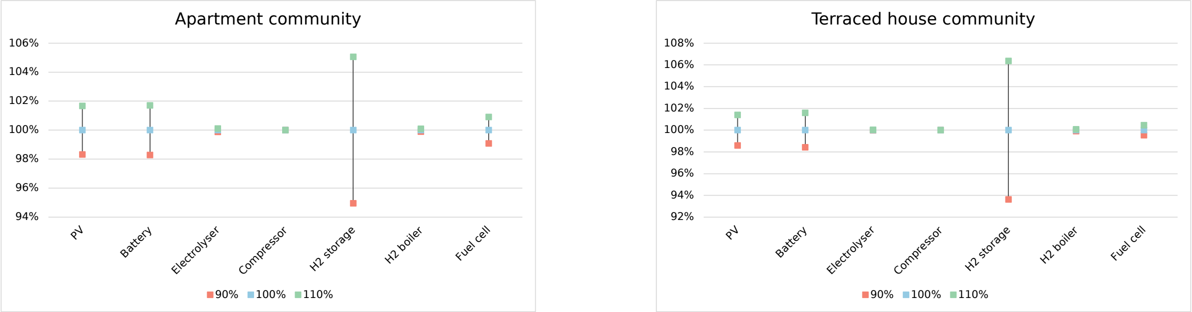
(d) Terraced house community

Figure H.2: Sensitivity analyses: hydrogen-based hybrid energy system



(a) Corner house

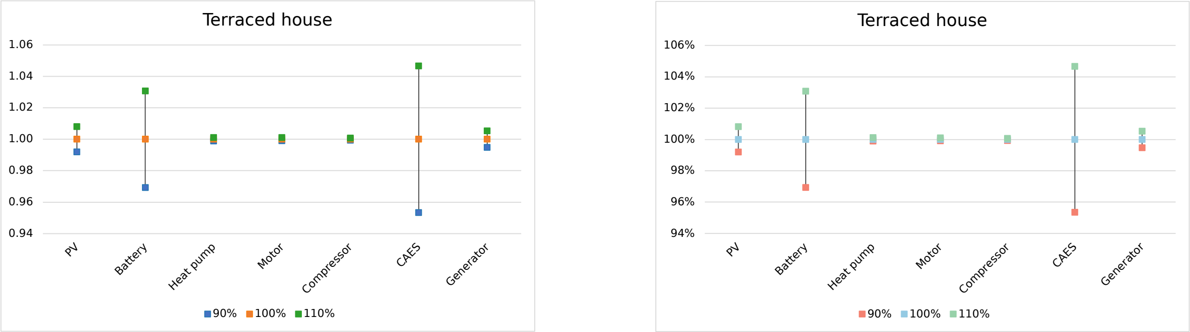
(b) Terraced house



(c) Apartment community

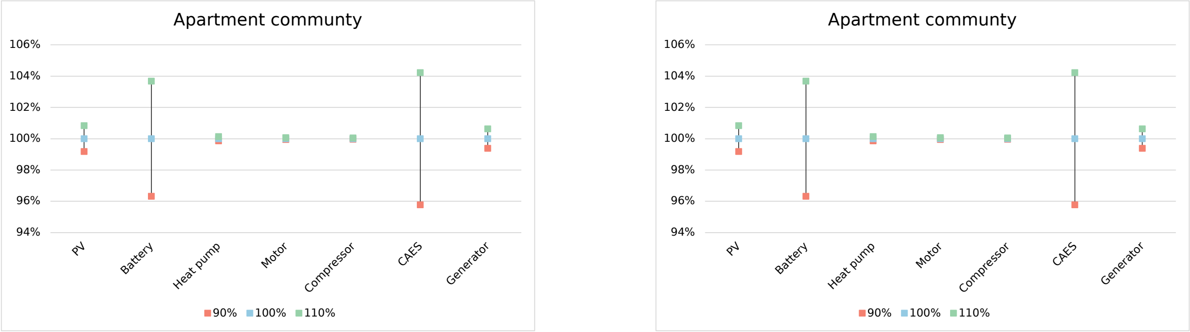
(d) Terraced house community

Figure H.3: Sensitivity analyses: hydrogen-based hybrid energy system with fuel cell



(a) Corner house

(b) Terraced house



(c) Apartment community

(d) Terraced house community

Figure H.4: Sensitivity analyses: compressed air energy storage-based fully electrified energy system

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