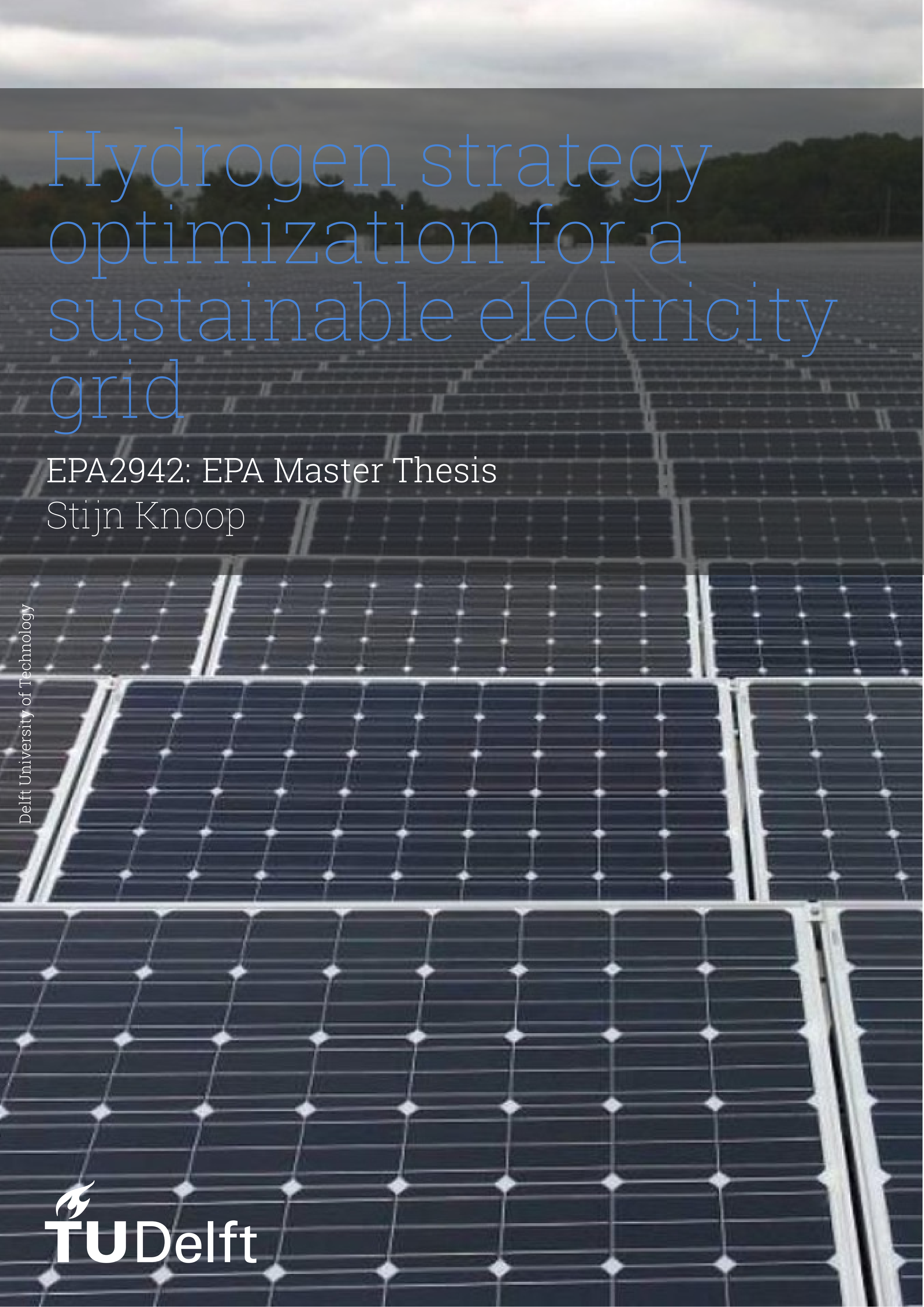

Hydrogen strategy optimization for a sustainable electricity grid

EPA2942: EPA Master Thesis

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Delft University of Technology

Hydrogen strategy optimization for a sustainable electricity grid

Research on strategy optimization of a sustainable electricity grid including hydrogen storage using particle swarm optimization

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Preface

It is with great pleasure that I present this thesis as the culmination of my Master of Engineering and Policy Analysis program at Delft University of Technology. Over the course of an extensive research period, I have investigated the optimization of an operating strategy for an electricity grid incorporating hydrogen storage. This endeavor has been driven by a desire to delve deeper into sustainable solutions and make a meaningful contribution to the existing body of knowledge in this field.

I would like to express my sincere appreciation to my supervisors for their invaluable guidance throughout the research process. I extend my gratitude to Jacopo De Stefani for his numerous feedback meetings, which have provided crucial guidance in shaping the structure and content of this master thesis. Additionally, I would like to thank the other members of the graduation committee, Emile Chapping and Yilin Huang. Although our interactions were less frequent, I am confident that your feedback has steered this thesis in the right direction.

Furthermore, I would like to acknowledge CGI Nederland for their support in facilitating this research project. During the period of writing this thesis, I have gained valuable insights into their organizational practices, which will undoubtedly benefit me in my future endeavors. I wish to express special thanks to Bas Willemse and Prashant Badaltjawdharie. Their efforts have been instrumental in enabling this research, and I am sincerely grateful for their guidance and insightful reflections.

Lastly, I would like to express my deepest gratitude to my family, with special appreciation to my parents, for their unwavering support throughout my entire academic journey. Their support and encouragement have been instrumental in my accomplishments and have provided me with the strength and motivation to overcome challenges.

Stijn Knoop
Delft, June 2023

Summary

Global warming is one of the biggest challenges in the world today. The cause of global warming is largely attributed to human activities, particularly the burning of fossil fuels, which releases greenhouse gases into the atmosphere. Electricity production has a significant contribution to the emission of greenhouse gases and other pollutants that adversely impact the environment. Renewable energy sources, such as solar and wind power, have the potential to provide sustainable electricity and thereby significantly reduce greenhouse gas emissions and mitigate climate change. Popular sustainable resources such as solar energy or wind energy, are highly dependent on weather conditions, which causes problems regarding availability of electricity. Hydrogen storage is emerging as a promising sustainable solution for reliability challenges that come with weather dependent sustainable resources. However, hydrogen storage systems also face challenges. The efficiency of hydrogen electricity is lower compared to electricity directly sourced from sustainable resources and costs associated with a hydrogen system are high.

This thesis aimed to determine an optimized operating strategy for an electricity grid including a hydrogen storage, considering three key performance indicators: financial costs, reliability, and sustainability. The objective is to deliver electricity in a sustainable manner while ensuring financial efficiency forming the following research question:

How can electricity demand be covered by a system of solar power, conventional power supply, and hydrogen systems, optimized for reliability, sustainability, and cost-efficiency, by adjusting the operating strategy?

The study expressed all key performance indicators in terms of costs, with sustainability measured by the price of carbon credits, quantifying CO2 emissions. To obtain the optimal strategy, this research uses discrete event modelling to simulate an electricity system on an hourly basis including solar energy, a hydrogen system, and non-sustainable energy. The particle swarm optimization algorithm, enhanced with linear decay, was employed to optimize operating strategies within this model and identify the most optimal operating strategies. Four scenarios were set up to analyze what the most optimal operating strategy was in different circumstances.

The study found that, in the scenario in which the price of hydrogen is significantly higher than that of conventional resources, the optimal strategy avoids using hydrogen electricity. The main cost drivers are the high costs associated with electrolysis, followed by the costs of fuel cells. In the scenarios in which hydrogen is competitive with conventional resources, the optimal operating strategy was found and only a slight portion of the total electricity produced came from non-sustainable resources.

In conclusion, this thesis addressed the main research question by optimizing the operating strategy of an electricity grid incorporating hydrogen technology. As of today, the sustainability benefits of hydrogen electricity do not outweigh the financial advantages of non-sustainable electricity. This research finds that to achieve a future scenario in which hydrogen electricity competes with natural gas, substantial cost reductions in the components of the hydrogen system are required, along with an increased price of carbon credits. The findings highlighted the challenges and opportunities in implementing hydrogen systems and provided valuable insights for stakeholders in the energy sector. Further research is needed to enhance the understanding and efficiency of operating hydrogen systems and to explore additional factors and components within the electricity system.

Contents

1

Introduction

1.1. Problem introduction

1.1.1. Problem

Global warming is one of the biggest challenges in the world today. The effects of climate change are already being felt, with rising sea levels, increased frequency and intensity of extreme weather events, and threats to biodiversity and ecosystems [19]. The cause of global warming is largely attributed to human activities, particularly the burning of fossil fuels, which releases greenhouse gases into the atmosphere [23]. The urgency of addressing this issue cannot be overstated, and the transition to renewable energy sources is a crucial step toward mitigating the impact of climate change. The Paris Agreement of 2015, which aims to limit global warming to well below 2°C above pre-industrial levels, highlighted the need to transition away from fossil fuels and move towards renewable energy sources [79].

Electricity production has a significant contribution to the emission of greenhouse gases and other pollutants that adversely impact the environment and human health. According to [2], electricity production accounted for 25% of total greenhouse gas emissions in 2021, making it the second-largest source of emissions. This highlights the need for urgent action to mitigate the environmental impact of electricity generation.

1.1.2. Renewable energy as a solution

Renewable energy sources, such as solar and wind power, have the potential to provide sustainable electricity and thereby significantly reduce greenhouse gas emissions and mitigate climate change [104]. However, the adoption of these sources of energy is not without its challenges. One such challenge is the transformation of electricity infrastructures. A well-functioning sustainable infrastructure can not be constructed overnight, and a lot of investment and development is required to create clean, efficient, and reliable infrastructures that supply societies with sustainable energy [112]. Another challenge is the issue of electricity security. Electricity security refers to the reliability and availability of electricity supply, which is essential for modern societies to function [45]. Popular sustainable resources such as solar energy or wind energy, are highly dependent on weather conditions, which causes problems regarding availability of electricity. When a society is completely dependent on sustainable methods of generating energy, coming directly from natural resources such as wind or solar power, it will not be able to fulfill the electricity demand at all times, which will result in moments of power shortages and all the costs that comes with it. Building a sustainable energy infrastructure only consisting of solar and wind energy alone is therefore not sufficient because it does not suffice the electricity demand and therefore does not comply with all the aspects of electricity security [20].

1.1.3. Integration of hydrogen storage as a solution

Hydrogen storage is emerging as a promising solution for reliability challenges that come with weather-dependent sustainable resources such as solar panels and wind turbines. This is due to the long-term storage capabilities of hydrogen storage [4] The integration of renewable energy sources such as wind and solar power into electricity grids has led to an increasing need for energy storage systems to ensure a reliable and stable electricity supply [11], which can be offered by including a hydrogen system.

The use hydrogen, two different chemical operations are required: electrolysis and electrochemical reactions in a fuel cell. Electrolysis is a method that converts water into hydrogen and oxygen. This process splits the water molecules into hydrogen and oxygen molecules using electricity, visualized in Formula 1.1 [95]. The hydrogen is then compressed and stored in tanks or underground reservoirs. When needed, this hydrogen can be used to generate electricity again. This is done in a fuel cell in which the hydrogen reacts with oxygen to create water and electricity, visualized in Formula 1.2.

$$2H_2O \rightarrow O_2 + 2H_2 \tag{1.1}$$

$$O_2 + 2H_2 \rightarrow 2H_2O \tag{1.2}$$

In times, when there is abundant sustainable electricity generated, the excess electricity can be used for electrolysis, to create hydrogen. In times when sustainable electricity production through solar and wind energy is scarce, hydrogen storage systems can provide a source of electricity, by transforming hydrogen into electricity using fuel cells [95]. Integrating hydrogen storage into an electricity grid can help to reduce the need for conventional non-sustainable power plants to meet electricity demand, improving the overall sustainability, while maintaining the reliability of the grid.

The storage of hydrogen poses several challenges that must be addressed. One of the challenges is the need for an infrastructure that supports the storage and distribution of hydrogen. In addition, another challenge is in regard to operating an electricity grid including a hydrogen system [116]. The intermittent nature of renewable energy sources such as wind and solar adds complexity to operating the storage and distribution of hydrogen. An efficient operating strategy for a hydrogen system is necessary to ensure a constant supply of electricity while being cost-efficient. Furthermore, the cost of hydrogen as a resource is not competitive with non-sustainable resources such as natural gas, which limits its widespread adoption despite its potential [46]. These challenges underscore the need for continued research and development to improve hydrogen storage technologies and overcome the economic and technical barriers associated with its use in the electricity grid.

1.2. Knowledge gaps

Despite ongoing research and development efforts to address the challenges mentioned in the preceding paragraph, there remain significant knowledge gaps in the literature that need to be explored. This section highlights the need for more research in hydrogen systems. It also delves deeper into the knowledge gaps, before explaining which specific gap this research aims to address and contribute towards closing.

While there is a wide variety of studies executed regarding hydrogen storage in a sustainable electricity grid, the literature states that there are a lot of knowledge gaps concerning hydrogen systems, regarding the challenges mentioned in 1.1.3 Integration of hydrogen storage as a solution. [30] state that there is a need for more research on integrating hydrogen storage with different combinations of energy storage systems, such as batteries, hydrogen storage in tanks, or hydrogen storage in salt caverns. Also, many articles that study hydrogen-related electricity systems state that the development of new technologies in hydrogen storage, fuel cells, and electrolysis require further research since these components are to become more developed in the future [59, 75, 97].

An additional aspect that requires more research in the hydrogen field is research on operating a hydrogen system efficiently [118]. The authors in the article [116] underline this lack of research by claiming that there is a significant knowledge gap in the integration of controls, operation, and maintenance requirements of these systems. The authors of [116] state that there is a deficit in the understanding of how to integrate hydrogen technology into an operational environment and be able to maintain power quality and reliability. Including hydrogen technology in a conventional electricity system will result in the electricity supply becoming more sustainable but at the same time less reliable if not managed correctly, which highlights the need for research on operating hydrogen systems.

What is striking is that most of the literature that is concerned with conducting an electricity system including hydrogen focuses on the ratio between the components in the electricity grid, such as the number of electrolyzers, the capacity of hydrogen storage, etc, and not on operating the system [74, 121, 65]. Studies that have been focusing on finding an optimal strategy are very limited and mostly focus on economic cost reduction [115, 88, 10]. The literature that focuses on balancing cost reduction with carbon emission is even more limited, and each research has a different approach regarding what electricity system it analyzes. For instance, [98] researches an electricity system including a hydrogen storage tank, proton exchange membrane fuel cells, and electrolyzers. There are much more variations possible with different types of components which are yet to be explored, as stated before in the second paragraph of this section by [30].

This research aims to contribute by exploring the knowledge gaps on hydrogen systems, stated above by including the following. This study will focus on including a hydrogen system in a conventional electricity grid using natural gas and solar panels to generate electricity. It will specifically try to optimize an operating strategy that will include balancing financial cost efficiency with carbon emissions. Furthermore, it will focus on a unique combination of components required for a hydrogen system, as well as unique data. Lastly, future scenarios, in which the components within a hydrogen system are more efficient will be analyzed.

1.3. Research goal

The goal of this thesis is to find an optimized operating strategy for an electricity grid that makes use of hydrogen technology taking three key performance indicators into account, which makes it a multi-objective operating strategy. An operating strategy is in this research defined as a set of rules which control the power supply and control which resources in the system are producing the power. The first key performance indicator that should always be honored is **reliability**. This indicator is focused on providing enough electricity to the electricity system so that the electricity demand is always covered. However this is a crucial indicator in electricity systems it will not be used in this research. Reliability should always be met and the consequences of power shortages, as mentioned earlier, are disastrous and very expensive if translated to financial costs. The second key performance indicator in the operating strategy is **sustainability**. Hydrogen systems are placed in the electricity system to enhance the use of sustainable resources as explained in 1.1.3 Integration of hydrogen storage as a solution. There are times when there is low electricity demand and excess renewable energy. Hydrogen systems are in place to generate and store hydrogen from this excess renewable energy through electrolysis. This stored hydrogen can be used as a sustainable resource to provide the electricity demand in times of peak demand or when renewable energy generation is low. The third and last key performance indicator is **financial costs**. Electricity should always be at accessible prices in order for a country to create prosperity [114].

The key performance indicators have different objectives which can be contradictive. For instance, if there is a scenario in which generating electricity in a conventional way, using natural gas, is cheaper than generating electricity in a sustainable manner with hydrogen, what strategy should be chosen? If the key performance indicator ”Sustainability” has a higher priority than the indicator financial ”Financial costs”, one can state that hydrogen is the best option to choose. But how costly can electricity, generated by hydrogen, become before the tipping point is reached, and electricity produced by conventional methods, such as natural gas, is the preferred method? This trade-off between the key performance indicators sustainability and financial costs is influenced by the acceptability of fossil fuels [53]. In Chapter 5 Model, elaboration will be provided on how the key performance indicators are assessed in this research.

Figure 1.1: Key performance indicators for an optimized strategy (own figure)

1.4. Research scope

To not over-complicate this study and maintain it at an achievable level, this research will have some demarcations.

One demarcation in this research is that the supply of energy will be delimited to solar energy and fossil energy. The reason for this demarcation is because solar energy provide over 10% of the global energy in 2021 and is therefore the largest source of sustainable energy [83]. In the future, this generation method will increase in usage across the world [104]. There are also other sustainable resources that have a significant share in producing electricity supply, such as wind energy[14], but to keep this thesis manageable, other resources will be excluded for this research[14].

This research will use weather data from the Netherlands on an hourly basis. Seasonal changes in weather conditions have a high impact on how much solar irradiance is present to generate solar power. Different parts of the world have different weather conditions and different seasons which is why it is important to demarcate a specific climate. Also, historical hourly data from the Netherlands on electricity demand is used in this research. This data, together with the data on solar irradiance in the Netherlands will be the only datasets used in this research.

Energy storage in this research will be limited to hydrogen storage in salt caverns. The Netherlands has the unique circumstance of having several depleted salt caverns that are already being repurposed for hydrogen storage [111]. The Hystock project in Groningen, for example, is exploring the potential of storing hydrogen in salt caverns [41]. Currently, six of them are used to store natural gas which already proves that this technology is feasible. Batteries for short-term power supply are not included because batteries are difficult to scale which makes them less suitable for large-scale storage [90]. Another reason is that batteries carry an environmental footprint due to factors such as raw material extraction, manufacturing processes, and end-of-life disposal, which make them not really a sustainable resource [13]. Fossil fuel will be included in the research to compensate for any shortage of sustainable energy, or to find a more efficient strategy.

Events such as cyberattacks, or unpredictable and unusual events, such as hurricanes, tsunamis, geopolitical conflicts, etc, which will have effects on the supply and demand of electricity will not be considered in this research.

1.5. Research question and sub-questions

1.5.1. Research question

The goal of this research is to find the most optimal operating strategy for an electricity system including hydrogen storage. Firstly, an operating strategy, existing out of a set of rules, will be constructed based on the literature review. Further, this strategy will be optimized according to the key performance indicators mentioned earlier in 1.3 Research goal. Lastly, attention will be given to the results of this research to obtain insights and will reflect on what components of the electricity system are having the most influence on the outcome of the strategy. The research question of this research is as follows:

> *How can electricity demand be covered by a system of solar power, conventional power supply, and hydrogen systems, optimized for reliability, sustainability, and cost-efficiency, by adjusting the operating strategy?*

1.5.2. Sub-questions

In order to obtain an answer to the research question, it is important to understand the problem on a deeper level. Hence the following sub-questions have been identified:

1. *According to the scientific literature, what are the most common approaches to finding an optimized operating strategy of an electric system including hydrogen technology?*

   The purpose of this question is to obtain more insight into how electricity is functioning. The literature review performed in Chapter 3 Literature review will be dedicated to answering this sub-question. To further break down this sub-question, three more questions are identified:

   (a) *What are the different interpretations of an electricity grid according to the literature that studies an electricity system including hydrogen storage?*
   (b) *What are the different operating strategies stated in the literature and what methods are being used to optimize them?*
   (c) *What are the properties of the components used in an electricity grid including hydrogen storage, according to the literature?*

   By splitting the sub-question into three topics, an elaborate overview will be accomplished that analyzes all the relevant topics required for this research. By answering question 1a an attempt will be made to gain an understanding of how the literature describes an electricity system that includes hydrogen storage. Exploring question 1b will delve deeper into what operating strategies are proposed in the literature and what methods are being used to optimize these. Question 1c describes the properties of the components in the electricity grids.

   The answers to these questions will provide the knowledge required to perform the analysis for this study.

2. *How should the key performance indicators in the operating strategy, referred to in 1.3 Research goal, be prioritized to conceptualize the optimal operating strategy?*

   This question will elaborate on how the sustainability, reliability, and financial costs of an operating strategy can be interpreted in an operating strategy. The indicators on which the performance of the strategies are being evaluated have different units which makes it difficult to express a final score for the strategies. Chapter 5 Model will be dedicated to answering this sub-question.

3. *According to scientific literature, which research approach, methodology, and methods are appropriate for determining an optimized operating strategy for electricity supply in the considered system?*

To find an answer to the research question, the literature will be reviewed and examined how similar studies have approached this problem. By finding an answer to this question a well-structured and grounded research approach will be found. This sub-question will be answered while studying the literature, performed in Chapter 3 Literature review, and discussed in Chapter 4 Research approach.

4. *In the considered case, how can an optimal, with respect to the key performance indicators defined in sub-question 2, operating strategy be determined?*

   This research will elaborate further on the multi-objective operating strategy and will delve deeper into what research is conducted to find the optimized operating strategy. This is done by modeling a discrete-time model, which will be optimized by particle swarm optimization. In Chapter 4 Research approach, and Chapter 5 Model this question will be elaborated on.

5. *How can the optimization model, found in sub-question 4 be used to optimize realistic future scenarios?*

   When the previous sub-question has found a solution, scenario analysis can be carried out. As mentioned previously in 1.2 Knowledge gaps, there is much literature stating that components, such as electrolysis, fuel cells, and hydrogen storage are becoming more developed. [59, 75, 97]. By defining scenarios the strategy can adapt to these more developed components in the future and conceptualize possible future circumstances.

6. *What are the recommendations that can be formulated to the problem's stakeholders based on the results of sub-question 5?*

   This sub-question will discuss the outcomes of the scenarios which are set up in the previous sub-question. The scenarios will be run to obtain insights in a changing environment and will reflect what components of the electricity system are having the most influence on the performance of the strategy. *These results will be interpreted and recommendations will be formulated for the stakeholders.*

1.6. Research relevance

This research is relevant from multiple perspectives, which are outlined below. Firstly, the scientific relevance and the social relevance of the research are discussed. Thereafter, the relevance of the study with respect to the master's program, Engineering and Policy Analysis (EPA), is described. Finally, the relevance for the stakeholders involved is discussed.

1.6.1. Scientific relevance

As discussed in Section 1.2 on knowledge gaps, this research seeks to address the integration of hydrogen technology into an operational environment by optimizing an operating strategy. It contributes to the existing literature by examining an optimal strategy for a hybrid electricity system that includes solar energy, hydrogen systems with hydrogen storage, and gas energy, which distinguishes it from previous studies. Unlike studies that solely focus on cost reduction as a one-dimensional objective, this research takes into account environmental factors as well. Section 1.3 on the research goal explains the three key performance indicators that define this objective, which sets it apart from most other research. By considering the additional dimension of "Sustainability," this research encompasses a multidimensional research objective, thereby making a valuable contribution to the scientific literature, which is scarce on this topic.

Furthermore, this research aims to contribute to the literature by utilizing different datasets compared to existing studies. As mentioned in Section 1.4 on research scope, this research employs Dutch load data and Dutch climate data on an hourly basis. Conducting research in a specific climate context, this research adds to the scientific literature as different regions experience distinct weather conditions and seasonal variations. This approach enhances the relevance and applicability of the optimized operating strategy.

Throughout Chapter 3 Literature review, the scientific relevance of this research will be further reinforced, establishing its position in relation to existing literature and emphasizing its valuable contributions.

1.6.2. Societal relevance

This research holds societal relevance by addressing two interconnected topics. The first topic focuses on the significance of this study for electricity grids, followed by a broader societal relevance concerning climate change.

Currently, in many parts of the Netherlands, the electricity grid is overloaded as of 2023. This can be attributed to two main factors. Firstly, the rapid installation of solar panels across the country in recent years has resulted in excess electricity production in certain areas, exceeding the capacity of the electricity grid to accommodate it [69, 76]. Consequently, sustainable energy sources are occasionally disconnected from the grid, hindering the energy transition process [69]. Secondly, the energy sector has primarily focused on efficiency and cost reduction, leading to insufficient long-term investments in supporting the energy transition [84]. Given the need for investments in the electricity grid and the surplus of sustainable electricity production during certain periods, the storage of excess electricity in the form of hydrogen presents a potential solution to alleviate the challenges faced by the Dutch electricity grid. Therefore, a hydrogen-based solution aligns with the current societal situation and challenges.

Furthermore, this thesis addresses the broader societal relevance of combating climate change by promoting a shift toward sustainable electricity production. Countries are urged to adopt low-carbon energy sources instead of relying on fossil fuels. However, these new energy resources, such as wind and solar power, are highly variable due to their dependence on natural conditions [27]. Consequently, ensuring electricity availability from sustainable resources becomes more complex compared to a grid powered by fossil fuels. Conducting research on a more sustainable system that addresses these challenges can contribute to a better future for society as a whole, highlighting its societal relevance.

The United Nations has established Sustainable Development Goals (SDGs) as a blueprint for a more prosperous future [110]. Access to a sustainable, clean, and well-organized energy grid is interconnected with almost all SDGs, as clean electricity plays a crucial role in fostering prosperity. Specifically, the main overlap lies with the following SDGs:

- UN SDG 7: Ensure access to affordable, reliable, sustainable, and modern energy for all
- UN SDG 12: Ensure sustainable consumption and production patterns
- UN SDG 13: Take urgent action to combat climate change and its impacts

In conclusion, the clear connection between the SDGs and the focus of this study underscores the societal relevance of researching an optimal strategy for electricity grids.

1.6.3. Masters' relevance

The relevance of this Master's thesis will be discussed based on three requirements outlined for the Master's thesis Engineering and Policy Analysis (EPA) [22]. The first requirement states that the subject should be related to Grand Challenges, inform decision-makers, and be relevant in the public or policy domain, or at the interface between public and private domains. The second requirement is that the work should demonstrate a systems perspective and a multi-actor perspective. Lastly, the thesis must utilize EPA methods and techniques for problem analysis and exploration systematically, and incorporate (conceptual) modeling and/or simulation techniques. The following paragraphs clarify how this study meets these three requirements.

Regarding the first requirement, the EPA master's program aims to address ”Grand Challenges.” This research, which analyzes the transition towards more sustainable electricity while maintaining accessibility and affordability, fulfills this requirement, as the energy transition is considered a Grand Challenge

[78]. The study provides a deeper understanding of integrating sustainable energy systems into conventional electricity systems and can serve as a guideline for policymakers. Unlike most literature that focuses solely on cost reduction, this research considers environmental factors, offering more comprehensive insights into energy provision and supporting discussions on effective environmental policies.

Furthermore, the second requirement is met as this thesis adopts both systems and a multi-actor perspective. It explores the integration of a conventional electricity system with a sustainable electricity system, including hydrogen storage. Additionally, the research's goal is multidimensional, encompassing both cost reduction and environmental factors, indicating a transdisciplinary objective. This demonstrates an awareness of the broader context. Transitioning towards a sustainable society inherently involves multiple actors, including the realms of the market, government, science and technology, and civil society, as described by Grin [38]. Similarly, the adaptation of hydrogen systems into electricity grids impacts electricity markets, society's energy resources, technological applications, and electricity provision policy.

Lastly, the third requirement is fulfilled as the thesis systematically employs EPA methods and techniques for problem analysis and exploration. Furthermore, the research utilizes modeling, simulations, and scenario analysis, which will be elaborated upon in subsequent chapters.

1.6.4. Stakeholder relevance

It is important to note that an internship was conducted at CGI consultancy for this study. However, while the thesis provides valuable research for CGI, the company itself will not be considered a stakeholder in this context. Instead, the focus will be on the organizations to which CGI provides advice on electricity systems. The following paragraphs elaborate on the stakeholders involved and how the key performance indicators mentioned in section 1.3 Research goal are linked to these stakeholders.

The first stakeholder to consider is energy companies. These companies have set goals to transition towards more sustainable energy supplies and are actively researching new technologies to achieve their objectives [94, 18]. The visualization presented by [42] shows a consistent increase in globally reported corporate energy research and development (RD) spending on renewable energy, electricity generation, and networks over the past decade. Given the growing need for research on renewables and electricity networks/generation, this study on finding an optimized operating strategy for an electricity system including hydrogen storage contributes directly to the interests of energy companies. The vision of energy companies aligns with all the key performance indicators considered in this study. They have an obligation to provide society with a reliable electricity supply, falling under the category of 'reliability'. Additionally, energy companies have a social responsibility to produce cost-efficient electricity, and addressing the demand for more sustainable energy sources has become increasingly important, to which they must respond.

The second stakeholder is the Dutch government, along with the Dutch society as a whole. A stable electricity grid is crucial for the prosperity of a country [36]. Consequently, the Netherlands benefits from maintaining a reliable electricity infrastructure. As mentioned in section 1.6.2 on societal relevance, investments need to be made to adapt the electricity infrastructure to accommodate the increasing capacity in the grid. Research on hydrogen storage, which could be part of a sustainable solution, has gained significant importance in society and can help release pressure on the overloaded electricity grid. Therefore, this research is relevant to the Dutch government and society, as it addresses both reliability and sustainability indicators that are important to these stakeholders.

1.7. Thesis structure

The research consists of eight chapters in total. Chapter 1 serves as an introduction to the problem and outlines the scope of the study. It provides an overview of the research objectives and sets the context for the subsequent chapters. Chapter 2 on the Theoretical Framework aims to clarify the terminology used in this research and provide a deeper understanding of the concepts and theories relevant to the study. It is not intended to substantiate research choices or discuss the literature extensively. Its primary goal is to provide additional context and background knowledge before delving into the main research. Chapter 3 focuses on the literature review, where previously conducted research on the topic will be analyzed. This chapter examines the existing body of knowledge to define an electricity grid, position this research within the relevant literature, and identify key insights for constructing the key performance indicators and developing an optimized strategy. Chapter 4 discusses the research approach, methodology, and methods employed in this study. It also introduces the data sources used for analysis and provides an explanation of their relevance. This chapter details the specific steps taken in conducting the research and ensures transparency in the methodology. Chapter 5 presents the conceptual model used in this research. It explains how the modeling objective function and the strategy was developed. Besides it describes the inputs and steps within the model and outlines the model's assumptions and limitations. Chapter 6 focuses on the presentation and interpretation of the results obtained from the model. It begins by clarifying the scenarios that were run in the model, followed by a detailed explanation and analysis of the results. Chapter 7 engages in a comprehensive discussion of the implications of the research findings. Lastly, Chapter 8 draws conclusions by addressing the main research question and sub-questions. It summarizes the key findings, discusses their implications, and offers a concise and coherent conclusion to the study. Also it provides recommendations for future research.

2

Background information

2.1. Introduction

This chapter aims to provide an overview of the research topic, clarify the terminology used in this study, and enhance the understanding of hydrogen systems. Its purpose is to establish a foundation for comprehending the subsequent chapters of this thesis. Importantly, this chapter does not aim to substantiate the research through an extensive literature review or justify research choices, as these aspects will be addressed in the following chapters. The primary objective is to offer contextual information on the subject matter.

The chapter begins with an introduction to electricity supply and how sustainable resources function within the electricity system. It highlights the challenges associated with electricity supply, with a particular emphasis on the potential role of hydrogen systems in addressing these challenges. Furthermore, this chapter provides a detailed explanation of the research problem, giving additional insights into the specific electricity system being examined in this research. Lastly, the components of the electricity system used in this research will be elaborated on by analyzing their properties.

2.2. Transitioning the electricity grid to sustainability

When examining the electricity system from a simplified perspective, it consists of two main components: electricity generators and energy consumers. Traditionally, the grid heavily relied on non-sustainable energy sources like natural gas and coal. These sources offered the advantage of resource storage, allowing flexibility in meeting fluctuating electricity demand. Managing the matching of electricity production with demand was relatively straightforward as grid operators had control over the utilization of these non-sustainable resources.

However, renewable energy operates differently. As mentioned in Chapter 1, renewable energy sources are highly dependent on external factors such as daily weather conditions. For instance, during favorable conditions with abundant sunshine and wind, solar panels and wind turbines can produce high amounts of energy, leading to an excess of electricity that surpasses demand. Conversely, unfavorable weather conditions like cloudy and windless days, coupled with high electricity demand due to factors like low outdoor temperatures, may result in a situation where renewable energy is insufficient to meet the electricity demand. This stands in contrast to the convenience offered by non-sustainable resources.

The ideal scenario is to provide sustainable electricity to the grid in both surplus and deficit scenarios, regardless of weather conditions. This is where hydrogen storage comes into play. As previously mentioned in Chapter 1 Introduction, electrolysis can be used to split water into oxygen and hydrogen particles using electricity. The generated hydrogen can then be stored and utilized at a later time. Essentially, the fuel hydrogen is created that produces no pollutants when used. When the electricity used for electrolysis, and thus the production of hydrogen, comes from sustainable resources, hydrogen generation becomes entirely sustainable. By integrating this system into the electricity grid, it can serve as a solution to the limitations of sustainable electricity generation dependent on weather conditions. In situations where weather conditions are unfavorable and sustainable energy generators cannot produce sufficient electricity, stored hydrogen can be utilized to compensate for the deficit in electricity supply and ensure the electricity demand is met.

However, hydrogen storage systems also face challenges related to efficiency and financial costs. The efficiency of hydrogen electricity is lower compared to electricity directly sourced from sustainable resources. This efficiency loss occurs in the three sequential steps involved: electrolysis, storage, and the utilization of hydrogen to generate electricity. Electrolysis incurs an efficiency loss, as does the storage of hydrogen, and generating electricity from hydrogen also incurs energy losses. Additionally, costs play a significant role. Establishing and maintaining a hydrogen system incurs expenses that are reflected in the price of electricity generated from such a system. If the costs associated with a hydrogen system are high, it may result in significantly higher electricity prices compared to other resources used for electricity generation. Consequently, utilizing electricity directly from sustainable resources proves to be more efficient.

Despite these challenges, a hydrogen system still offers a solution to the limitations of sustainable resources dependent on wind and solar irradiance. However, it is important to investigate ways to mitigate these challenges and enhance the functionality of hydrogen systems.

2.3. Study of this research

Having established the significance of a hydrogen system in an electricity grid with sustainable resources, this section will now discuss the focus of this research. Subsequently, the components within the electricity grid used in this study will be elucidated. Finally, an explanation will be provided on how the research goal will be approached based on the outlined electricity grid.

This research examines an electricity grid incorporating hydrogen storage. The objective is to deliver electricity in a sustainable manner while ensuring financial efficiency. To achieve this, the research focuses on determining an optimal operating strategy, which involves deciding when to utilize different energy resources such as solar panels, hydrogen, or non-sustainable resources like natural gas. To facilitate the development of an effective operating strategy, a simulation model has been created to replicate an electricity grid. The conceptualization of this model is visualized in Figure 2.1, and the components within this system are listed in the following bullet points. The subsequent paragraphs will provide further clarification on the outlined electricity system and the concept of the operating strategy.

- Energy source (Electricity source + inverter)
- Electrolysis
- Hydrogen storage
- Fuel cells
- Inverter (fuel cell)
- Electricity demand
- Fossil fuel
- Gas turbine

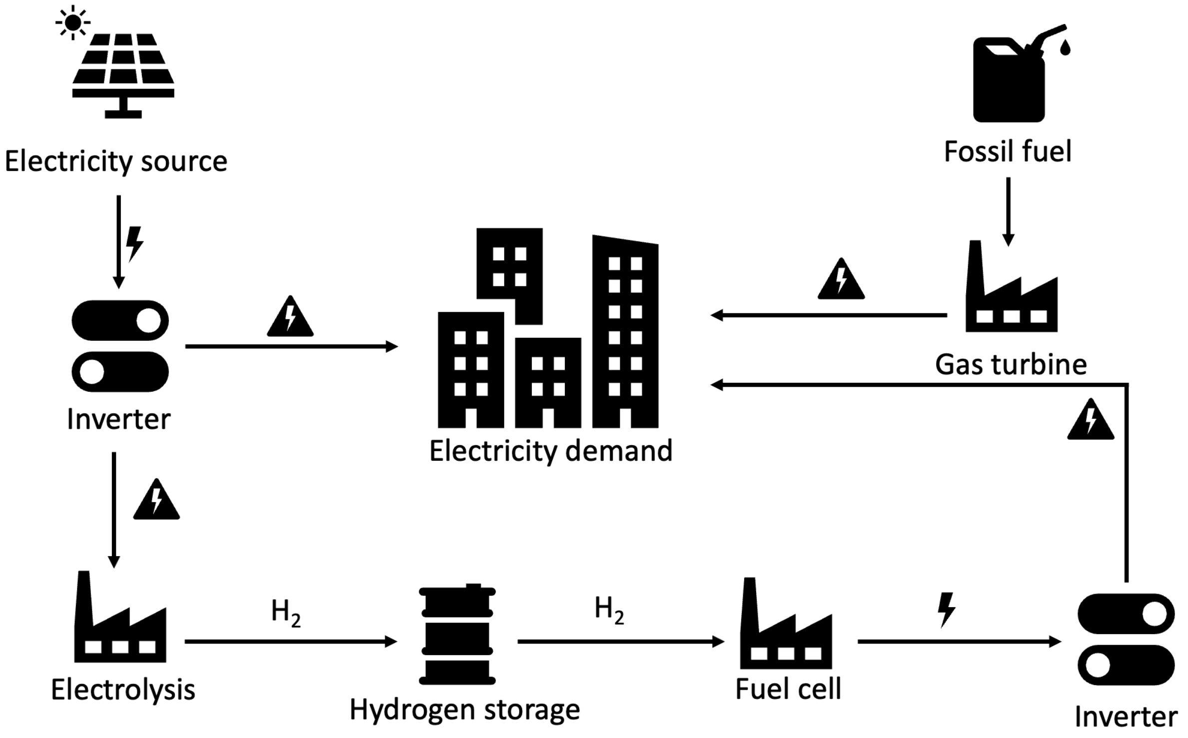


Figure 2.1: Electricity system including hydrogen storage (own figure)

The electricity system used in this research, as depicted in Figure 2.1, comprises three methods of providing electricity to meet the demand. The first method is electricity generated from solar panels, representing the sustainable source considered in this study. The figure represents a specific number of hectares of solar panels defined for analysis. Prior to the electricity flowing from the solar panels to the demand, an intermediate step is shown in the figure: the inverter. This device converts the electricity into a usable form for meeting the demand.

In addition to the sustainable source, the figure also includes a non-sustainable source depicted as Fossil fuel. The non-sustainable resource used in this research is natural gas, which can also be used to generate electricity. Although this energy source emits emissions, it provides a reliable form of electricity and is therefore included in the research to ensure the reliability of the electricity system.

Lastly, there is the hydrogen system. As seen in Figure 2.1, the only input to the hydrogen system is electricity from the electricity source. This means that the hydrogen system in this research is solely powered by sustainable electricity. The hydrogen system consists of four components. As mentioned earlier, electrolysis splits water into hydrogen and oxygen using sustainably produced electricity. The hydrogen can then be stored in the hydrogen storage until needed. When required, this stored hydrogen can be used to generate electricity through a fuel cell. It is worth noting that continuous on-off cycling of the fuel cell can cause rapid deterioration, which is also a consideration for the smart operating system. Finally, the electricity needs to be converted into a usable form for meeting the demand, which is achieved through the inverter.

With the system outlined, the focus now shifts to the operating strategy. As previously mentioned, the objective of this research is to deliver electricity in the most sustainable and financially efficient way possible. Based on the depicted electricity system, the research aims to optimize an operating strategy that can best achieve this objective. This strategy will determine which energy source (hydrogen, solar, or natural gas), or combination thereof, is used to supply electricity to the grid. Challenges associated with this include the costs of electricity production from each resource and the associated emissions. Additionally, the possibility of depleting the hydrogen storage, rendering hydrogen electricity unavailable, will be investigated. This research aims to identify the best operating strategy for different scenarios.

2.4. System properties of components in the electricity system

So far, this chapter has elaborated on how a electricity system consists of and what challenges it posses, the potential role of the implementation of hydrogen storage into this electricity system, and what this research will study. This section will discuss what the literature tells about the properties of photovoltaic panels (PVs or solar panels), electrolyzers, fuel cells, hydrogen storage, and inverters, which are referred to in figure 2.1. The properties of the various components will be used in the model, which will be elaborated on in chapter 5 Model. The choices on why these components are chosen for this research will be elaborated on in 3.5 Research choices after reviewing the literature.

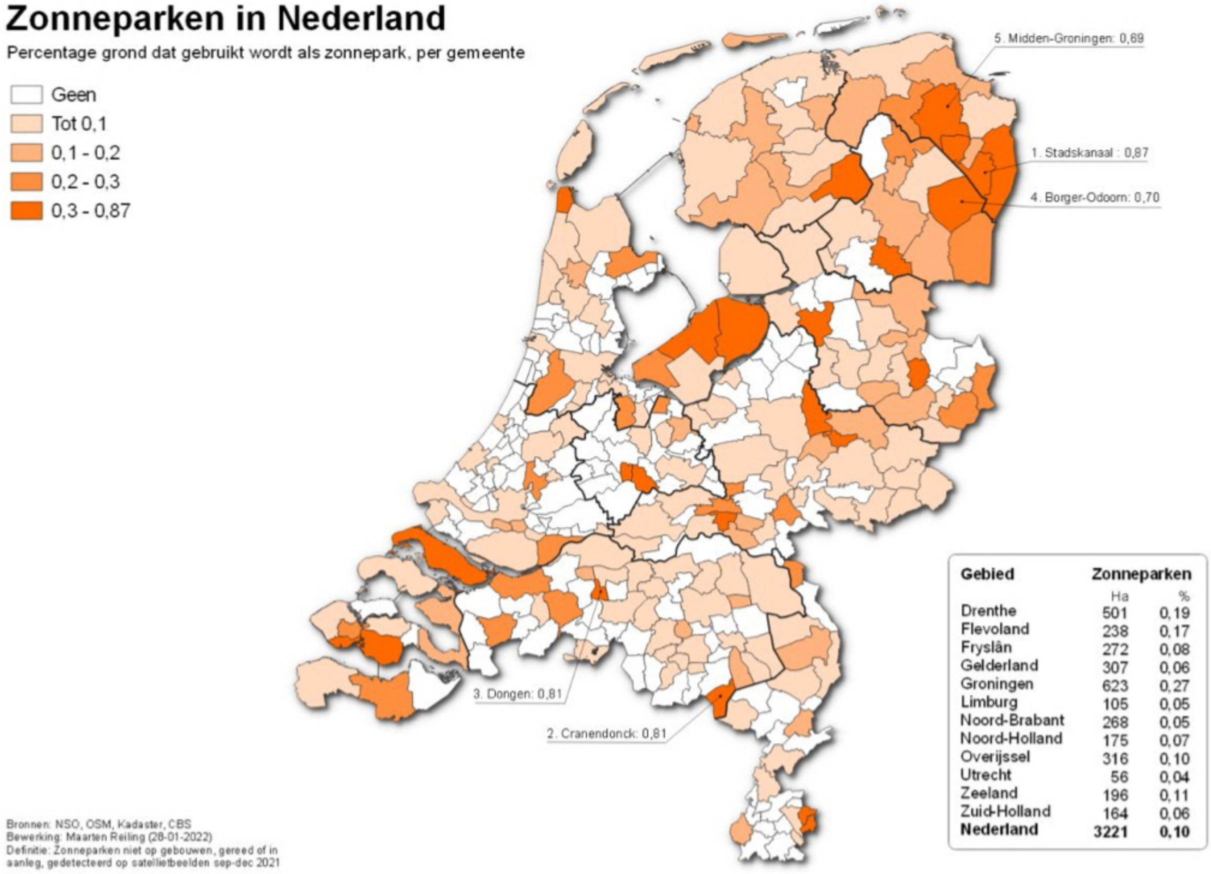
2.4.1. Solar panels

Hectares

For the modeling part of this research, it is important to have an indication of how many hectares of solar panels are present in the Netherlands which will be explored in this section. As will be elaborated on in 3.5.1 Scale, this research scope will be the electricity coverage of the Netherlands which is why the electricity produced by solar power in the Netherlands will be considered. Solar power will be divided into two groups: solar power retrieved from solar parks and solar power retrieved from installations on roofs.

The demography of solar parks in the Netherlands is visualized in Figure 4.5. According to [70] 3221 hectares of Dutch ground was covered with solar panels at the beginning of 2022. The data obtained by [16] show that the installation of new solar panels is strongly increasing each year which is why can be assumed that there are even more hectares covered as the number stated in Figure 4.5. However, this data is a well-substantiated point of reference as input for the model, discussed in chapter 5 Model.

Besides solar parks, there is also solar power retrieved from solar panel installation on roofs. Data on how much roof is covered in the Netherlands is not available but an estimation can be made. [80] states that the Netherlands has 60,000 hectares of roof surface and 40,000 hectares of roof surface available for solar panels. According to [68] 20% of the Dutch houses have installed solar panels. Under the assumption that the houses that have installed solar panels have covered all of their available roofs with solar panels, 8000 hectares of solar panels are installed on roofs.


Zonneparken in Nederland

Percentage grond dat gebruikt wordt als zonnepark, per gemeente

Gebied	Zonneparken	
	Ha	%
Drenthe	501	0,19
Flevoland	238	0,17
Fryslân	272	0,08
Gelderland	307	0,06
Groningen	623	0,27
Limburg	105	0,05
Noord-Brabant	268	0,05
Noord-Holland	175	0,07
Overijssel	316	0,10
Utrecht	56	0,04
Zeeland	196	0,11
Zuid-Holland	164	0,06
Nederland	**3221**	**0,10**

Bronnen: NSO, OSM, Kadaster, CBS
Bewerking: Maarten Reiling (28-01-2022)
Definitie: Zonneparken niet op gebouwen, gereed of in aanleg, gedetecteerd op satellietbeelden sep-dec 2021

Figure 2.2: Solar parks in the Netherlands ([70])

Technical details

This section will discuss what type of solar panel is most common, what the efficiencies are, and what costs are involved. According to [48] it is likely that the lifetime, efficiency, stability, and manufacturability will increase in the future and the cost will decrease over the years. To not overcomplicate this study, this section will assign static parameters and will not include the technological advancements over the years in the study.

The most used type of solar panels is panels with crystalline silicon cells [21] which are also used in this research. The performance of solar panel modules depends on the temperature and the solar irradiance, as well as on the spectrum of the sunlight [35]. In the literature, there is not a general consensus on the efficiency of these solar panels. For instance, [119] claims that the efficiency is around 15-21 % taking dust and damages into account while [105] argues that the efficiency is already up to 28%. For this research, an efficiency of around 20% will be asserted because this is an efficiency that is compliant with most literature [17, 72, 37]. However, it will be interesting to adjust the efficiency of the solar panels in the modeling part of this research.

For asserting the total costs of solar panels, the purchase and installation costs, maintenance costs, and lifespan are considered. Realistically, the costs of solar parks are different from solar panels on roofs. For this research, the cost properties of solar parks will be explored and will be used for all hectares of solar panels in the model. The reason for this scoping is for the sake of simplicity and for policy reasons. However, one should keep in mind that solar panels on houses are owned and paid for by the house owner. Therefore the total costs assumed in this thesis might vary from other literature. The investment costs (purchase and installation costs) are €650.000 per hectare [99]. These costs include the cost of solar panels, inverters, foundation, construction, wiring, installation, and security. Yearly costs stated in [99] are tenancy, security, maintenance, and unforeseen costs which are adding up to €2.000 per hectare per year. Lastly, the lifetime of solar panels will be discussed so the depreciation over time can be calculated. [99] states that the depreciation period is 15 years while other sources are stating that the life expectancy is between 20 to 35 years [106, 50]. This dissimilarity can be explained by the rapid technological advancements of solar panels which will continue in the future [64]. Based on the literature the life expectancy will be set at 25 years for this research. However, for the scenario analysis later on in this research, it will be insightful to change these parameters.

2.4.2. Electrolysers

In this section a clarification will be provided on what type of electrolyzer is used in this research, why this type is used, what the efficiency is, and what costs are implied. As explained earlier in 1.1.3 Integration of hydrogen storage as a solution, electrolyzers are activated by electricity and generate hydrogen by splitting water into hydrogen and oxygen. This process is visualized in Figure 2.3

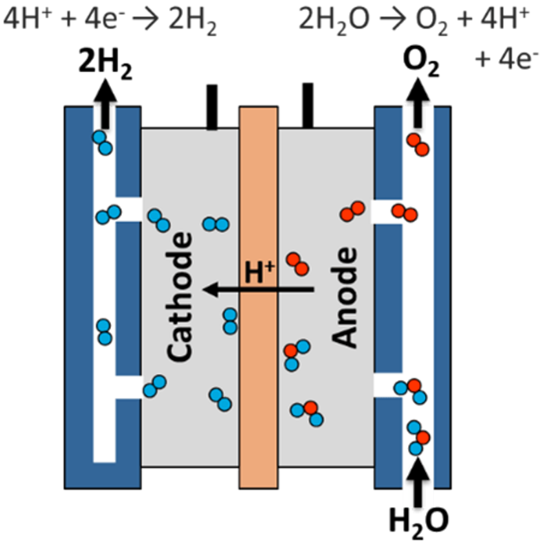


Figure 2.3: Electrolysis, [107]

There are several types of performing electrolysis. The literature doesn't elaborate on the details of the electrolyzers used to conduct research, or why certain types of electrolyzers are chosen. Alkaline water electrolysis is the most mature and widely used technology for hydrogen production. [120]. It uses an alkaline electrolyte, such as potassium hydroxide, and operates at relatively low temperatures and pressures. Alkaline water electrolysis can achieve high efficiency and can be scaled up for large-scale hydrogen production [55]. For this research alkaline water electrolyzers will be used in the model due to their maturity, high efficiency, and scalability.

In a typical industrial-scale alkaline water electrolysis system it takes 51.2 kWh to produce 1 kilogram of hydrogen, depending on the operating conditions and efficiency of the system ([47]). According to [8], one alkaline water electrolysis installation can handle up to 6MW of electricity to create hydrogen and oxygen, with an efficiency of around 70%.

To obtain the total cost of an electrolyzer the lifespan, maintenance costs, and investment costs should be determined. As will be presented in the remainder of this paragraph, the data on electrolyzers in the literature is dispersed which is why the following approach is carried out in this research. According to [29] the cost of electrolysis is $6/kilogram of hydrogen produced. However, the cost of electrolyzers has been decreasing over the years due to technological advancements and economies of scale and may decrease in the future as well([47]). For this research, the cost of $6/kilogram of hydrogen produced will be used.

As mentioned earlier, the literature is very dispersed on the properties of electrolyzers. According to [55], an alkaline electrolyzer's lifespan is about 90,000 hours. Other sources, such as [47], claim that electrolyzers for alkaline water electrolysis can have a lifespan of 10-20 years or more, with some systems lasting even longer. According to [66] the cost of electrolyzers for alkaline water electrolysis varies depending on the size and complexity of the system. Large-scale electrolyzers can cost millions of dollars, while smaller systems can be less expensive. Because of this indistinctness, the value presented in [85] is used for this project.

2.4.3. Fuel cell

In this section a clarification will be provided on what type of fuel cell is used in this research, why this type is used, what the efficiency is, and what costs are implied. As explained earlier in 1.1.3 Integration of hydrogen storage as a solution, fuel cells generate electricity by combining hydrogen with oxygen. When these two molecules are combined, water and energy are produced as visualized in Figure 2.4.

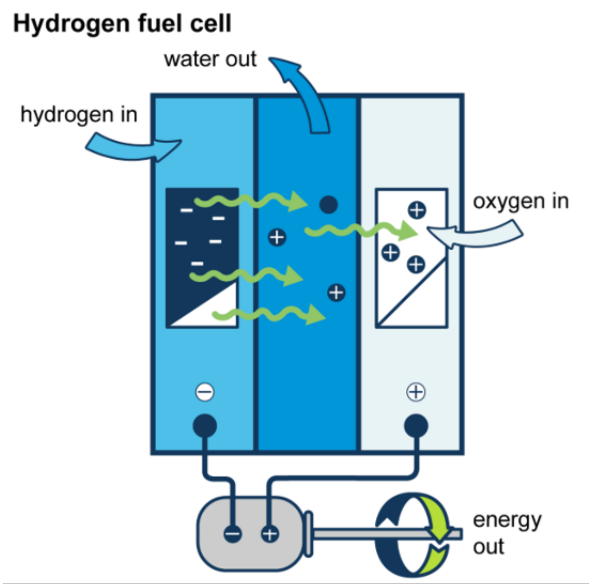


Figure 2.4: Hydrogen fuel cell, [67]

Choice of fuel cell

There are multiple types of fuel cells for the production of energy from hydrogen. What type of fuel cell is the best fit is very dependent on what scale the study is performed on [3]. [3] use Proton exchange membrane fuel cells (PEMFCs) which typically generate between 1 W and 100 kW of output power. This research focuses on small-scale applications which is why the PEMFCs were chosen. However, the study performed in this thesis is large-scale which requires different properties. [108] has put together an overview of different types of fuel cells which shows that a solid oxide fuel cell (SOFC) is the most suitable fuel cell for the purpose of powering a grid on a large-scale level and thus for this research. [63] claim that the solid oxide fuel cell is the most efficient power-to-power technology but also the most expensive.

Technical details

As stated in the overview presented in [108] the solid oxide fuel cell has a production range of 1kW up to 2MW, needs a long start-up time of about 3 hours [28], and has a limited number of shutdowns. The reason for the limited number of shutdowns is because of the high temperatures required for this type of fuel cell, and too much thermal stress can cause degradation and breakdowns [108].

The solid oxide fuel cell has an efficiency of 60%. The specific energy of a hydrogen fuel cell (which is the measure of how much energy can be produced per unit mass of hydrogen fuel) typically falls within the range of 40-60 MJ/kg, depending on the type of fuel cell and its operating conditions [7]. This means that to produce 1 MWh of electricity, it would require about 72 kg of hydrogen per hour, assuming a fuel cell with a specific energy of 50 MJ/kg. This efficiency will be adopted in the modeling of this research.

[52] has performed research on solar panel and Solid oxide fuel cell electricity production and concludes that the levelized cost of electricity, or break-even price is 0.11/kWh. The model will include this specific price to perform model runs on.

2.4.4. Inverter

An inverter is an electronic device that converts direct current (DC) to alternating current (AC) and will be modeled in the model in this research. Inverters are commonly used in renewable energy systems such as solar photovoltaic (PV), wind turbine systems, and fuel cells, where the DC electricity generated by the system needs to be converted to AC electricity to be used in the grid or in buildings [61].

Technical details

For this research, the system loss due to cable loss and inverters will be set at 14%. This is because of the reason that the dataset of solar irradiance, which will be elaborated on in 4.6, also uses this number and there is no reason to adopt another value. Besides, the literature is indifferent to the efficiency of inverters. According to [50] the efficiency of an inverter depends on several factors, such as the duration of the inverter operation, or the temperature. [12] state that high-performance inverters have an efficiency of 98%. Other literature, such as [62] states that modern inverters designed for large-scale electricity supply applications can be highly efficient, with conversion efficiencies typically ranging from 90% to 95% or higher. The costs of the inverter are already included in the costs of solar parks as stated in 2.4.1. For simplicity's sake, the cost of inverters required for fuel cells will be left out of this research. However, the efficiency loss will be adapted.

2.4.5. Hydrogen storage

In 3.5.3 Energy storage a substantiated perspective is provided on why salt caverns are being used in this research. This section will focus on what type of storage is commonly used in the research, the efficiencies, and the cost of hydrogen storage in salt caverns.

Common practice in literature

In the literature studied for this research, the common approach to storing hydrogen is in hydrogen tanks [77]. However, as mentioned earlier in this chapter, the scale of the research matters when determining what components to use in the model [77]. Since the scale of this research is larger than the most common research studied in the literature, underground hydrogen storage in salt caverns will be chosen above storage in hydrogen tanks.

The choice for a large-scale underground hydrogen system implementation is influenced by the unique circumstances in the Netherlands, which make it feasible to construct a nationwide hydrogen infrastructure. For instance, the Hystock project in Groningen investigates the possibility of storing hydrogen in salt caverns ([41]). The project website reports that there are 10 salt caverns in Groningen, each capable of holding at least 6000 tons of gas. At present, six caverns are used for natural gas storage, demonstrating the viability of this technology. The remaining four caverns are reserved for hydrogen storage, but the allocation of salt caverns for natural gas and hydrogen storage can be altered in the future, making it worthwhile to explore an enlarged capacity of hydrogen storage in the model.

Technical details

The efficiency of the storage is, according to [41] 98%. This value can be interpreted in many ways. However, for this research it will be interpreted as, if accessed, only 98% of the hydrogen stored will be accessible, and 2% is going to waste.

The cost of hydrogen storage in salt caverns depends on several factors, including the cost of constructing and maintaining the storage infrastructure, and the cost of extracting and distributing the hydrogen when it is needed [117]. Another key factor that influences the costs, according to [58], is the electricity price and electrolytic activity. According to an article that studied the costs of hydrogen storage in salt caverns, the costs of storage is always under 5% of the overall cost [58]. Another study claims that the cost of hydrogen storage in salt caverns is approximate €0.13/kg of Hydrogen for daily storage [1]. For this research, the costs related to storage will be determined based on the study performed by [58], which means that the hydrogen costs will be calculated as a percentage of the total costs (lower than 5%).

2.4.6. Gas turbine

In this section, the choice of a gas turbine as a non-sustainable resource will be explained, and general information on how much gas the Netherlands consumes as well as the technical details will be discussed.

Natural gas in the Netherlands

One of the reasons for choosing gas turbines is the significant contribution of natural gas to total energy production. According to the most recent available data, in the second quarter of 2022, 11 billion kWh of electricity was generated out of a total of 28 billion kWh in the Netherlands [15]. As argued by [14], in 2022, the Netherlands consumed 66.52 billion kWh of electricity, out of which approximately 56.2% was generated from fossil fuels, primarily natural gas.

Natural gas power plants are more efficient than other fossil fuel power plants, such as coal and oil [91]. This means that they can generate more electricity with the same amount of fuel, resulting in lower operating costs and fewer greenhouse gas emissions [25]. Besides, natural gas power plants are highly reliable and can be turned on and off quickly to meet changes in electricity demand. This makes them ideal for providing backup power during times of high demand or in the event of power outages ([102]).

In this research, the gas turbines will only be used when the sustainable energy resources and hydrogen fuel cells do not produce enough electricity for the grid. Therefore, it is valuable to have gas turbines as a backup because it is able to start up fast when there is a peak in electricity demand.

Technical details

In this section, it is valuable to obtain the efficiency of a gas turbine, the costs of energy produced by this resource, and the fuel used per kWh.

The literature assigns different efficiencies on power production via gas turbines. For this research, only one type of gas turbine will be considered, for simplicity's sake, which will be the Rolls-Royce Trent 60. This gas turbine is known to be a high-performance gas turbine that is commonly used in peaking power plants. The Trent 60 has a capacity of up to 58 MW and is known for its fast start-up and rapid response times [34]. According to [34] the efficiency of a general gas turbine is about 35.8%. Therefore, this efficiency will be used in this research.

Furthermore, the costs of one MWh are according to [73] 90.9$/MWh. According to [26] it takes 7.36 cubic feet of natural gas to produce one kWh and [33] states that 0.0550 kg CO2 is produced per cubic foot of natural gas. This data provides enough leads to model the emissions and prices of natural gas to find a value for the key performance indicators 'Cost efficiency' and 'Sustainability'.

3

Literature review

3.1. Introduction

This chapter delves deeper into the existing literature on optimizing the operating strategy of an electricity system using hydrogen storage. As mentioned in Chapter 1 Introduction, significant research has already been conducted on this topic, although with slightly different approaches. It is crucial to analyze how these studies were conducted and how they addressed the problem, as it provides a foundation for further understanding of the subject and contributes to this research.

The aim of this chapter is to answer sub-question 1: ”*How can an electricity system including hydrogen technology be defined?*”. As presented in Chapter 1 Introduction, this sub-question is divided into three specific questions (a), (b), and (c) to obtain a comprehensive answer. Question (a) will be investigated in the section 3.2 Electricity system including hydrogen storage, followed by the answer to question (b) in the same section. The focus will then shift to discussing the position of this thesis in the existing literature and its contribution to it in section 3.4 Positioning. Additionally, in section 3.5 Research choices, the research choices made in this thesis will be elaborated upon, which are based on the findings of the literature studies in this chapter so far.

The method used in this chapter involves gathering academic literature using search engines such as Google Scholar and Scopus. Keywords such as ”electricity grid,” ”hydrogen storage,” ”strategy optimization,” ”hybrid electricity systems,” and ”sustainable electricity grid” will be used to retrieve relevant literature. The selected literature and their citations will provide a comprehensive overview of how electricity grids and the optimization of operating systems are defined in the literature. In addition to academic sources, grey literature will also be collected through Google searches using terms such as ’hydrogen initiatives’ combined with keywords like ’electricity grid,’ ’renewable energy,’ and ’energy supply.’ The results and their citations will be reviewed to select relevant literature that provides a comprehensive overview of hydrogen systems, the state of affairs of electricity in the Netherlands, and the combination of both.

3.2. Electricity system including hydrogen storage

To gain a comprehensive understanding of an electricity system that includes hydrogen storage, the literature search in this section focuses on the design of electricity grids in previous studies. The criteria that are looked for are the following: the literature should examine electricity demand and sustainable electricity supply. Furthermore, it should include a hydrogen system, and studies that investigate both sustainable and non-sustainable electricity will be sought. Sustainable electricity is generated from sources that can meet present energy requirements without compromising the needs of future generations, while non-sustainable electricity does not meet these criteria [89]. Exploring studies that consider both sustainable and non-sustainable electricity provides insights into the relationship between ”cost efficiency” and ”sustainability,” as described in section 1.3 on Research Goal. The composition of electricity systems from various studies is presented in the table below.

The literature in the table below, dedicated to obtain a comprehensive understanding of an electricity system that includes hydrogen storage, will be limited to the sustainable resources solar panels, and wind turbines, for simplicity's sake and because these resources are the most used sustainable resources in existing research. Non-sustainable resources in this literature search are defined as any resources that are coming from fossil fuels. Furthermore, the storage component in the literature is split into hydrogen storage and batteries. Again, these two storage methods were the most common practices to store energy which is why these two methods are chosen to present in this table. All methods to store hydrogen are considered in this table as hydrogen storage, as well as all types of batteries, are considered as batteries

Table 3.1: Composition of electricity grids in the literature

Article	**Resource**			**Storage**		**Scale**
	PV	*Wind*	*Non-sustainable*	*Hydrogen*	*Battery*	
[57]	X			X	X	Microgrid
[88]	X		X		X	Small scale - Medium scale Corsica - Ajaccio
[121]		X		X		Eastern Iran - Remote area
[118]	X	X		X		China - Remote industrial park
[51]	X	X	X	X	X	Canada - Newfoundland
[54]	X	X		X	X	-
[82]	X	X			X	-
[24]	X		X	X	X	-
[87]	X	X		X		Microgrid
This study	**X**		**X**	**X**		**Large scale** **The Netherlands**

Judging from the literature analyzed in the table above the following can be stated. Due to the highly complex nature of electricity systems, simplified representations of reality are commonly used in research. This is reflected in the literature presented in Table 3.1, where models typically consist of a sustainable electricity supply, electricity demand, energy storage systems including hydrogen storage, and an electricity management unit. In an electricity system including hydrogen storage, the studies show that electrolyzers and fuel cells are required to store and generate energy. As explained in 1.1.3 Integration of hydrogen storage as a solution, electrolyzers create hydrogen from electricity and water (see Formula 1.1), and fuel cells generate electricity from hydrogen and oxygen (Formula 1.2). Section 3.5 Research choices after reviewing the literature will delve deeper into the choices made in this research regarding what type of components are being used.

3.2.1. Contribution

As can be observed in the table, the compositions of the electricity systems in previous studies differ from the composition analyzed in this research. As stated before by [30] there is a need for more research on integrating hydrogen storage with different combinations of energy storage systems. Studying the specific composition of the electricity system used in this research does not overlap with the already available literature and will add to the already existing literature. Therefore it will add value to the existing literature and will contribute to the knowledge gap referred to in the introduction.

Additionally, it should be noted that the majority of research on hydrogen storage systems has mainly focused on optimizing the scaling of the different components in the system. This study, on the other hand, will concentrate on the ideal operating strategy for a given ratio between the elements in the system (e.g., a set size of solar parks, a set size of hydrogen storage, etc.) and is therefore not aimed at optimizing the proportions between these components. In 3.3 Optimizing operating strategy an elaboration will be given specifically on literature that aims to optimize the operating strategy.

3.3. Optimizing operating strategy

This section focuses on the various strategies and their optimization methods as described in the literature. During the literature review of this specific section, it was observed that nearly all studies concentrate solely on cost minimization, with very little literature available that incorporates environmental considerations into the operating strategy. The table below presents several research studies found that optimize their electricity operating strategy and the methods they employ. Only studies that focus on optimizing a strategy are included, while research that optimizes the optimal ratio between components within the electricity system, such as fuel cells, electrolyzers, and solar panels, are excluded.

Table 3.2: Strategies and optimization methods in the literature

Article	Details article	Optimization method
[88]	- Fuzzy logic controller as operating system - 24 parameters for Particle swarm optimization - Inputs: net power flow, battery state of charge - Wind and solar power, battery hydrogen storage - Hourly data	Particle swarm optimization
[115]	- Fuzzy logic controller as operating system - Mamdan type of fuzzy controller - 216 rules for operating system - Inputs: solar energy, battery state of charge, electricity load hourly - Solar power, battery - Hourly data	Particle swarm optimization
[113]	- Neural net algorithm as operating system - Solar power, battery, hydrogen storage - Hourly data	Neural net does not require optimization
[90]	- Markov decision process as operating system - Involves electricity market in research and strategy - Wind power, hydrogen storage - Hourly data	Backward dynamic programming
[86]	- Distributed energy resource (DER) as operating system - Trade-off between economic and environmental performances - Solar power, gas - Hourly data	Multi-objective linear programming methodology
[5]	- A rule-based strategy as operating system - Wind and solar power, hydrogen storage - Solar power not directly to the grid but only used for hydrogen production - Wind power directly to the grid but also used for hydrogen production - Hourly data	Grey wolf four objectives optimization technique
[10]	- A rule-based strategy as operating system - Rules contain mostly ”if” and ”then” statements - Wind and solar power, battery, diesel generator - Hourly data	Grasshopper optimization algorithm
[24]	- A rule-based strategy as operating system - Wind, solar and hydropower, diesel, battery, hydrogen storage - Hourly data	Genetic algorithms
[98]	- The economy and environment as main indicators to evaluate the energy system - Optimize two strategies: economic and environmental strategies optimized seperately - Solar power, gas, hydrogen storage - Hourly data	Mixed integer linear programming
This study	**- A rule-based strategy as operating system** **- Trade-off between economic and environmental performances** **- Solar power, gas, hydrogen storage** **- Hourly data**	**Particle swarm optimization**

Based on the literature reviewed in Table 3.2, several observations can be made. Firstly, hourly data is the most commonly used data for optimizing operating strategies. Secondly, the studies differ in their approach, as they utilize different resources. Additionally, it is noteworthy that many studies employ rule-based or fuzzy logic controllers, which are also rule-based, to determine an optimized operating strategy. Finally, it is worth mentioning that artificial intelligence methods are often used in the optimization of these strategies. In fact, of the eight research studies presented in the table above, six have adopted an artificial intelligence approach to optimize their strategies. As noted by the authors of [10], newly-emerged algorithms have been explored to find more suitable optimization techniques, which is why artificial intelligence optimization methods are employed.

3.3.1. Contribution

This research aims to contribute to the existing literature by providing a multi-dimensional approach to optimize an operating strategy. It focuses on the trade-off between cost efficiency, sustainability, and reliability by using key performance indicators. Specifically, it will attempt to blend a sustainable energy supply (in this case, solar energy and hydrogen energy) with a non-sustainable energy supply and determine the best trade-offs in the operating strategy. As mentioned in the first paragraph of this section, the majority of literature focused on optimizing operating strategy is based on cost reduction. This one-dimensional approach only reduces costs and neglects the trade-off explained earlier. Article [86] and article [98] in the above table seems to be the only articles that emphasize both environmental and economic factors when optimizing the operating strategy. However, these studies use a different optimization technique and do formulate their objective function, which will be elaborated on Chapter 5 Model, differently. Therefore, the research in this thesis, which focuses on both environmental and economic factors, includes hydrogen storage and uses an up-to-date optimization method, will add value to the existing literature, and thereby contribute to filling the knowledge gap regarding multi-objective operating strategies.

3.4. Positioning

In an effort to position this research in the literature, this section will decorate the similarities and contradictions in the literature and will justify this research within the literature.

There are many similarities between the literature and the research which are visualized in Table 3.1 and Table 3.2. Table 3.1 shows that there is research that analyses a system with sustainable and/or non-sustainable resources. Also in combination with hydrogen storage has been evaluated. Regarding the operating strategy in Table 3.2, the same can be perceived. Rule-based operating strategies have been optimized using particle swarm optimization and multi-objective strategies have been executed.

However, the combination of the different methods and components in the electricity system is what sets this research apart. To the knowledge of the author, there is yet to be research performed with the same energy resource composition, the same energy storage system, the same research objective, and the same methods used in this research. The research that optimizes their operating strategy with an artificial intelligence method, does not optimize over a multi-dimensional objective function, as this research does. The literature that performs analyses on a multi-dimensional objective, does not use an artificial intelligence approach. Also, the data regarding electricity supply and electricity demand, elaborated on in 4.6 Datasets are unique and have not been studied in the literature so far.

This new combination of the multiple facets of this research is justifiable because of the ample other research that has been written on this topic that has similar research on this topic. This research differentiates itself from, as explained in this chapter, but at the same time is very in line with the existing literature. Therefore it will complement the research on this topic with its findings and will thereby contribute to the academic literature.

3.5. Research choices after reviewing the literature

I intend to start this section with the following: this thesis has not yet provided an explanation for the chosen composition of the electricity grid to be analyzed, the strategy, and the optimization method. After analyzing the literature in the previous sections of this literature review, an attempt will be made to clarify the rationale behind the choices of this study and how it relates to the existing literature. This is required to substantiate the components used in this research elaborated on in section 2.4 System properties of components in the electricity system since this section delves deeper into the properties chosen for this research. Firstly, the scale of the research will be discussed followed by the composition of the electricity grid, the operating system, and the optimization method.

3.5.1. Scale

The scope of this study encompasses the electricity grid of the Netherlands. This choice was motivated by the fact that most research has been focused on microgrids and small to medium-scale grids and not a lot of studies have investigated a nationwide approach to hydrogen storage. Subsequently, datasets of solar irradiance and electricity demand in the Netherlands will be utilized in this study. These will be discussed in detail in Chapter 4: Research Approach.

3.5.2. Sustainable resources

The sustainable energy source in this research is solar energy. To keep this research manageable other sustainable resources such as wind energy or biomass are excluded. Solar energy refers to the energy derived from the sun's radiation, which is captured and converted into usable electricity using solar panels. This renewable energy source has become increasingly popular in recent years and is considered a good alternative for non-sustainable energy resources such as gas or coil [9]. As the world continues to move towards a more sustainable future, solar energy is likely to play an increasingly important role in meeting our energy needs which is why it is being used in the research [40].

3.5.3. Energy storage

The choice for a large-scale hydrogen system implementation is influenced by the unique circumstances in the Netherlands, which make it feasible to construct a nationwide hydrogen infrastructure. For instance, the Hystock project in Groningen investigates the possibility of storing hydrogen in salt caverns ([41]). The project website reports that there are 10 salt caverns in Groningen, each capable of holding at least 6000 tons of gas. At present, six caverns are used for natural gas storage, demonstrating the viability of this technology. The remaining four caverns are reserved for hydrogen storage, but the allocation of salt caverns for natural gas and hydrogen storage can be altered in the future, making it worthwhile to explore an enlarged capacity of hydrogen storage in the model. The choices regarding the type of electrolyzers, fuel cells, and other components are also based on a large-scale (national) hydrogen system implementation and will be detailed in section 2.4.

Some studies have included battery systems as a short-term storage option. However, this research purposely excludes batteries since their production involves polluting processes, as noted in [10]. Thus, only hydrogen is considered as a storage option in this study.

4
Research approach

4.1. Introduction

This chapter will provide an elaboration on research question 3: ”*Which research approach, methodology and methods are appropriate for finding the objective, which is an optimized operating strategy for electricity supply?*. By answering this question, this chapter will elaborate on when and how the other research questions designed in 1.5 Research question and sub-questions will be answered.

This chapter is organized into several sections. Initially, the type of research to be conducted will be discussed. This will be followed by an explanation of the chosen methodology and the tools that will be used in the study. The chapter will then clarify the methods used and delve into an extensive elaboration of particle swarm optimization. Subsequently, research biases will be discussed, and strategies for minimizing their effects will be proposed. Finally, the datasets used in the study will be described.

4.2. Type of research

It can be inferred that the thesis is an applied research project rather than a basic research project. This is because the aim of the research is to develop techniques or strategies to solve a practical problem, which is in the field of hydrogen storage. Additionally, the research is explorative in nature, as the field of hydrogen storage is under-researched [116], and the research is focused on exploring the main aspects of the problem. The research also employs a flexible design, as the timescale and location were not set before data collection began. The main focus of the research is on developing an optimized strategy given a certain dataset, rather than establishing generalizable facts or testing hypotheses. Furthermore, the research involves computational modeling and simulation runs, which makes it a quantitative research approach. Besides a quantitative approach, this research also involves a qualitative by reviewing the literature on the subject. The simulations will manipulate the control variables, indicating that this research also involves experimental research.

4.3. Methodology

The methodology utilized in this research project will be based on the simulation modeling design proposed by Law and Kelton in their book ”Simulation Modeling and Analysis” [56]. This approach provides a systematic framework for carrying out modeling research projects that involve simulations. The simulation modeling design consists of ten stages, which include problem definition, conceptual model development, data collection, validation, computer modeling, verification through pilot runs, validation again, experimentation, output analysis, and reporting. The validation process is conducted twice during the design to ensure the accuracy and reliability of the model. This approach is particularly relevant to our research as it provides a structured and rigorous methodology for conducting simulation-based research. By following this approach, we can ensure that all necessary steps are taken to develop a comprehensive and robust model that can effectively address our research question. The visualization of the design in Figure 4.1 serves as a helpful guide to the various stages involved in the simulation modeling process. Overall, this methodology will enable us to create a reliable and accurate simulation model that can effectively support our research objectives. The remainder of this section will discuss each step individually and clarify what tools and methods will be used, and what research question will be answered.

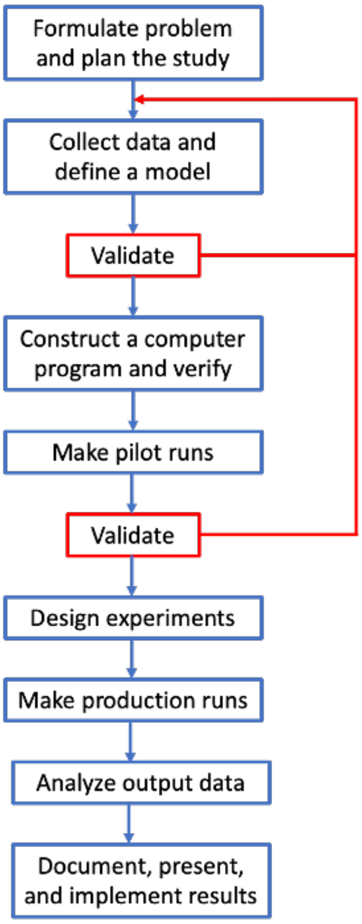


Figure 4.1: modeling research design (own figure)

The first step in the simulation modeling design proposed by Law and Kelton is already settled in Chapter 1 Introduction and this chapter, which clarifies how the study will be executed. The next step, data collection, and conceptual model development are partially executed already. In Chapter 3 Literature review qualitative data is gathered by exploring how the literature designs the electricity system including hydrogen storage and how the strategy is defined in common literature. Quantitative data is gathered by retrieving the properties of components in the electricity system discussed in the literature review, and by retrieving the datasets from open data sources. The datasets will be elaborated on in 4.6 Datasets. By examining the literature this step will provide an answer to sub-question 1. The conceptual model will be discussed in Chapter 5 Model. In this chapter sub-question 2, regarding the key performance indicators and how they are influencing the strategy, will be clarified Afterward, a validation is planned to evaluate whether the collection of data and the conceptual modeling are performed appropriately.

The subsequent step in the research process involves the creation of the computer model using the Python programming language, which will be discussed in more detail in the tools section of this chapter. The model's accuracy will be assessed through pilot runs to determine if it aligns with the conceptual model, produces appropriate interactions, and provides logical output data. If any discrepancies are detected, the model will be adjusted during the validation stage, which will revisit previous stages in the research design. In addition to the validation stage, another evaluation is scheduled to track the research's progress.

After creating a simulation model, the research will focus on the experiments (or scenarios) to be run and will create output data. Sub-question three will be answered by defining the settings of the experiments. These settings will be determined by the data retrieved from the extensive literature research and interviews. Once, the experiments are executed, the output data will be analyzed to eventually answer the sub-question four, sub-question five, and the research question.

4.4. Tools

In this research, several tools have been employed to aid in data collection, analysis, and modeling. Google Scholar and Scopus were utilized to conduct a comprehensive literature review, which helped to identify existing knowledge and research gaps in the field of operating strategy optimization of electricity systems including hydrogen storage. Python, a programming language, was used to create the computer model and perform simulations. For ease of use and accessibility, Google Colaboratory was utilized as the coding platform for the simulations. Additionally, namely two Python packages, Pandas and NumPy, were used to manage the data and perform mathematical operations in the model. The use of these tools allowed for efficient and effective data analysis, model creation, and simulation runs.

4.5. Methods

4.5.1. Simulation

Discrete event simulation is a method used in this research, which involves modeling an organizational system as a set of entities evolving over time based on the availability of resources and triggering of events. [100] states the following: *”A good DES model can replicate the performance of an existing system very closely and provide a decision-maker insights into how that system might perform if modified, or how a completely new system might perform”.* This is exactly what is performed in analyzing the subject of this research. This study aims to optimize the operating strategy of an electricity grid which provide insights in the performance of the system, and is therefore useful for decision-making. Scenario simulation is another method used in this research, which involves testing the model’s sensitivity to different input parameters and scenarios. This method is used to explore the system behavior under different conditions, such as changes in resource availability or demand, and to identify critical factors that affect system performance. Together, these methods provide a powerful tool for understanding and analyzing complex organizational systems and for evaluating the effectiveness of different strategies and therefore policies.

4.5.2. Optimization: Particle swarm optimization

Particle swarm optimization is a heuristic-based optimization algorithm and a method used in this research to optimize the operating strategies proposed. This section will elaborate on why this method is chosen. It will not yet elaborate on the details of how particle swarm optimization is implemented in this research since model specifications are needed which are not discussed yet. Therefore, an elaborate introduction to particle swarm optimization will be given in the remainder of this section. In Chapter 5 Model the implementation of the objective function and what parameters are being mutated by the optimization algorithm will be discussed.

Why Particle swarm optimization?

There are multiple algorithms that can be implemented for finding an optimal solution. The exhaustive search, for instance, searches the solutions for all parameter combinations. One can imagine that this is a very thorough way of finding the best solution but is not very efficient, since all combinations need to be explored. As mentioned earlier artificial intelligence techniques to optimize operating strategies are not uncommon which is also visualized in Table 3.2. To efficiently find the best parameter setup to find the most optimized solution PSO has proven in previous research that it is a qualified method to use. For this research, the algorithm will also implement linear decay which is explained below.

What is it and how does it work?

Particle swarm optimization (PSO) is a computational heuristic-based optimization algorithm that mimics the social behavior of bird flocks and fish schools. Kennedy and Eberhart introduced PSO in 1995

[49]. The algorithm consists of a swarm of particles, each representing a candidate solution to an optimization problem. The particles all have a different, random setup of the parameters, which move through the search space by adjusting their parameters, based on their own best-known position, as well as the best-known position of their neighboring particles. The objective of the algorithm is to find the optimal solution to the optimization problem by iteratively updating the position of each particle. A visualization of this principle is given in Figure 4.2 in which a parameter has different outcomes on the objective, based on the different setups of the parameter.

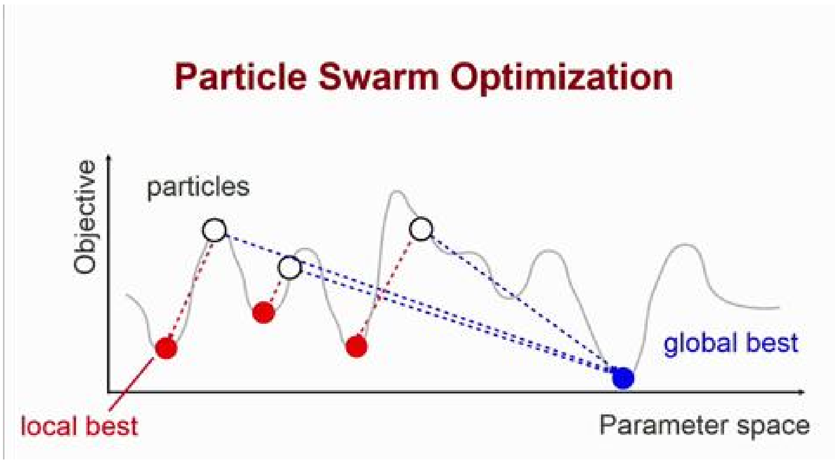


Figure 4.2: PSO - one parameter ([103])

In the same way, multiple parameter dimensions can be added. In Figure 4.4 the search space is defined by the X and Y axis, and the objective is given in the third axis. The particles, visualized as black dots, move over the search space to look for new objective scores. This is also visualized by the black arrows/vectors. If a particle recognizes that a neighboring particle has a better best-known position, the particle's direction will be adjusted in the next iteration. The direction and speed will be determined by its own best-known position, the global best-known position, and stochastic factors. By moving around across the search space the particles may find other best-known positions on the way, which will trigger other particles to move to this position. The logic behind each particle is visualized in the flowchart presented in Figure 4.3. This algorithm is therefore exploring new positions while also converging toward the best-known position in the search space.

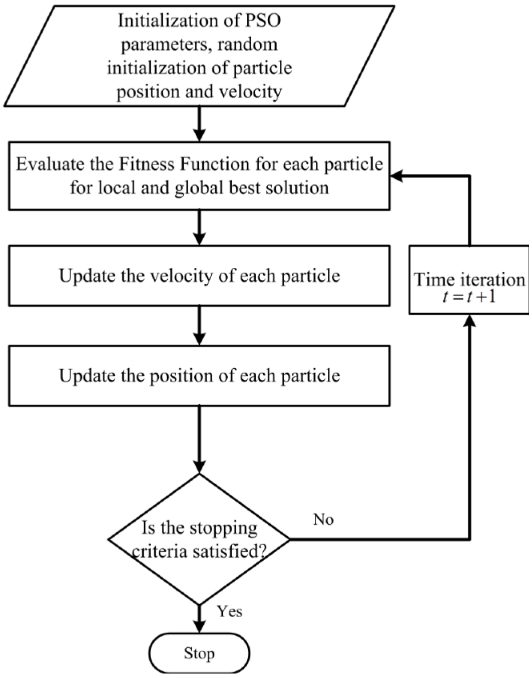


Figure 4.3: Flowchart PSO particle ([109])

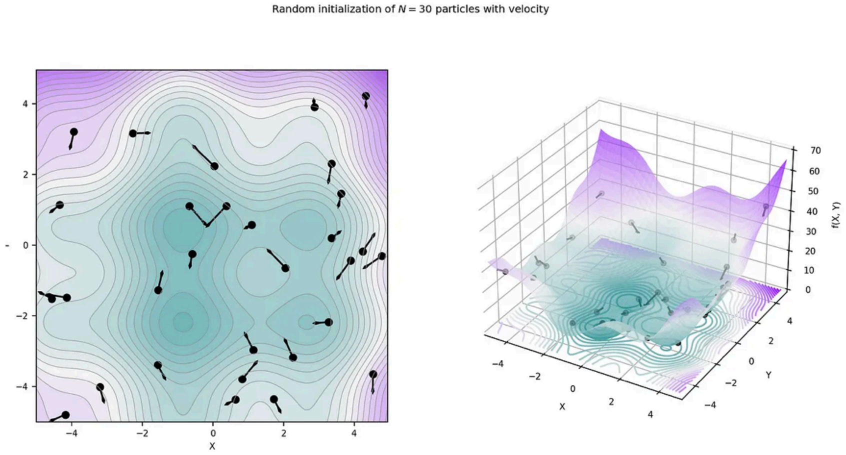


Figure 4.4: PSO - two parameters ([101])

The elements required to perform PSO to find an optimal solution are:

- **Variables and a defined objective**
  The defined objective of this research is to secure electricity stability, limit the use of fossil fuels by using sustainable energy resources, and minimize cost. These objectives are expressed in different units which creates room for interpretation. While constructing the model the output needs to represent all the objectives in an overall score. To get to this score the person running the model should estimate how much costs are acceptable to prevent a certain amount of pollution.

  The variables in the model are found in the previous chapter in the description of the elements of the conceptual model. The variables will be related to the objective and define the search space of the problem
- **(Number of) particles**
  The number of particles is an important setting of PSO. It determines, among other things, how

many places in the search space are investigated in one iteration. If the number is too low, the optimal solution might not be found and will settle for a local best (see Figure 4.2). On the one hand, it is not efficient if the number of particles is set too high, and for each iteration, a lot of places on the search spaces are discovered.

- **Particle hyperparameters**
  The particle has three parameters which are its cognitive ratio, its social ratio, and its inertia weight. The cognitive ratio is the place of the particle in the search space. The particle can translate the location and the corresponding score to the rest of the particles. The second parameter is the cognitive ratio which is the ability to receive the best location found by any particle. Lastly, the personal velocity of the particle, or the inertia weight, is considered. This parameter defines the size of the step it takes closer to the global best, found by other particles.
- **Balanced stochastic parameters**
  The balanced stochastic parameters are implemented to find positions in the search space that are different than the best-known solution. Once there is a best solution in the search space, a neighboring solution might be better, and should also be investigated. The stochastic parameter allows the particles to move around a bit and not keep still in the ”perfect spot”. It is important that the stochastic parameter are balanced among the variables in the model. All particles should move in all directions with the same randomness.

Linear decay

In this research, we utilized a technique called particle swarm optimization, specifically a modified version known as linear decay proposed by [96]. The idea behind it is to create a group of particles that can make the most out of their numbers to explore a wide range of possibilities in the search space. Initially, the particles have a more adventurous nature, thanks to the linear decay approach. They are in the beginning free to roam around and discover various solutions. However, as the simulation progresses and the number of iterations increase, the particles gradually start to pay more attention to the global minimum. They become more influenced by it and converge towards that promising point. This way, a balance between exploration and exploitation is obtained throughout the simulation.

Pros and cons

Even though PSO is an efficient way to optimize a model it also has some downsides. One downside is that there are quite some parameters that need to be set up [92]. Among other things, what inertia the particles have, how many particles should be initiated, and when to stop running, all need to be determined. When using an advanced version of PSO parameters also need to be assigned to the weights of the particle’s inertia. Another disadvantage of PSO is the high computational cost [92]. For each iteration of the algorithm, all particles need to be run, with the assigned variables. If there are 50 iterations of 50 particles, the model will be run 2500 times in total. Lastly, it requires a high level of programming skills which could be seen as a restricting factor. However, PSO is simple to implement in code. It is also flexible and can be used with other optimization algorithms [92]. Furthermore, the research discussed in the chapter Literature Study has demonstrated that PSO is a very suitable approach to optimize a model on.

In conclusion, PSO is a powerful optimization algorithm that has been successfully applied to various optimization problems in different fields. Its ability to mimic the social behavior of bird flocks and fish schools makes it an attractive approach for solving complex optimization problems, which is why its implementation can be found in this study.

4.6. Datasets

Two open-source datasets will be used as input to generate the outcomes of the simulations. One dataset will be used to define how much sustainable electricity can be generated from sustainable resources. The dataset will contain hourly data regarding solar irradiation. The second dataset will contain hourly data about the electricity demand in the Netherlands. Together these datasets are input for the model to create the most optimal strategy. This section will individually discuss both datasets.

4.6.1. Electricity generation

The data on solar irradiance used in this research is retrieved from the Science Hub of the European Commission and is provided with hourly electricity output. Furthermore, the dataset contains data from the beginning of 2005 until the end of 2020. The dataset already includes the conversion from solar irradiance to electricity. This is different from the studies previously discussed in this thesis. For instance, [60] use hourly solar irradiance and wind speed to find the electricity generated per time step using mathematical formulas. The data used in this research does not require formulas for conversion. The method used in the literature, in which the electricity output is calculated based on wind speed or solar irradiance and finds formulas to determine the electricity output [121, 60] is in my opinion, more prone to errors than directly using the data from the Science Hub of the European Commission, assuming that this entity is a reliable source.

The remainder of this section will elaborate on the choices made while retrieving the data from the EU Science Hub to obtain a deeper understanding of the data used in this research. In addition, visualizations of the data will be shown to check the validity of the data.

Setting up the data

The first choice that must be made is the location of the solar park. Since we want to generate electricity for all of the Netherlands multiple locations will need to be occupied. For the model to not become too complex, this research will consider one big solar park. In future studies, this could be split up and multiple smaller solar parks could be used in the model to obtain more detailed data on electricity generation from solar energy. The reference point of the one solar park being used in the model will be the city of ”Utrecht”. This decision is made based on that this city is considered the middle of the Netherlands and since there are solar parks all over the Netherlands, shown in Figure 4.5, it is a convincing choice to choose Utrecht as the reference point.

The second choice that must be made in the settings of the solar panels (PVs) used in the solar parks. Factors that play a role in the amount of electricity that can be generated are: the mounting type, slope, azimuth, PV technology, installed peak power, and system loss. For this research, the mounting type ‘fixed’ is chosen, which means that the solar panels do not rotate or move during the day. According to the Science Hub of the European Commission, this is the most common type of PV system which is why it is chosen in this research [35]. The solar panels will be installed with the optimal slope and azimuth so that the electricity generation is as efficient as possible. The slope is the angle of the PV modules from the horizontal plane and the azimuth (or orientation) is the angle of the PV modules relative to the direction due South, according to [35]. On the website of [35] there is the possibility to set the position of the PVs in the most optimal setting. For this research, the slope and azimuth are set at the optimal setting which is a slope of 39 degrees, and an azimuth of -1 degrees.

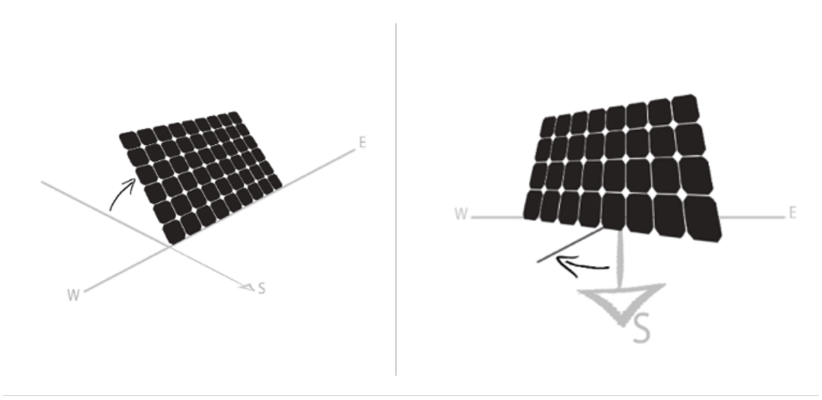


Figure 4.5: Slope (left) and azimuth (right), ([35])

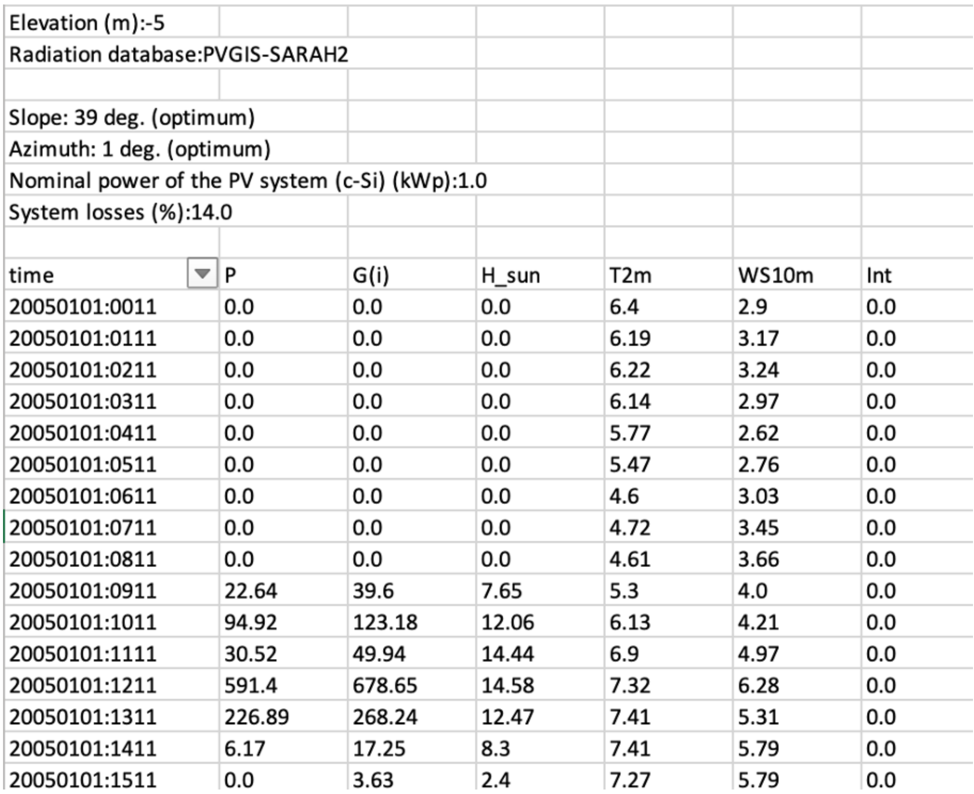
Installed peak PV power is also a variable in the dataset that can be modified. Installed peak PV power is the power that the PV array can produce under standard test conditions, which are a constant 1000W of solar irradiance per square meter, at a temperature of 25°C. Because this research assumes that the efficiency of solar panels is only 20% as stated in 2.4, it means that 5m2 is needed to produce 1 kWp.

The last variable that can be modified to set up the database of electricity generation from solar panels is system loss. [35] have included estimated losses such as losses in cables, power inverters, dirt (sometimes snow) on the modules, and so on, to create a dataset that considers real-world inefficiencies. They also include the degradation of the solar panels in a linear manner: *“Over the years the modules also tend to lose a bit of their power, so the average yearly output over the lifetime of the system will be a few percent lower than the output in the first years”* [35].

One last important note is that [35] states that a standard overall loss of 14% is incorporated. This includes, among other things, the loss of electricity which is created by the inverter, which means that the dataset already includes the inefficiencies of an inverter ([35]). Therefore, the computational model does not require to include an inverter.

Visualisation

The data will be delivered in a table consisting of seven columns, which is visualized in Figure 4.6. The column names are as follows: time, P, G(i), H_sun, T2m, WS10m, Int, which meanings can be found in Table 4.1. For this research, the most important columns in this dataset are P and Time which will be used as input for the model. The other columns indicate variables to determine how much power is being generated from the solar panels, but will not be taken into consideration in the model. In Figure 4.7 the energy production is shown of a random day in the dataset (with 35,000 hectares of solar park). It shows that the electricity generation is mostly during the day, which makes sense because of the absence of sunlight in the night. In Figure 4.8 the electricity production of two years is visualized. The figure shows a pattern that indicates that more electricity is produced during the summer and less during the winter. Needless to say, this is also a very logical phenomenon since the summer has an increased presence of sunlight.



Elevation (m):-5
Radiation database:PVGIS-SARAH2

Slope: 39 deg. (optimum)
Azimuth: 1 deg. (optimum)
Nominal power of the PV system (c-Si) (kWp):1.0
System losses (%):14.0

time	P	G(i)	H_sun	T2m	WS10m	Int
20050101:0011	0.0	0.0	0.0	6.4	2.9	0.0
20050101:0111	0.0	0.0	0.0	6.19	3.17	0.0
20050101:0211	0.0	0.0	0.0	6.22	3.24	0.0
20050101:0311	0.0	0.0	0.0	6.14	2.97	0.0
20050101:0411	0.0	0.0	0.0	5.77	2.62	0.0
20050101:0511	0.0	0.0	0.0	5.47	2.76	0.0
20050101:0611	0.0	0.0	0.0	4.6	3.03	0.0
20050101:0711	0.0	0.0	0.0	4.72	3.45	0.0
20050101:0811	0.0	0.0	0.0	4.61	3.66	0.0
20050101:0911	22.64	39.6	7.65	5.3	4.0	0.0
20050101:1011	94.92	123.18	12.06	6.13	4.21	0.0
20050101:1111	30.52	49.94	14.44	6.9	4.97	0.0
20050101:1211	591.4	678.65	14.58	7.32	6.28	0.0
20050101:1311	226.89	268.24	12.47	7.41	5.31	0.0
20050101:1411	6.17	17.25	8.3	7.41	5.79	0.0
20050101:1511	0.0	3.63	2.4	7.27	5.79	0.0

Figure 4.6: Data regarding solar power per hour, ([35])

Table 4.1: Strategies and optimization methods in the literature

Column name	Explanation
Time	Time period per hour
P	PV system power (W)
G(i)	Global irradiance on the inclined plane (plane of the array) (W/m2)
H_sun	Sun height (degree)
T2m	2-m air temperature (degree Celsius)
WS10m	10-m total wind speed (m/s)
Int	1 means solar radiation values are reconstructed

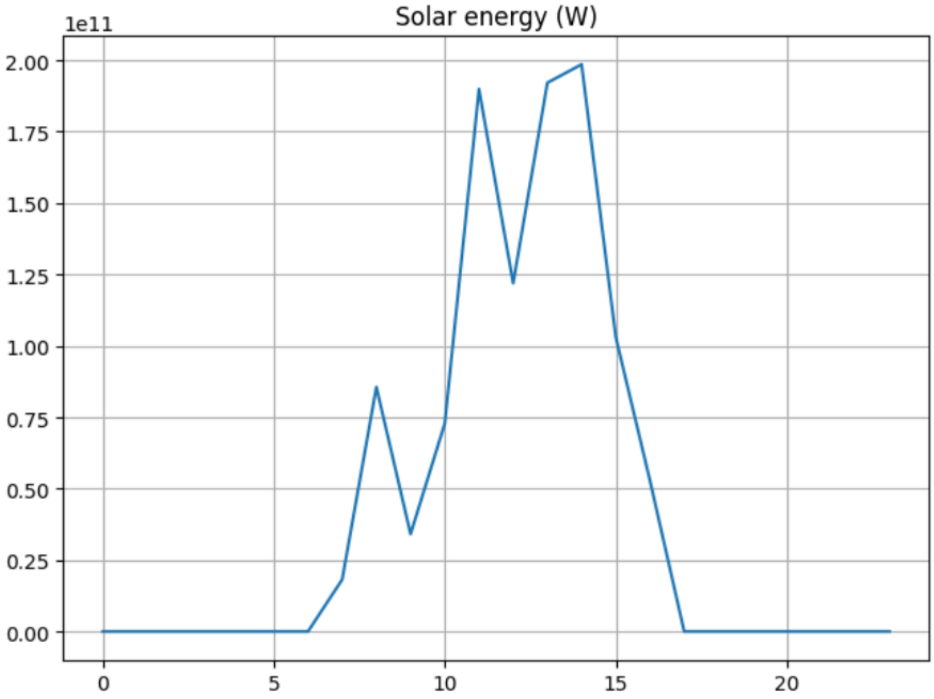


Figure 4.7: Solar power data of one day, (own figure)

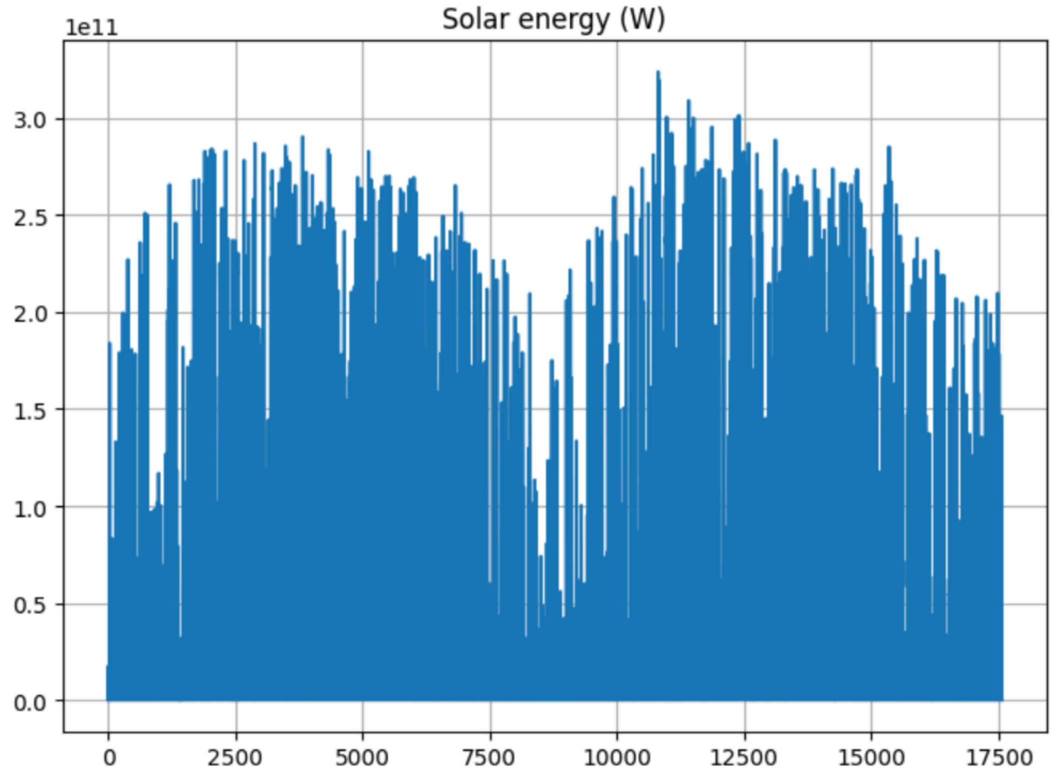


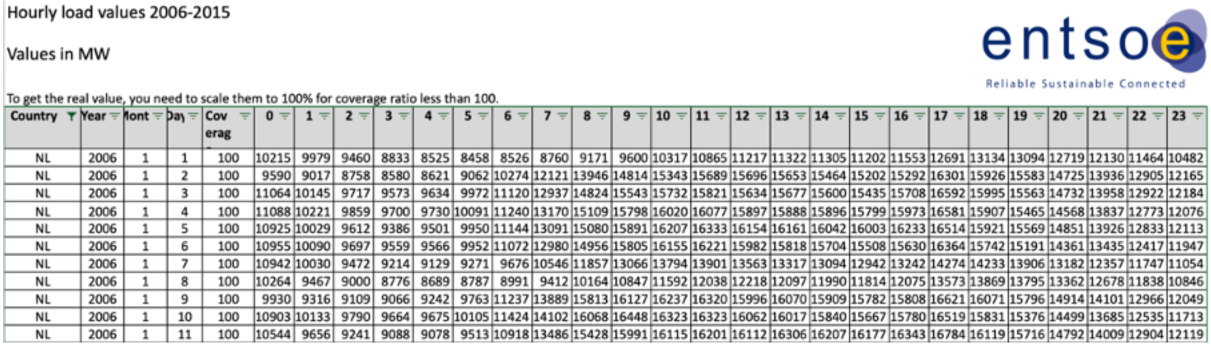
Figure 4.8: Solar power data of 2012 until 2013, (own figure)

4.6.2. Electricity demand

This section will elaborate on the dataset regarding electricity demand. It will first address how it is retrieved before explaining the data and presenting figures about the data.

The data regarding electricity demand is retrieved from the European Network of Transmission System Operators for Electricity (ENTSOE) [32]. ENTSOE is a non-profit organization that represents 43 electricity transmission system operators from 36 countries across Europe and its main mission is to ensure the reliable, secure and efficient operation of the European electricity transmission system, as well as to promote the integration of renewable energy sources and the development of a pan-European electricity market [31].

The dataset contains data about multiple countries but can be filtered down in the column ‘Country’ to only data about the Netherlands. Furthermore, the columns in the dataset contain the year, month, day, coverage, and amount of electricity consumed for each hour in the day, measured in MW. The data ranges from the beginning of 2006 until the end of 2015. In this research the most interesting columns are the columns that indicate the date (Year, month, day), and the columns that present the load values each hour. The country is not important since the data is filtered on the Netherlands already. Also, the column coverage is insignificant because one of the key performance indicators in this research is reliability. The data about coverage provides insight that the Netherlands have 100% coverage of all hours between 2006 and 2015, which will be interpreted as the benchmark for this research. A visualization of the dataset is presented in Figure 4.9. Figure 4.10 and Figure 4.11 show the behavior of electricity demand throughout a day and two years. In the behavior during the day one can state that the demand increases during the day and decreases during the night, which is logical behavior. Additionally, we see that during the winter the electricity demand is higher than during the summer, which is also coherent with a common rational.



Hourly load values 2006-2015

Values in MW

To get the real value, you need to scale them to 100% for coverage ratio less than 100.

Country	Year	Mont	Day	Coverag	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
NL	2006	1	1	100	10215	9979	9460	8833	8525	8458	8526	8760	9171	9600	10317	10865	11217	11322	11305	11202	11553	12691	13134	13094	12719	12130	11464	10482
NL	2006	1	2	100	9590	9017	8758	8580	8621	9062	10274	12121	13946	14814	15343	15689	15696	15653	15464	15202	15292	16301	15926	15583	14725	13936	12905	12165
NL	2006	1	3	100	11064	10145	9717	9573	9634	9972	11120	12937	14824	15543	15732	15821	15634	15677	15600	15435	15708	16592	15995	15563	14732	13958	12922	12184
NL	2006	1	4	100	11088	10221	9859	9700	9730	10091	11240	13170	15109	15798	16020	16077	15897	15888	15896	15799	15973	16581	15907	15465	14568	13837	12773	12076
NL	2006	1	5	100	10925	10029	9612	9386	9501	9950	11144	13091	15080	15891	16207	16333	16154	16161	16042	16003	16233	16514	15921	15569	14851	13926	12833	12113
NL	2006	1	6	100	10955	10090	9697	9559	9566	9952	11072	12980	14956	15805	16155	16221	15982	15818	15704	15508	15630	16364	15742	15191	14361	13435	12417	11947
NL	2006	1	7	100	10942	10030	9472	9214	9129	9271	9676	10546	11857	13066	13794	13901	13563	13317	13094	12942	13242	14274	14233	13906	13182	12357	11747	11054
NL	2006	1	8	100	10264	9467	9000	8776	8689	8787	8991	9412	10164	10847	11592	12038	12218	12097	11990	11814	12075	13573	13869	13795	13362	12678	11838	10846
NL	2006	1	9	100	9930	9316	9109	9066	9242	9763	11237	13889	15813	16127	16237	16320	15996	16070	15909	15782	15808	16621	16071	15796	14914	14101	12966	12049
NL	2006	1	10	100	10903	10133	9790	9664	9675	10105	11424	14102	16068	16448	16323	16323	16062	16017	15840	15667	15780	16519	15831	15376	14499	13685	12535	11713
NL	2006	1	11	100	10544	9656	9241	9088	9078	9513	10918	13486	15428	15991	16115	16201	16112	16306	16207	16177	16343	16784	16119	15716	14792	14009	12904	12119

Figure 4.9: Data regarding solar power per hour, [32]

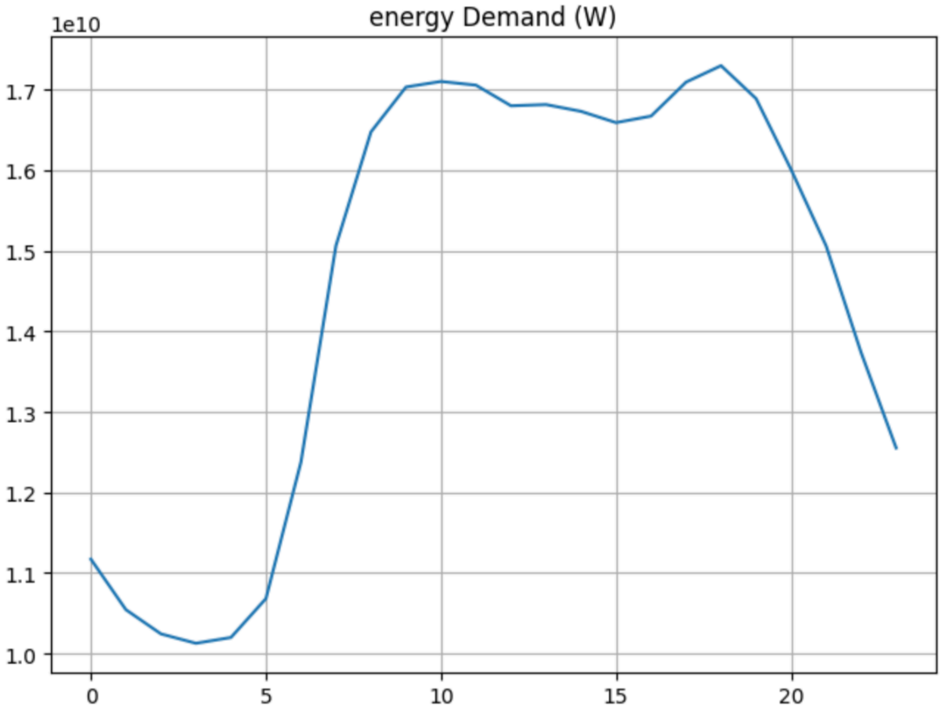


Figure 4.10: Electricity demand of one day (own figure)

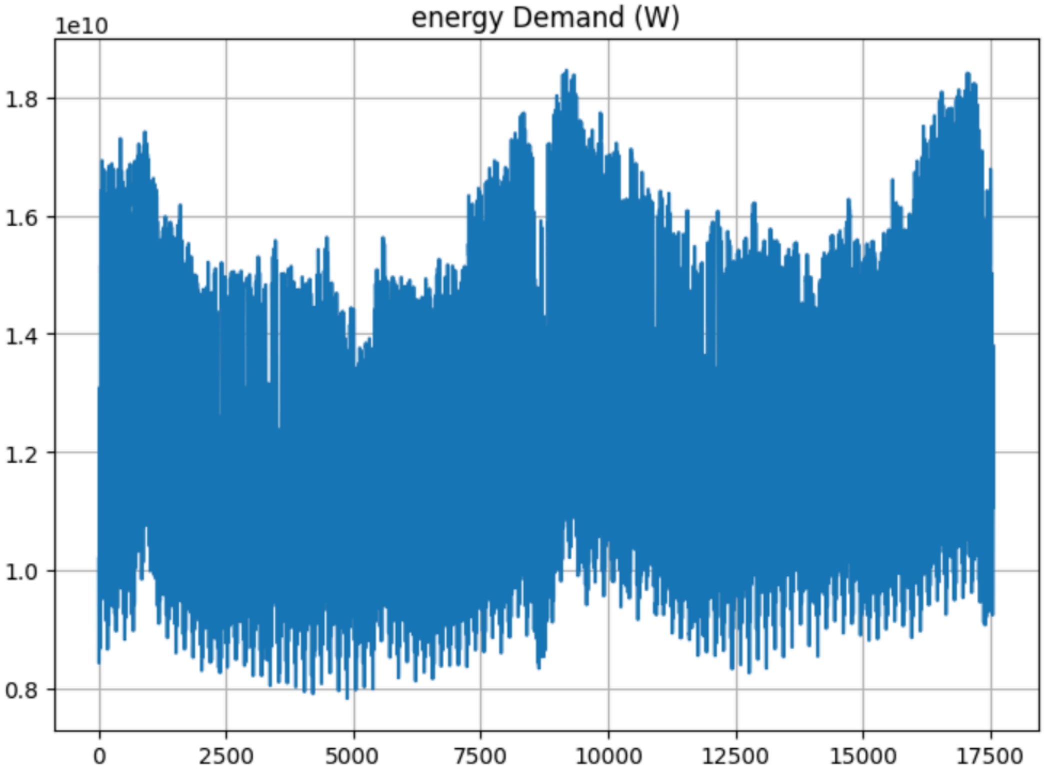


Figure 4.11: Electricity demand of two years, (own figure)

4.6.3. Modification of datasets

As discussed in the preceding sections, the two datasets used in this thesis are in different formats. To make the datasets usable, they were modified using the Python programming language and the Pandas package. The modified datasets were transformed and now only contain columns for date, time, and electricity demand/supply. The code used to accomplish this can be found in Appendix. A

5

A Simulation model for finding the optimal operating strategy

5.1. Introduction

This chapter aims to introduce the model used in this study. Chapter 3 Literature review, will be consulted to determine the models in this chapter. Firstly, a conceptual model will be presented to describe a delimited system, including the boundaries and assumptions made. Subsequently, a computational model will be developed in Python based on the conceptual model, in which the mathematical relationships between the elements in the system will be applied. Section 5.4 will first explain the model, followed by an explanation of the mathematical relationships within the model, including the objective function. Limitations of the model will then be discussed before moving on to the implementation of Particle Swarm Optimization.

5.2. Conceptual model

The conceptual model for this research is based upon the conceptual models of other research and can be considered straightforward due to its clear structure. Other studies that have done similar studies on finding an optimal strategy have defined similar conceptual models with similar components in the system [121, 60, 93]. These components are:

- Energy source (Electricity source + inverter)
- Electrolysis
- Hydrogen storage
- Fuel cells
- Inverter (fuel cell)
- Electricity demand
- Fossil fuel
- Gas turbine

This section will first describe the electricity demand, followed by an explanation of the electricity inflows from solar energy and non-sustainable energy sources. Finally, the hydrogen system will be described. The interaction between these components is illustrated in the figure below.

Figure 5.1 depicts the electricity demand, which in this study represents the electricity needs of the Netherlands. As shown, there are three arrows connected to this component, all providing electricity. Two of these arrows generate electricity from resources that come from outside of this model: ’Electricity source’ and ’Fossil fuel’. In this model, ’Electricity source’ defines the electricity coming from solar panels. The solar electricity dataset in the Netherlands discussed in the previous chapter will simulate the behavior of solar energy and will be used as input for this component. To make this solar energy usable, the electricity must be transformed by an inverter before it is delivered to the electricity demand.

When the inflow of solar energy is not sufficient and the operating strategy indicates the need to switch to non-sustainable energy, the inflow of fossil fuel will increase. In this model, 'Fossil fuel' represents natural gas, which will be converted into electricity using gas turbines. The last inflow which will be discussed is the hydrogen system consisting of four components. This hydrogen inflow starts with electricity that is not being used by the electricity demand and is instead used to generate hydrogen through electrolysis. The produced hydrogen is then stored in hydrogen storage. In case solar energy does not provide sufficient electricity, the operating strategy decides to activate the fuel cells and use the stored hydrogen to generate electricity. This generated electricity still needs to be converted into usable electricity through an inverter and is then ready to be supplied to the electricity grid.

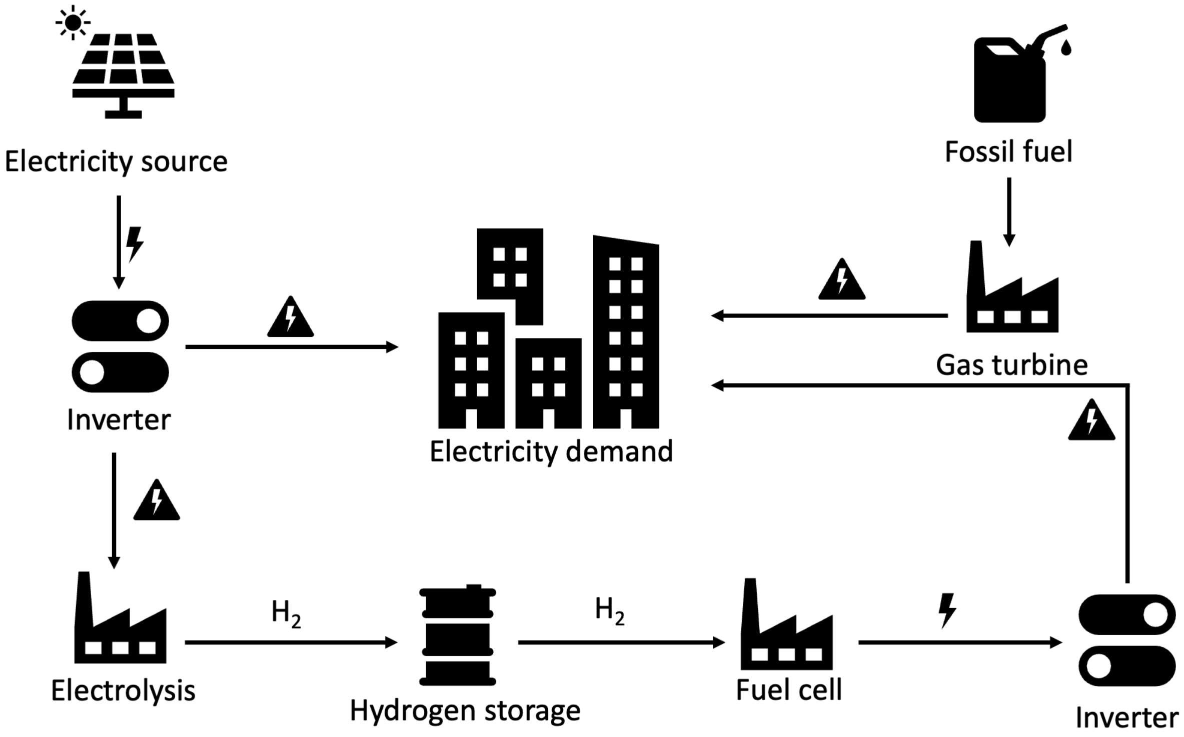


Figure 5.1: Conceptual model (own figure)

5.2.1. Assumptions and limitations

This model only concerns the electricity supply and leaves out other factors, which will be discussed further in this section. This was done to avoid making the model too complex, given the time frame of this project. Additionally, the research focuses on an operating strategy regarding hydrogen and is not intended to incorporate various factors that are not of significant value to the research goal. The remainder of this section will explain the assumptions and demarcations made in the model.

The assumption is made that there is always exactly enough electricity being produced: the model does not incorporate any predictive value to estimate how much electricity will be demanded in the coming hours. This study does not aim to investigate the prediction of energy demand for the upcoming hours but only focuses on how to optimize a hydrogen strategy. However, such a predictive model could be included in the future for expansion to examine the problem in a more complex and detailed manner.

Furthermore, the price of electricity varies throughout the day. Electricity is traded on electricity markets where providers aim to sell electricity at a high price while consumers aim to buy electricity at a low price. Hydrogen storage can optimize strategies so that energy companies can time when to sell their electricity. Developing a strategy that maximizes profit for energy companies is interesting, but it is not the focus of this research and therefore not included in the model. In this model, the price of electricity is defined as the break-even cost. Profit or complex strategies that take into account electricity market trends are not considered in the model.

In addition, the costs in the model are evenly distributed across time steps, meaning that each hour carries an equal cost. This is a limitation since investments that span multiple years, which is applicable in this model, have a net present value, and costs have a different value in the future. Additionally, the degradation of solar panels, as determined by [35], is linear, which is not realistic. The final limitation that will be discussed is the efficiency of the fuel cells, electrolyzers, gas turbines, and solar panels. One can imagine that different inputs to these components correspond to different efficiencies. For example, at a certain hydrogen supply, the fuel cell will achieve its maximum efficiency, while it may not at a higher or lower hydrogen supply. However, this model has chosen to keep all efficiencies static and not allow them to vary. This was done to make the project manageable and not overly complex. However, it is of great interest to investigate this further in future studies to improve simulation runs.

Finally, this model only considers two states for the fuel cells: either all fuel cells are on, or all fuel cells are off. If future research considers different efficiencies, it may be possible to switch on or off a certain percentage of fuel cells. However, for the scope of this research, this is too complex as it would also affect the costs and lifespan of the fuel cells. Therefore, in this study, the fuel cells are represented with less complexity.

5.3. Strategy

This section will discuss the rules and the variables with reference to the operating strategy. By delving deeper into the strategy, a deeper understanding will be obtained of the reasoning behind the methods to obtain the optimal strategy. The operating strategy considered for this research aims to find the most optimal solution to minimize the objective function. The objective functions contain three key performance indicators that relate with each other as explained before in 1.3 Research goal.

As mentioned in Chapter 3 Literature review this research will aim to find an optimal solution by practicing a rule-based strategy as the operating system. It considers six rules and five flexible variables to execute this study. This configuration of the strategy is based on the literature studied in Chapter 3 Literature review. The rules and variables are designed to create different behaviour of the strategies that will be tested. For further research these could be refined or be made more complex to obtain an advanced strategy.

The variables will be labeled with letters A through E, and their discussion will be presented in the bullet points below. The variables will be optimized with respect to the objective function using particle swarm optimization, which will be discussed later in this chapter. Also, the rules will be presented in the bullet points. The rules applicable are as follows:

- ***Rule 1:*** *If the hydrogen storage is below threshold A, the solar energy does not suffice the electricity demand, and the fuel cells are not turned on, the remaining electricity will be produced by a gas turbine that uses non-sustainable energy*

  To ensure a steady supply of electricity to the grid, it is imperative that the demand for electricity is met. In the event that solar energy is insufficient to meet the demand, the hydrogen system or gas turbine can be employed. It has been established in the literature, as discussed in section 2.4 System properties of components in the electricity system, that frequent start and stop cycles of the fuel cell are inefficient and may lead to thermal stress, thereby reducing the lifespan of the fuel cell. Therefore, the rule presented in this bullet point takes into account the state of the hydrogen storage to determine a strategy that rejects scenarios in which the fuel cells operate for only a short duration. It is illogical to activate the fuel cells when there is insufficient hydrogen in the hydrogen tank, as they require this resource to generate electricity. Thus, this rule favors the use of non-sustainable resources such as natural gas.

- ***Rule 2:*** *If the hydrogen storage is above threshold B, the solar electricity does not suffice the electricity demand, and the fuel cells are not turned on, the fuel cells are turned on*

In accordance with rule 1, there should be a moment when the fuel cells are turned on. Rule two is examined when the solar panels do not supply enough energy to the electricity grid and the hydrogen storage in the model is above threshold B. The rationale behind this rule aligns with Rule 1, namely, to minimize the frequency of starting and stopping the fuel cells in order to prevent a shortened lifespan of the fuel cells. If solar energy and hydrogen energy combined, do not supply enough electricity to fulfill the electricity demand, the gas turbine will be activated to generate the remaining demand. If the activation of fuel cells results in an excess of electricity, the remaining electricity will be used to generate hydrogen again.

- ***Rule 3:*** *Considering the fuel cells are on, the solar energy combined with the hydrogen energy does not suffice the electricity demand, and the hydrogen in the tank is used up during the timestep, the fuel cells will be turned off and the gas turbines will produce the remaining electricity to fulfill the electricity demand*

  In this scenario, the fuel cells are operating and producing electricity through the use of hydrogen. However, in this particular time step, there is not enough energy available from renewable resources and the hydrogen storage has been depleted. Consequently, the fuel cell cannot continue to function and is turned off. As previously mentioned, this is not a scenario that should occur frequently as a high frequency of starting and stopping the fuel cell is detrimental to its lifespan. To still meet the demand for electricity, the gas turbine is activated and will provide the remaining electricity needed.

- ***Rule 4:*** *Considering the fuel cells are on, the solar energy combined with the hydrogen energy does not suffice the electricity demand, and the hydrogen in the tank is above threshold C, the fuel cells will produce B Watt and the gas turbines will produce the remaining electricity to fulfill the electricity demand*

  This scenario is a variation of the situation described in rule 3. However, in this scenario, the hydrogen storage is above the threshold C while the hydrogen storage in rule 3 is empty or nearly empty. Since the hydrogen storage is above the threshold and the fuel cells are already operating, the fuel cells will attempt to meet the energy demand by producing B Watt. However, if this is insufficient, the gas turbines will provide additional support and meet the remaining electricity demand.

- ***Rule 5:*** *Considering the fuel cells are on, the solar energy combined with the hydrogen energy does not suffice the electricity demand, and the hydrogen in the tank is below threshold C, the fuel cells will produce B Watt and the gas turbines will produce the remaining electricity to fulfill the electricity demand*

  This scenario essentially describes the same situation outlined in rule 4 but with a different state of hydrogen storage. In this scenario, the storage is below threshold C, triggering a different strategy for managing the hydrogen supply. The fuel cells will produce D watts of electricity in this situation, and the remaining electricity will be generated by gas turbines. The rationale behind this rule is that it is more advantageous to run the fuel cells less intensively in order to slow down the depletion of hydrogen storage. This approach can help prevent the hydrogen storage from becoming depleted, which would result in the fuel cells being turned off.

- ***Rule 6:*** *Considering the solar panels are providing enough electricity in the given time step and the fuel cells are turned off, the excess electricity will be used to start electrolysis and produce hydrogen, if there is an excess of electricity.*

  Rule 6 is a straightforward rule. When the solar panels generate sufficient electricity, and the fuel cells are turned off, it is logical that the electricity supplied by solar panels supplies the electricity grid. If there is an excess of electricity, the redundant electricity is utilized to initiate electrolysis, producing hydrogen. This ensures that the surplus electricity is still utilized effectively.

- ***Rule 7:*** *Considering the solar panels are providing enough electricity in the given time step and the fuel cells are turned on, the fuel cells will stay on and produce E Watt. Additionally, the excess electricity will be used to start electrolysis and produce hydrogen, if there is an excess of electricity.*

  This rule, as well as the final rule, is in line with rule 6, where the solar panels produce enough electricity to serve the electricity demand. However, in the scenario described in this rule, the fuel cells are on. As it is not optimal to turn the fuel cells on and off frequently, as described earlier in this thesis, the fuel cells will not be turned off but will produce electricity at a different intensity, namely E Watt. If there is excess electricity produced, it will be used to initiate electrolysis and produce hydrogen. An important note to make is that there may be situations where hydrogen storage runs out when producing E Watt in this scenario. In that unlikely case, the fuel cells will be turned off and the solar panels will produce all the electricity.

The previous bullet points have provided detailed explanations of the rules that constitute the operating strategy in this research. Table 5.1 summarizes these rules in a structured and concise manner. One notable aspect is that at the beginning of each time step, the gas turbine is always considered to be off. This, however, does not imply that the gas turbine is always off and it can certainly be turned on for multiple iterations in a row. If there are multiple time steps where the fuel cells and solar panels are insufficient to meet the electricity demand, this means that the gas turbines are also turned on for multiple time steps consequently. However, the strategy is aimed at generating as much electricity as possible from sustainable resources, which is why the focus is on using fuel cells and solar energy. Gas turbines are only used as a backup source, which makes them well-suited for their quick start-up time, as described in Section 2.4 System properties of components in the electricity system. Another observation is that solar panels do not differentiate between not producing electricity or not producing enough electricity. The reason for this is that the strategy always wants to supply available solar energy directly to the grid before turning to other resources. This is because the direct supply of solar energy is much more efficient than electricity via hydrogen, which involves multiple conversions that result in energy losses. Finally, it is important to mention that A is always greater than C. Otherwise, scenarios may arise where both Rule 2 and Rule 5 meet the criteria simultaneously, resulting in the production of both B Watt and D Watt. This cannot happen, and therefore, the consideration was made to always prioritize A above C.

Table 5.1: Rules for operating strategy

Rules	Solar panels	Fuel cell	Hydrogen storage	Gas turbine	Energy demand	Strategy
Rule 1	Off/Not sufficient	Off	Below A	Off	Not met	Gas turbines: turn on
Rule 2	Off/Not sufficient	Off	Above A	Off	Not met	Fuel cell: turn on produce B Watt Shortage electricity: turn on gas turbine Excess electricity: produce hydrogen
Rule 3	Off/Not sufficient	On	Empty	Off	Not met	Fuel cell: turn off Gas turbine: turn on
Rule 4	Off/Not sufficient	On	Above C	Off	Not met	Fuel cell : keep on produce B Watt Gas turbine: on produce remainder
Rule 5	Off/Not sufficient	On	Below C	Off	Not met	Fuel cell : keep on produce D Watt Gas turbine: on produce remainder
Rule 6	Sufficient	Off	-	-	Met	Excess electricity: produce hydrogen
Rule 7	Sufficient	On	-	-	Met	Excess electricity: produce hydrogen Fuel cell: Produce E Watt

5.4. Computational model

The aim of this paragraph is to provide an overview of what is to be discussed in this section. Firstly, a brief summary will be given to indicate the progress made prior to constructing the computational model. Subsequently, an explanation will be provided regarding the tools employed for creating the model before delving into how the model interprets the data in the dataset. This section will then address the implementation of the strategy defined in the previous section. Furthermore, attention will be given to how the key performance indicators, referred to in the main research question, are interpreted in the model.

Sufficient input has been collected to develop a computational model. In this paragraph, a brief summary will be provided of the work done so far and the input for the computational model. Firstly, the problem to be investigated was identified in Chapter 1 Introduction. Then, in Chapter 3 Literature review, the literature was examined to understand how the problem is perceived and approached in the field. This led to a better understanding of how an electricity system with hydrogen is conceptualized, as well as the techniques and methods employed to optimize the operating system. Additionally, research was conducted into the properties of important components in the electricity system. In Chapter 4 Research approach, the methods, tools, and datasets that will be employed in this study were identified. Based on this information, a conceptual model with an associated strategy was established in this chapter. All this information will be used to construct the computational model, which will be described in the following paragraphs.

Tools for model

As mentioned earlier in Section 4.4, Python, a programming language, was chosen for modeling purposes. For ease of accessibility and convenience, the coding platform Google Colaboratory was utilized. Moreover, two Python packages, namely Pandas and NumPy, specialized for data analysis and manipulation were employed to manage the data and to perform mathematical operations in the model. The use of these tools facilitated efficient and effective data analysis and model creation. To visualize the outcomes in graphs, the package matplotlib was employed.

Data interpretation

As previously mentioned in section 4.6, this research will utilize two datasets: one containing hourly electricity production from solar power, and the other containing hourly electricity demand based on usage in the Netherlands. The computational model will iterate through each hour, using the energy resources within the model (solar panels, hydrogen system, and gas turbine) to fulfill the electricity demand according to the strategy. At every iteration, new data is used as input, and the model must respond accordingly based on the chosen strategy.

The solar energy dataset presents the electricity production of one square meter of solar panels. Therefore, it needs to be converted into the number of hectares of solar panels in the Netherlands, as illustrated in Formula 5.1. The rationale for determining the total surface area of solar panels in the Netherlands can be found in Section 2.4: System properties of components in the electricity system.

The formula 5.1 will determine whether the solar electricity produced at a given time is sufficient to meet the electricity demand. If the outcome of the formula is positive, it indicates that the solar panels are producing sufficient electricity, and the model will determine whether rule 6 or rule 7 should be applied. If the outcome of Formula 5.1 is negative, it means that the solar panels are not providing enough electricity, and the other rules will be examined. Once the appropriate rule is applied, the model will move on to the next iteration, as illustrated in Formula 5.2, until the end of the dataset is reached.

$$Solar_t * hectares - Demand_t \rightarrow Electricity_{shortage/surplus} \tag{5.1}$$

$$Solar_{t+1} * hectares - Demand_{t+1} \rightarrow Electricity_{shortage/surplus} \tag{5.2}$$

$Solar$	Dataset on solar irradiance [35]
$Demand$	Dataset on electricity demand of the Netherlands [32]
t	Specific hour in the dataset being studied
$hectares$	The number of hectares of solar panels in the Netherlands
$Electricity$	Outcome, defining if there is a shortage or surplus in solar electricity on timestep x

Strategy implementation

This paragraph will discuss how the model is programmed to determine which rule to use for a specific time step in a structured manner, as illustrated in Figure 5.2. The following paragraph will attempt to explain this visualization. Finally, there will be a brief explanation of how the steps in the visualization are implemented in the code. A detailed explanation can be found in Appendix B.

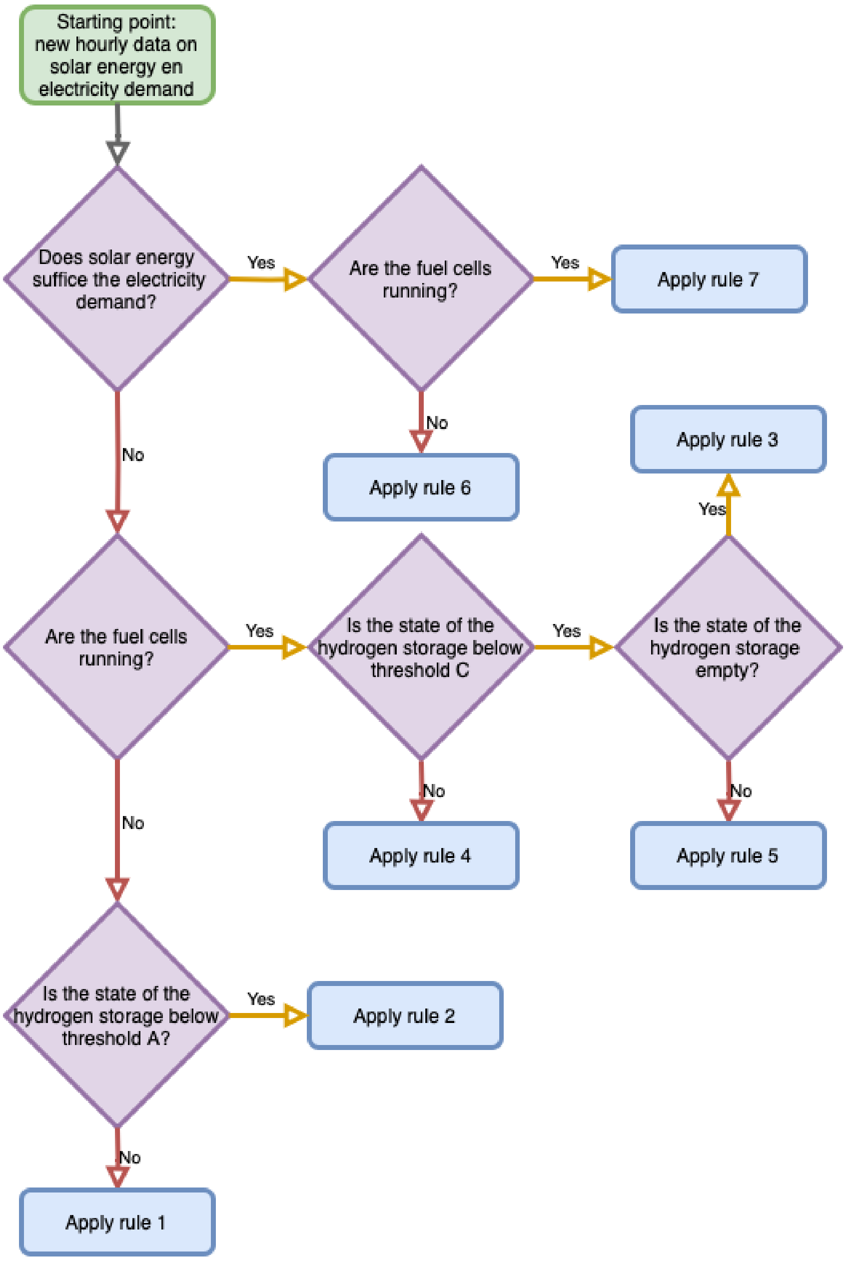


Figure 5.2: Flowdiagram for computer model (own figure)

The aim of the flow diagram is to assign a rule to each hour of the dataset. Starting at the green ”starting point,” each new entry with hourly data on solar electricity and electricity demand is processed. The first question asked is whether there is sufficient solar electricity to meet the electricity demand. The formula stated in Formula 5.1 will be used in this step. If the answer is yes, the status of the fuel cells is examined. If the fuel cells are on, Rule six is applied, while Rule seven is applied when the fuel cells are considered off. If there is not enough solar electricity, the next step is to assess the fuel cell status. In this case, if the fuel cells are not on, Rule one is applied if the hydrogen storage is above threshold A, while Rule two is applied if it is below threshold A. If the fuel cells are on, the next step is to check the status of the hydrogen storage. If the hydrogen storage is not below threshold C, Rule four is applied. If the hydrogen storage is below threshold C, the question is asked whether the storage is empty. If the storage is empty or becomes empty after supplying electricity in this step, Rule three is applied. If there is still sufficient hydrogen in the tank, Rule five is activated.

In order to implement these steps in a structured manner within the code, functions have been utilized. A function is a block of code that is executed when called by the main code. In this strategy, four functions have been identified and are listed below.

- surplus_off()
- surplus_on()
- shortage_off()
- shortage_on()

The functions are self-explanatory when called in the main code. When solar energy is sufficient to meet electricity demand, functions starting with 'surplus' are utilized. If the fuel cells are already activated at the start of the time step, surplus_on() is executed, whereas surplus_off() is executed if the fuel cells are not activated yet. Similarly, functions beginning with 'shortage' are used when solar electricity is unable to meet the demand. When the fuel cells are already activated at the start of the time step, shortage_on() is executed, whereas shortage_off() is executed if the fuel cells are deactivated.

For more elaboration, the code used to navigate through the model, and the code in the functions, are provided in appendix B

Objective function

In this section, the objective function in the computational model will be discussed. Firstly, the objective function will be elaborated upon, before it is divided into the three key performance indicators. These indicators will then be individually addressed, and an attempt will be made to demonstrate how they are incorporated into the code.

The objective function, as described in 1.3 Research goal, consists of the key performance indicators reliability, sustainability, and financial efficiency. One of the challenges mentioned is that these objectives can be contradictory. For example, a scenario may perform very well in terms of cost efficiency but poorly in terms of reliability and sustainability, rendering it an inadequate strategy for supplying the electricity grid. The equation presented in Formula 5.3 takes all these indicators into account by minimizing the sum of the indicators, expressed in Euros. By doing this, all the indicators will be matched and a scenario can be sought acknowledging all key performance indicators. In order to minimize the sum of the indicators, they must be expressed in the same unit, which will be explained in the following paragraphs.

$$Objective\ function(€) = Sustainability(€) + Reliability(€) + Financial\ efficiency(€) \tag{5.3}$$

The key performance indicator that is the most straightforward to follow is cost efficiency, which encompasses the cost of depreciation of the components used to generate sustainable electricity, as well as the costs of resources such as natural gas. This is represented by Formula 5.4. However, a different approach is used in this model. In this research, the levelized cost of electricity production methods is considered. The levelized cost of electricity represents the revenue that an investor in a production facility would need to obtain to break even, and therefore, it reflects the minimum costs. The values of these levelized costs used during the runs are explained in the section 2.4 System properties of components in the electricity system. The equation used in this study for the cost efficiency key performance indicator is presented in Formula 5.5.

$$Cost\ efficiency(€) = Cost\ of\ depreciation(€) + Cost\ of\ resources(€) + Cost\ of\ ...(€) + \tag{5.4}$$

$$\begin{aligned} Costs\ efficiency(€) = levelized\ cost\ of\ solar\ electricity(€) + \\ levelized\ cost\ of\ hydrogen\ electricity(€) + \\ levelized\ cost\ of\ solar\ electricity(€) \end{aligned} \tag{5.5}$$

The next key performance indicator to be discussed is sustainability. As seen in the objective function presented in Formula 5.3, sustainability is defined as a variable measured in Euros. This may seem counter-intuitive since sustainability is concerned with how much reduction there is in CO2 emissions or other harmful pollutants. However, nowadays, there is already a measure that couples emissions to financial costs, which are carbon credits. carbon credits are tradeable tokens that give the right to the owner to emit CO2 into the atmosphere. One carbon credit equals one tonne of carbon dioxide or the equivalent amount of a different greenhouse gas [67]. Governments hand these carbon credits out to companies, and some carbon credits are sold on the market. The market is in place so when a polluter has exceeded its credits, it can buy credits from other polluters. Because carbon credits are tradeable the price will fluctuate over time. As of May 14th, 2023, the price of one carbon credit is €88.93.

In this model, the amount of natural gas used during a simulation run is tracked. A certain amount of natural gas produces a certain amount of CO2, which is already determined in section 2.4 System properties of components in the electricity system. To obtain the costs of sustainability, as input for the objective function, the equation in Formula 5.6 is presented. The outcome will be in Euros to match the other key performance indicators in the objective function.

$$Sustainability(€) = CO_2(kg) \quad \times \quad Carbon\ credit(€/1000\ kg) \tag{5.6}$$

The last key performance indicator to be conceptualized is reliability. In this thesis, reliability should always be honored, since the consequences of a power blackout are devastating. According to [81] a power blackout will lead to disrupted communications and transportation, closure of business and services, and water contamination among other things. This is such a disruptive event that this model will not even consider a scenario in which the reliability is low, resulting in a power shortage. The importance of electricity coverage is also underlined in the dataset of electricity demand [32]. This dataset states that the electricity coverage in the Netherlands is always 100% throughout the whole dataset.

The equation used to conceptualize reliability is presented in Formula 5.7. However, as mentioned earlier, reliability is so important that it will not be used in the model because the consequences of failure are just too disruptive and the costs are therefore too high.

$$Reliability(€) = Cost\ of\ failure\ per\ hour(€/hour) \quad \times \quad Hour(hour) \tag{5.7}$$

5.5. Optimization through particle swarm optimization

This section will discuss how the particle swarm optimization algorithm aims to optimize the operating strategy. This is done by minimizing the objective function presented in Formula 5.3. The upcoming paragraphs will elaborate on what the algorithm will be optimizing before delving deeper into how this is done. For this research, Python was used to code the algorithm. The coding on how the particle swarm optimization algorithm is constructed is presented in appendix C

The particle swarm optimization algorithm used in this study aims to optimize the objective function, which measures the combined costs of the different key performance indicators. It will be considered well-performing when these costs are minimized. As described in section 4.5.2 Optimization: Particle swarm optimization, the algorithm works by changing parameters. In this study, these parameters are as follows:

- A: threshold hydrogen storage
- B: electricity production fuel cell
- C: threshold hydrogen storage
- D: electricity production fuel cell
- E: electricity production fuel cell

Together, these parameters form the search space to be explored by the algorithm. The algorithm aims to find the optimal combination of parameters that minimizes the objective function.

Lastly, the parameter ranges will be discussed. Parameter A and parameter C indicate the fill level of the hydrogen storage tank, expressed in percentages. Therefore, these values cannot be lower than 0 or higher than 100. Additionally, parameter C cannot exceed parameter A, as discussed in Section 5.3. Parameters B, D, and E are adjustments for the amount of Wattage a fuel cell can produce. These adjustments are linked to the rules discussed in Section 5.3. The range of the chosen fuel cell for this research is between 1 kW and 2 MW, as discussed in Section 2.4.3. Therefore, the parameters will fall within this range.

6

Results

6.1. Introduction

This chapter will discuss the results obtained by running the model and optimizing the operating strategy discussed in the previous chapter. It will first elaborate on the different scenarios set ups and will elaborate on why these set ups have been chosen to perform research on. Afterward, the results of each scenario will be discussed individually. Lastly, the results will be interpreted by comparing the results with each other. Consequently, the nuances of the model will come forward in this section and will be discussed as well.

6.2. Scenario setup

6.2.1. Introduction

In this chapter, four different scenarios will be presented. This section will explain the rationale behind the selection of these scenarios and the corresponding parameter set up. The set up will be visualized in tables that display the configuration of the components in the electricity system under analysis. These components include:

- Hydrogen storage
- Fuel cells
- Electrolysers
- Gas turbines
- Solar panels

Scenario 1: Current state

The first scenario 'Current state' will focus on the current situation without hydrogen systems implemented in the electricity system. This scenario will provide insight into the model outcomes if hydrogen is not implemented, and provides a baseline measurement of the system, to compare the other scenario setups with. The setup can be found in the table below. On the left side of Table 6.1 the hydrogen system is visualized, which is non-existing in this scenario, and on the right side of the table the electricity system including solar energy and non-sustainable energy is visualized. The properties of the solar panels and gas turbines used in this scenario are elaborated on in 2.4 System properties of components in the electricity system

Table 6.1: Setup scenario 1: Current state

Hydrogen system

Hydrogen storage	
Hydrogen storage capacity (kg)	0
Initital hydrogen in storage	-
Efficiency hydrogen storage	-
Costs hydrogen storage	-
Fuel cells	
# fuel cells	-
Start-up time fuel cells	-
Range electricity produced	-
kWh per kg hydrogen	-
depreciation/ costs fuel cell	-
Depreciation fuel cell switch	-
Electrolyzers	
# electrolyzers	-
Maximum W per electrolyser	-
kWh needed for 1 kg hydrogen	-
Depreciation costs electrolyzers	-

Solar panels and gas turbine

Gas turbine	
Cost per MW	$90.9/MWh
CO2/cubic foot	0.0550 kg CO2/cubic foot
Gas used per kWh	7.36 cubic feet/kWh
Costs carbon credit	$93,07/1 tonne of CO2
Solar panels	
Hectares solar park	11000
Life expectancy	25 years
Efficiency	20%
Investment costs	€650000/ha
Yearly costs	€2000/ha
Depreciation costs/ha	€3,19/hour - $3.51/hour

Scenario 2: Hydrogen implementation

The second scenario 'Hydrogen implementation' will be the same as the first scenario but with the implementation of a hydrogen system. The rules created in 5.3 Strategy will be carried out to find the optimized objective function described in Formula 5.3 by finding the most efficient setup of the parameters A until E. Just like the other tables described in the other scenarios, on the left side of Table 6.2 the hydrogen system is visualized and on the right side of the table the electricity system including solar energy and non-sustainable energy is visualized.

The properties of the solar panels and gas turbines used in this scenario are elaborated on in 2.4 System properties of components in the electricity system. However, some values need some more elaboration because they are not clear when reading the table. The cost of hydrogen storage is 5% of the total price of hydrogen energy. For instance, if the price of electricity, produced from hydrogen is 20 cents, 1 cent will be added to include the price of hydrogen storage. Also, the "Depreciation fuel cell switch" needs more elaboration. The literature state that shutting down a solid oxide fuel cell can cause degradation and breakdowns due to the high temperatures required for this type of fuel cell. However, after thorough research in the literature, I wasn't able to find literature on how much degradation occurs with a single switch-off. Because of this unknown information, degradation of 5% is assigned to the fuel cells. This means that every time a fuel cell is turned off, the efficiency of the fuel cell will decrease by 5%. For instance, if a fuel cell is turned off three times, it will produce 33 * (0.95)**3 = 28.3 kWh from one kilogram of hydrogen. Lastly, the number of electrolysis and fuel cells will be explained. This number has been set by running the model and thus has been obtained through empirical practice. The goal was that the model would be able to produce enough electricity coming from hydrogen. The number does not affect the costs because the costs are based on the relationship of kWH and kg, and not how many electrolyzers or fuel cells are present in the model.

Table 6.2: Setup scenario 2: Hydrogen implementation

Hydrogen system

Hydrogen storage	
Hydrogen storage capacity (kg)	2400000
Initital hydrogen in storage	50 %
Efficiency hydrogen storage	2 %
Costs hydrogen storage	5 %*

Fuel cells	
# fuel cells	5000
Start-up time fuel cells (h)	4
Range electricity produced	[1kW-2MW]
kWh per kg hydrogen	33kWh
depreciation/ costs fuel cell	$0.11/kWh
Depreciation fuel cell switch	5%**

Electrolyzers	
# electrolyzers	5000
Maximum W per electrolyser	6MW
kWh needed for 1 kg hydrogen	51kWh
Depreciation costs electrolyzers	$6/kg

Solar panels and gas turbine

Gas turbine	
Cost per MW	$90.9/MWh
CO2/cubic foot	0.0550 kg CO2/cubic foot
Gas used per kWh	7.36 cubic feet/kWh
Costs carbon credit	$93,07/1 tonne of CO2

Solar panels	
Hectares solar park	11000
Life expectancy	25 years
Efficiency	20%
Investment costs	€650000/ha
Yearly costs	€2000/ha
Depreciation costs/ha	€3,19/hour - $3.51/hour

Scenario 3: Sustainable priority

Scenario 3 ’Sustainable priority’ will evaluate the optimal strategy when only the key performance indicators ’sustainability’ and ’reliability’ are included and ’financial costs’ is excluded. It will provide more insight into how the strategy would interact with hydrogen storage when its aim is to provide as much sustainable energy as possible. This scenario is relevant as it demonstrates how the strategy can be optimized when the costs of sustainable energy resources are significantly lower than those of non-sustainable resources. A world where sustainable resources are significantly cheaper than non-sustainable resources is an important step towards reducing the ecological footprint of electricity production and combating climate change. Therefore, this scenario deserves attention. Just like the other tables described in the other scenarios, on the left side of Table 6.3 the hydrogen system is visualized in this scenario, and on the right side of the table the electricity system including solar energy and non-sustainable energy is visualized.

The properties of the solar panels and gas turbines used in this scenario are elaborated on in 2.4 System properties of components in the electricity system. From reading the table ”Depreciation fuel cell switch” it is not clear what the 5 % means. In 6.2.1 Scenario 2: Hydrogen implementation an explanation for this value is provided. Logically, the costs of sustainable resources, such as solar panels and hydrogen systems, are removed.

Table 6.3: Setup scenario 3: Sustainability priority

Hydrogen system

Hydrogen storage	
Hydrogen storage capacity (kg)	2400000
Initital hydrogen in storage	50 %
Efficiency hydrogen storage	2 %
Costs hydrogen storage	-

Fuel cells	
# fuel cells	5000
Start-up time fuel cells (h)	4
Range electricity produced	[1kW-2MW]
kWh per kg hydrogen	33kWh
depreciation/ costs fuel cell	-
Depreciation fuel cell switch	5%**

Electrolyzers	
# electrolyzers	5000
Maximum W per electrolyser	6MW
kWh needed for 1 kg hydrogen	51kWh
Depreciation costs electrolyzers	

Solar panels and gas turbine

Gas turbine	
Cost per MW	$90.9/MWh
CO2/cubic foot	0.0550 kg CO2/cubic foot
Gas used per kWh	7.36 cubic feet/kWh
Costs carbon credit	$93,07/1 tonne of CO2

Solar panels	
Hectares solar park	11000
Life expectancy	25 years
Efficiency	20%
Investment costs	-
Yearly costs	-
Depreciation costs/ha	-

Scenario 4: Competitive hydrogen

The fourth scenario, named ”Competitive hydrogen,” is included to provide insights into what needs to be done to make electricity, produced with hydrogen as a resource, competitive with natural gas. This scenario assumes that hydrogen electricity is not currently competitive and aims to determine what changes would be necessary for it to be competitive, according to the model. The scenario is particularly important because if hydrogen electricity becomes competitive, it could be integrated into the electricity grid, reducing the reliance on non-sustainable energy sources. For this scenario, drastic changes have been made making electricity coming from hydrogen 10 times cheaper whilst the cost of a carbon credit is increased 10 times. Table 6.4 illustrates the setup for this scenario, and the electricity system consists of both sustainable and non-sustainable energy sources. The table’s left side shows the hydrogen system and the right side shows the components of the electricity system.

Table 6.4: Setup scenario 4: Competitive hydrogen

Hydrogen system

Hydrogen storage	
Hydrogen storage capacity (kg)	2400000
Initital hydrogen in storage	50 %
Efficiency hydrogen storage	2 %
Costs hydrogen storage	5 %*

Fuel cells	
# fuel cells	5000
Start-up time fuel cells (h)	4
Range electricity produced	[1kW-2MW]
kWh per kg hydrogen	33kWh
depreciation/ costs fuel cell	$0.0011/kWh
Depreciation fuel cell switch	5%**

Electrolyzers	
# electrolyzers	5000
Maximum W per electrolyser	6MW
kWh needed for 1 kg hydrogen	51kWh
Depreciation costs electrolyzers	$0.06/kg

Solar panels and gas turbine

Gas turbine	
Cost per MW	$90.9/MWh
CO2/cubic foot	0.0550 kg CO2/cubic foot
Gas used per kWh	7.36 cubic feet/kWh
Costs carbon credit	$9307/1 tonne of CO2

Solar panels	
Hectares solar park	11000
Life expectancy	25 years
Efficiency	20%
Investment costs	€650000/ha
Yearly costs	€2000/ha
Depreciation costs/ha	€3,19/hour - $3.51/hour

6.3. Scenario results

6.3.1. Introduction

Now that the setups of the scenarios have been created and the rationale behind the setups has been explained, it is time to execute the scenarios in the computational model and optimize them using particle swarm optimization. This section will provide individual explanations of the outcomes of each scenario. Afterward, the results will be interpreted by examining the scenario results combined.

6.3.2. Scenario 1: Current state

The setup of this scenario does not incorporate the integration of a hydrogen system into the electricity grid. As a result, it serves as a baseline measurement for comparing the other scenario setups that involve the implementation of a hydrogen system. Figure 6.1 depicts the visualization of electricity production per resource over accumulated time, revealing that hydrogen does not contribute to electricity production. This observation is further illustrated in Table 6.5, where it is evident that the fuel cell either did not operate or did not generate any electricity. Consequently, the associated costs are also zero.

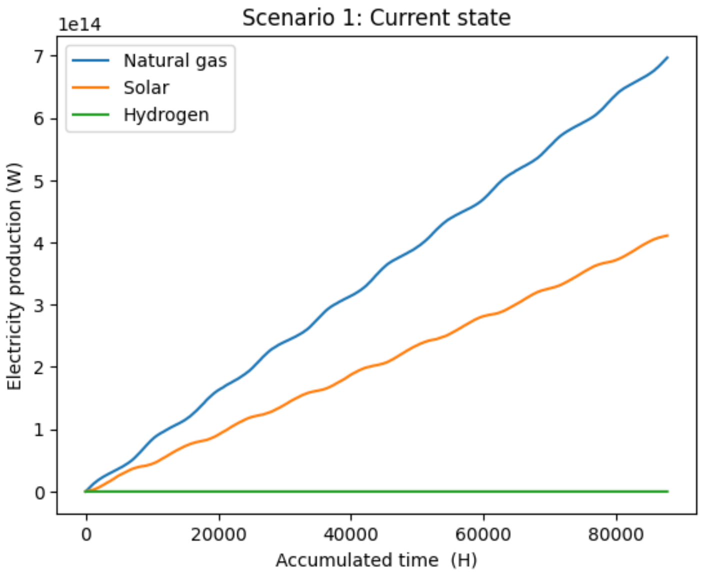


Figure 6.1: Electricity production per resource visualized in accumulated over time (own figure)

Table 6.5: Results of Scenario 1: Current state

	Hours running	MW produced	costs $
Solar panel	41394	411042345.1	3384.05
Hydrogen system	0	0	0
Gas turbine	64604	696772994.9	89587.4

Interpretation of result

As the information presented in the table and figure above, natural gas is responsible for most of the electricity production, followed by solar power. In the model natural gas is producing 63% of the electricity and the solar panels are producing 37%. According to [16], solar energy accounted for approximately 14 % of the total electricity generated in 2020 in the Netherlands. Therefore, it can be stated that the assumptions made in 2.4 System properties of components in the electricity system were off and that too many hectares of solar panels were assigned to the model. In this section, the assumption was made that the roofs that have solar panels have covered the maximum area possible.

However this setup does not represent the exact same outcomes of solar energy in the current situation of the Netherlands, this setup is still a valuable representation which will be explained in the remainder of this paragraph. According to [14], the percentage of sustainable production, including other resources such as wind energy, in 2022 in the Netherlands is around 40 %. It also states that the share of sustainable resources in electricity production is increasing. This research aims to optimize the operating strategy of a hydrogen system within an electricity grid. Even though wind energy has different behavior compared to the behavior of solar energy, which can affect the strategy, it is useful to have a model that produces more or less the same amount of sustainable energy as in the real world. The reason for this is that the hydrogen system, which will be implemented in the other scenarios will have to manage approximately the same amount of sustainable energy, as it would have to manage in the real world.

6.3.3. Scenario 2: Hydrogen implementation

As stated in 6.2 Scenario setup, The second scenario 'Hydrogen implementation' will be the same as the first scenario but with the implementation of a hydrogen system. The rules created in 5.3 Strategy will be carried out to find the optimized objective function described in Formula 5.3 by finding the most efficient setup of the parameters A until E. In Figure 6.2, in which the electricity production per resource is visualized of one week, we see that hydrogen is still not really participating in the electricity production. This is also visualized in Table 6.6, in which we see that the fuel cell has only produced 438164.6 MW, which accounts for approximately 0.04% of the total electricity production. However, regarding the costs, hydrogen energy is responsible for approximately 35.3% of the costs. These results will be interpreted in the following paragraph.

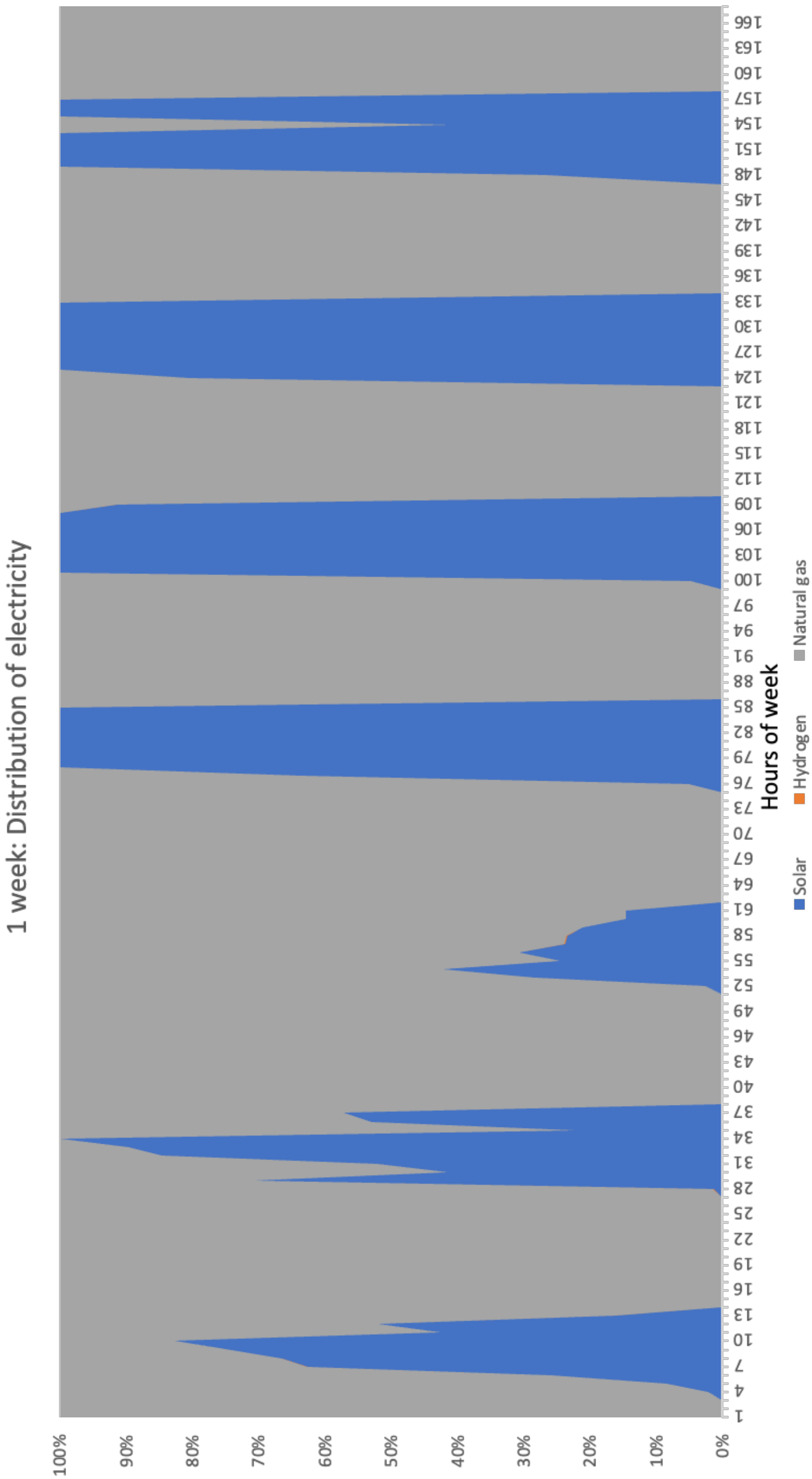


Figure 6.2: Electricity production of 1 week in % (own figure)

Table 6.6: Results of Scenario 2: Hydrogen implementation

	Hours running	MW produced	costs ($)
Solar panel	41394	410927175.1	3384.05
Hydrogen system	87634	438164.6	50608.01
Gas turbine	64601	696450000.3	89545.87

Interpretation of result

Based on the information presented in the table and figure above (see Table 6.6 and Figure **??**), it can be observed that the electricity is predominantly generated by the non-sustainable resource natural gas and the sustainable resource solar panels. Despite the intended strategy of utilizing hydrogen, the model demonstrates a tendency to minimize the utilization of hydrogen for electricity generation. From this, it can be concluded that the sustainability aspect of electricity derived from hydrogen does not outweigh the associated costs. This observation aligns with the findings presented in the previous paragraph, indicating that hydrogen accounted for approximately 0.04% of the electricity produced while constituting approximately 35.3% of the total costs. The behavior of the optimized operating strategy will be further elucidated in the subsequent paragraph, utilizing Figure 6.3 and Table 6.7.

Firstly, the operating strategy will be analyzed based on the behavior in the hydrogen storage. Figure 6.3 shows that, in the model with optimized parameters, the hydrogen storage remains mostly full and there is little effort made to utilize this stored hydrogen. This indicates that the parameters have been adjusted in such a way that the optimized strategy avoids using hydrogen in order to maximize the objective function value presented in Formula 5.3. This reasoning is supported by the visualized optimized parameter values presented in Table 6.7, which will now be discussed. It is notable that the fuel cells operate at their minimum value, namely 1 kWh. Additionally, parameter D deviates from this pattern and produces 922,177.2 W per fuel cell. This setting is activated when Rule 5, stated in Section 5.3, is applicable. Rule 5 is triggered when the hydrogen storage needs to be below parameter value C and the solar energy is insufficient to cover the entire electricity demand. However, upon analyzing Figure 6.3, it can be observed that the hydrogen storage never falls below parameter value C, which in this case has a value of 7.16% as indicated in Table 6.7. As a result, Rule 5 is never applied in this scenario, rendering the value of parameter D irrelevant. Therefore, in this scenario, the fuel cells will always produce 1000 Watts, operating at their minimum capacity.

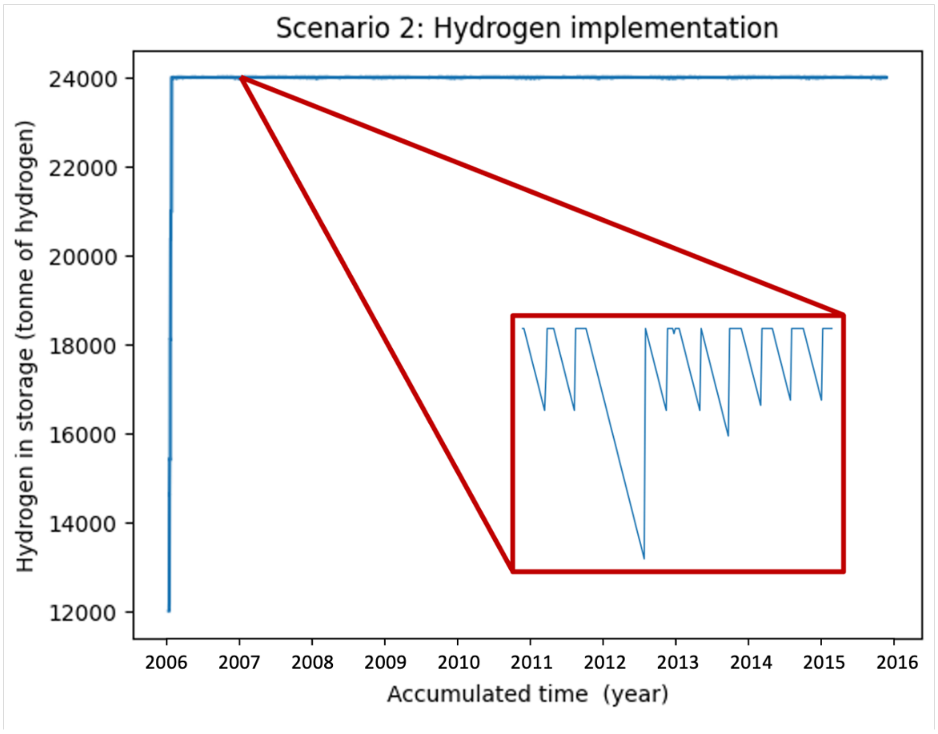


Figure 6.3: State of hydrogen storage over time (own figure)

Table 6.7: Parameter values of scenario 2 after optimization

Parameter	Value
A	32.162 %
B	1000 Watt
C	7.16 %
D	922177.2 Watt
E	1000 Watt

Particle swarm optimization

This section will provide further details regarding the process of obtaining the optimized parameter values, which is performed through the utilization of the particle swarm optimization algorithm, as explained in Section 4.5.2. The progress of optimization in Scenario 2 is visualized in Figure 6.4. This figure illustrates a graph depicting the global best solution of the objective function found at each iteration. In each iteration, the parameters A through E are adjusted to obtain a solution with a different configuration.

As observed, there is a slight improvement in the second iteration compared to the first iteration. The most significant improvement is seen in the third iteration, resulting in a substantial decrease in the graph. In the fourth iteration, a further improvement is achieved, which marks the last improvement obtained. No further enhancements to the objective function are found thereafter. This outcome is expected since the lower bounds of parameter B and parameter E have been reached, and this scenario aimed to minimize the production of hydrogen energy, as explained in the section on the interpretation of results.

Figure 6.5 illustrates the movement of particles throughout the iterations. In each iteration, the particles adjust their positions by modifying the parameter values. Since it is not feasible to visualize all parameters, we have chosen to focus on parameter A and parameter B separately and examine how three particles move within the search space. In this case, it can be observed that the particles move directly toward their respective targets with little directional fluctuation. This suggests that there are not many global minima, in terms of the objective function, found in other regions of the search space.

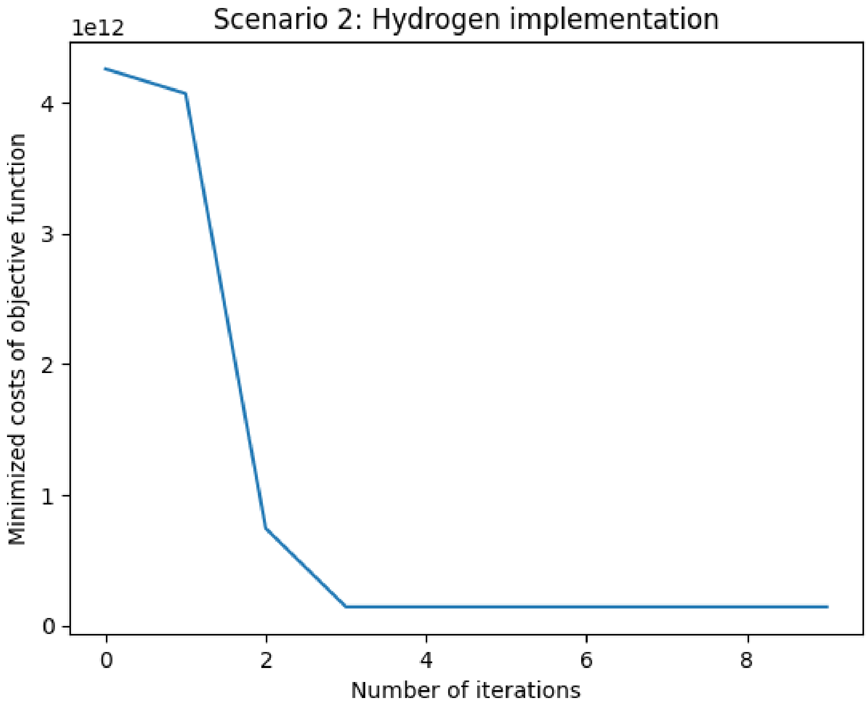


Figure 6.4: Particle swarm optimization: global best through out the iterations (own figure)

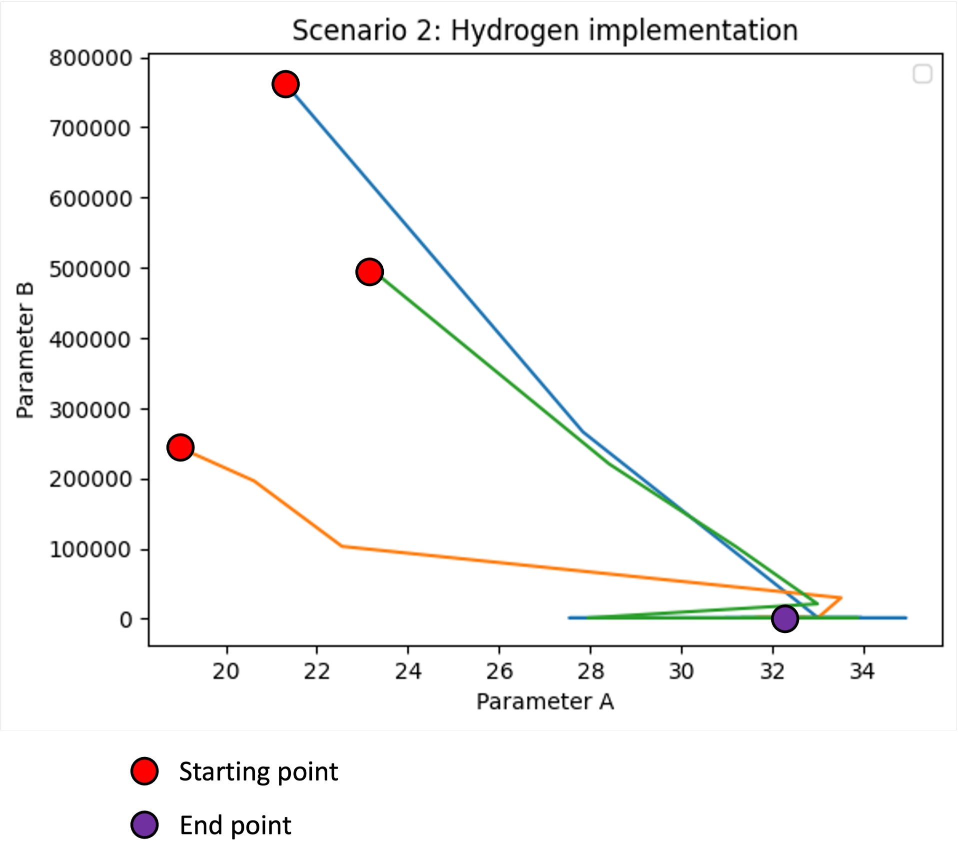


Figure 6.5: Particle swarm optimization: the path of three particles on the search space of parameter A and parameter B (own figure)

6.3.4. Scenario 3: Sustainable priority

This scenario aims to investigate the optimal strategy when the key performance indicator of cost efficiency is not considered. In this context, the focus is on maximizing electricity production from sustainable resources, as mentioned earlier in Section 6.2. Figure 6.6 presents the visualization of electricity production per resource of one week in this scenario. It can be observed that hydrogen emerges as the preferred method of electricity production, contributing to 57.4% of the total electricity production. Solar energy follows with a production share of 33%, while natural gas accounts for 9.2% of the total electricity production. These statistics are derived from the data presented in Table 6.8. The subsequent paragraph will provide a more detailed interpretation of these results.

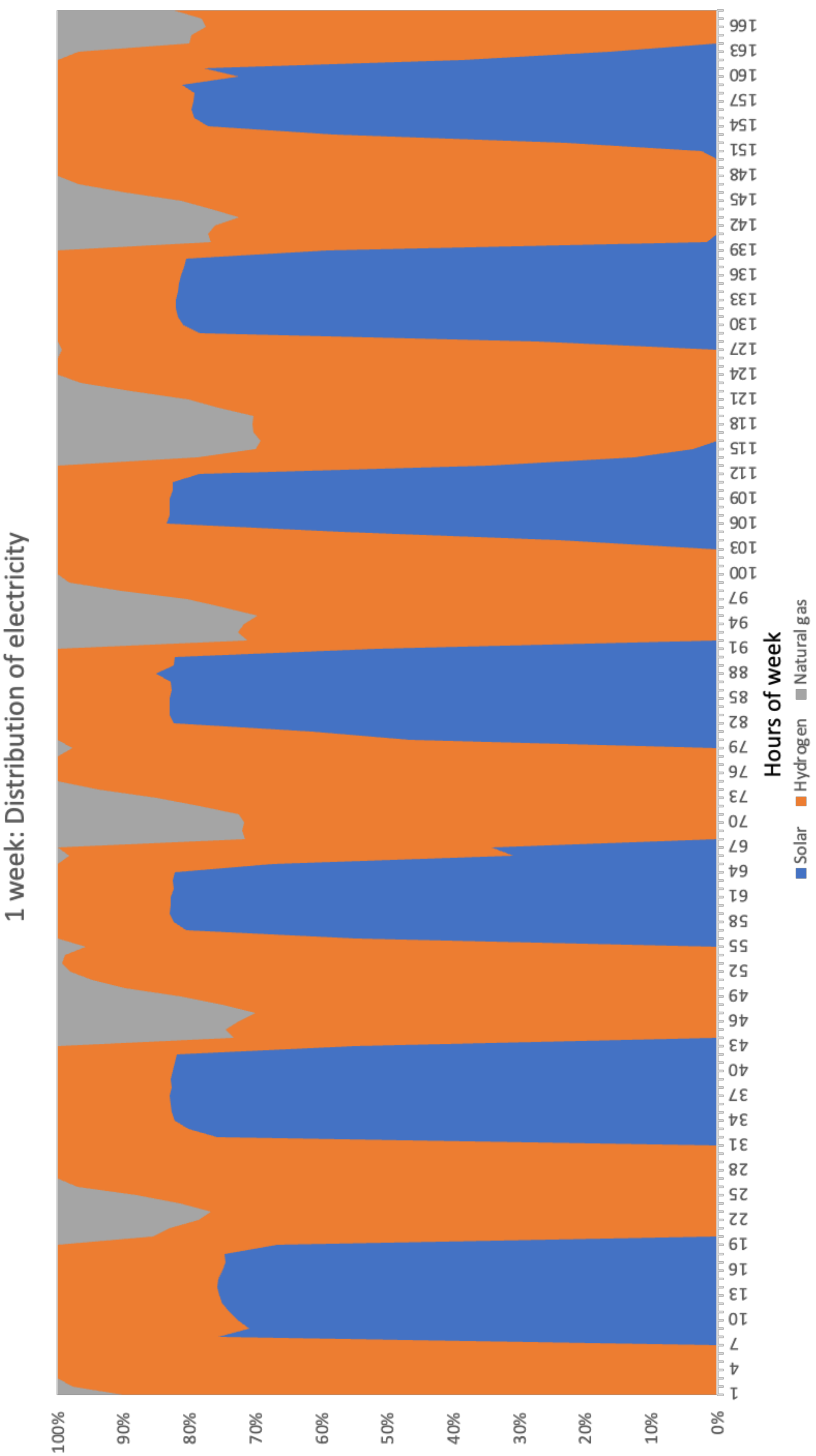


Figure 6.6: Electricity production of 1 week in % (own figure)

Table 6.8: Results of Scenario 3: Hydrogen implementation

	Hours running	MW produced	costs ($)
Solar panel	41394	370569413	3384.05
Hydrogen system	83181	635438469.25	0
Gas turbine	38531	101807457.8	304993.41

Interpretation of result

The logical expectation in this scenario would be that hydrogen energy is indeed utilized, considering that in Scenario 2, it was not used due to the high associated financial costs. In this scenario, however, the financial costs of hydrogen have been reduced to zero, eliminating this obstacle. The obtained results align with this expectation, as hydrogen is extensively utilized in this scenario. The following paragraphs in this section will explain how the parameter values can be interpreted, as visualized in Table 6.9. Furthermore, the behavior of hydrogen consumption will be elucidated by examining the state of the hydrogen storage over time, as visualized in Figure 6.7.

First, we will examine the hydrogen storage depicted in Figure 6.7. It can be observed that hydrogen storage is frequently at maximum capacity but also experiences significant declines during the winter months. These downward spikes may give the impression that the hydrogen storage is rapidly depleting once it is tapped into, but this is not the case. The dataset used for this research spans from early 2006 to the end of 2015, indicating that Figure 6.7 is highly compressed. However, these abrupt downward fluctuations appear impulsive. Additionally, noteworthy is the consistent frequency of the downward movements in the graph. This pattern arises because hydrogen storage primarily declines during the winter season. During winter, solar energy generation is reduced due to decreased sunlight, as visualized in Figure 4.8. Furthermore, Figure 4.11 demonstrates the inverse pattern concerning electricity demand: it increases during winter compared to summer. These two factors influence hydrogen storage. In winter, there is less solar energy available, leading to a greater reliance on hydrogen production. Moreover, the lack of solar energy intake means that hydrogen storage receives fewer replenishments from newly produced hydrogen. From 2006 to 2015, the hydrogen storage depleted completely six times, resulting in a 5% decrease in the efficiency of electricity production by fuel cells, each time the fuel cells are turned off, affecting the remaining iterations through the scenario. This aspect has been discussed in more detail in Section 6.2.1: Scenario 2: Hydrogen Implementation.

This paragraph focuses on the optimized parameters in this scenario and their influence on the strategy's behavior. Similar to scenario 2, it is evident that the parameters have been pushed to the boundaries of the search space. Parameter A has been set to 99%, while parameter C is set to 1%. Additionally, both parameter B and parameter D are assigned a value of 2000000 W, also reaching the search space limits. The only parameter that does not lie at the extreme end of the search space is parameter E, set at 535206 W. This particular combination of parameters results in the following behavior. When the fuel cells are active, they will always produce 2000000 W during electricity shortages. However, when the hydrogen storage is full and there is an excess of solar energy production, the fuel cell will only generate 535206 W to maintain operation. Furthermore, this strategy is characterized by the fact that when the fuel cells are inactive, they will activate only when the hydrogen storage surpasses parameter A. This is when the hydrogen storage is practically full of hydrogen. This explains why the hydrogen storage, as visualized in Figure 6.7, quickly reaches maximum capacity again after being depleted.

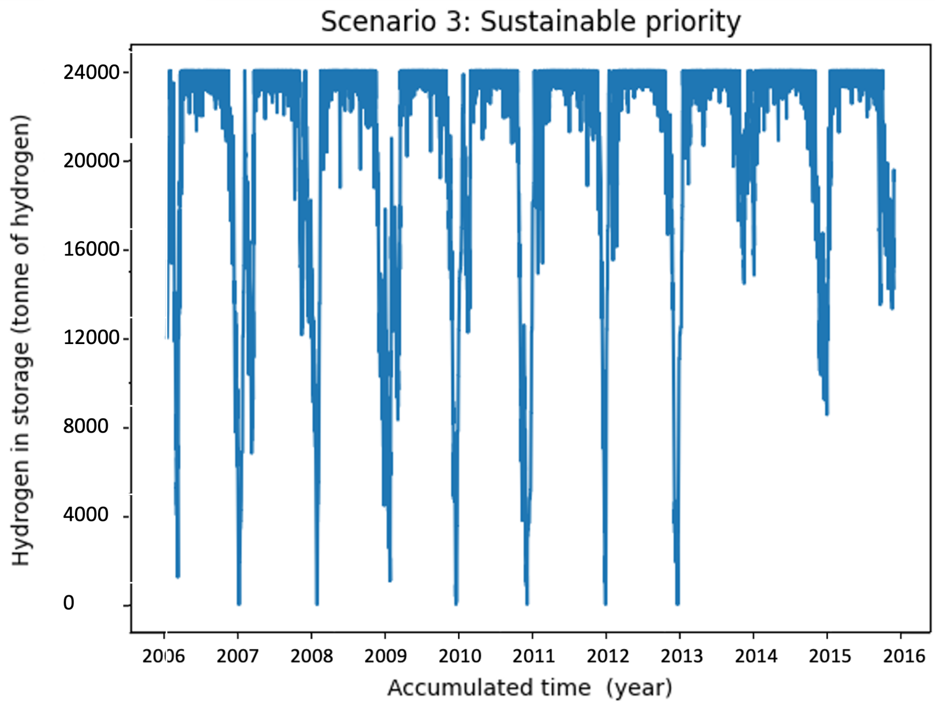


Figure 6.7: State of hydrogen storage over time (own figure)

Table 6.9: Parameter values of scenario 3 after optimization

Parameter	Value
A	99 %
B	2000000 Watt
C	1 %
D	2000000 Watt
E	535206 Watt

Particle swarm optimization

Similar to scenario 2, attention will be given to the optimization process executed by the particle swarm optimization algorithm, as explained in 4.5.2. The progress of optimization in scenario 3 is depicted in Figure 6.8. This figure shows a graph of the global best solution of the objective function found per iteration. In each iteration, parameters A to E are adjusted to obtain a solution from a different setting.

As observed, there is a slight improvement in the second iteration compared to the first one. Subsequently, between iteration 2 and iteration 6, the line consistently finds better values for the global minimum and the objective function at an almost constant speed. Further improvements are found in subsequent iterations, including the last and tenth iterations. However, the rate of improvement significantly decreases, indicating that the minimum has been nearly reached. Consequently, the results obtained from the optimized parameters also provide a good indication of the location of the global minimum within the search space.

Finally, the movement of particles throughout the iterations has been captured. Figure 6.9 illustrates how the particles shift by adjusting their parameter values in each iteration. A more detailed explanation of this process can be found in Section 6.3.3. In this case, we observe that the selected particles change direction multiple times. This indicates that there have been several global minima in different locations within the search space before the ultimate global minimum is determined.

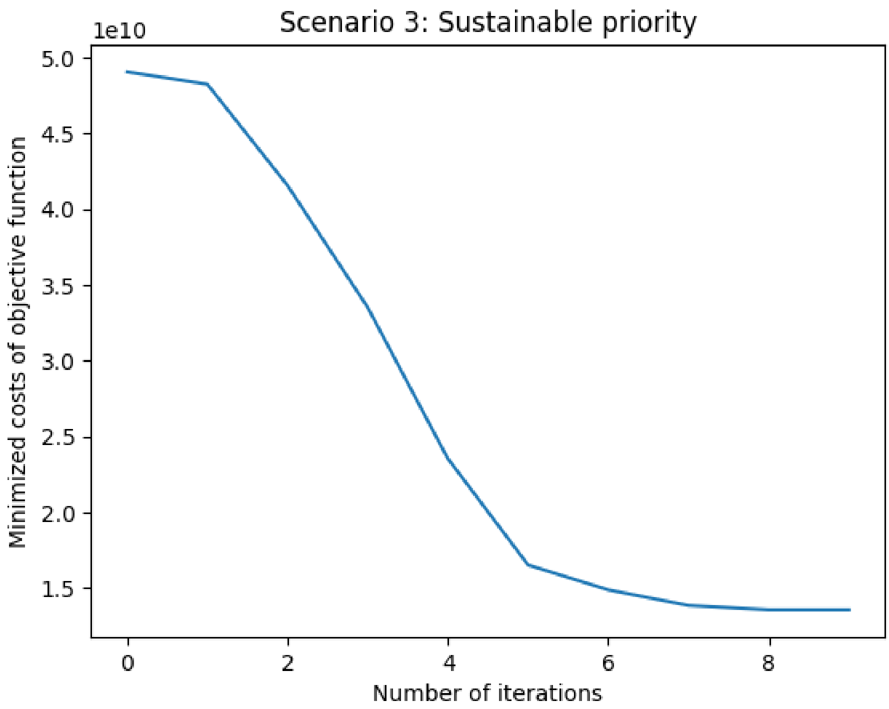


Figure 6.8: State of hydrogen storage over time (own figure)

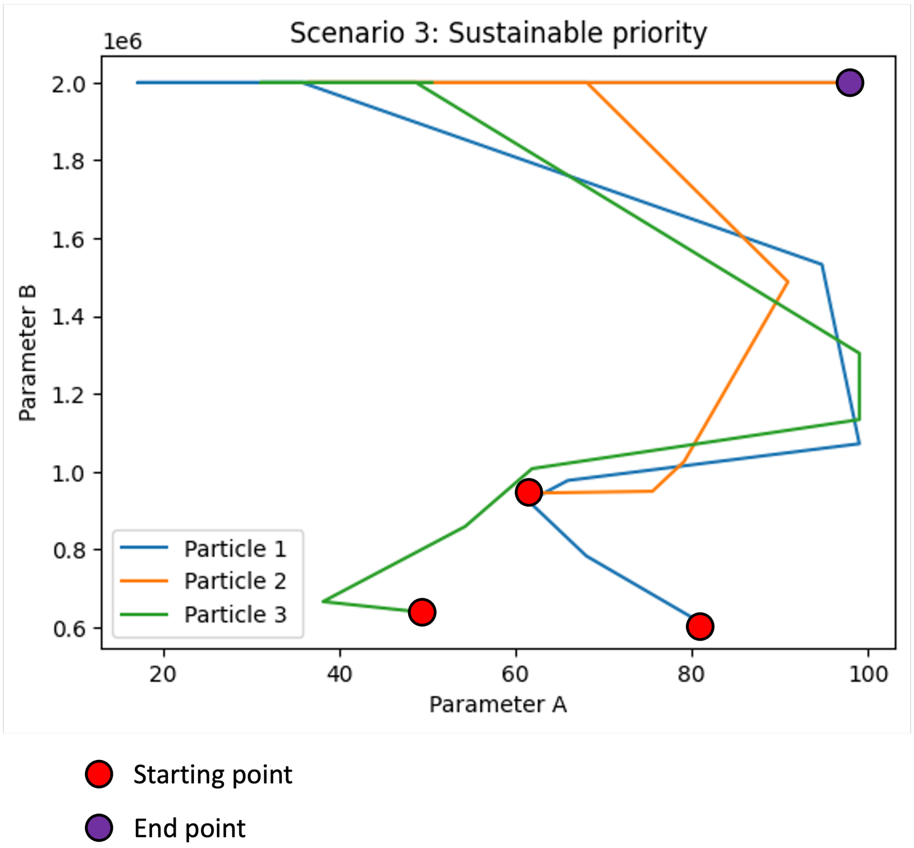


Figure 6.9: State of hydrogen storage over time (own figure)

6.3.5. Scenario 4: Competitive hydrogen

This is the final scenario among the four, aiming to investigate the optimal parameter settings to achieve the best strategy when hydrogen is competitive. The results from scenario 2 revealed that the sustainability key performance indicator does not outweigh the financial costs associated with it. Subsequently, scenario 3 examined how the strategy is optimized when electricity production using hydrogen as a resource incurs no financial costs. Therefore, it is interesting to analyze how the strategy behaves when hydrogen can be produced competitively. For this purpose, a specific scenario setup, as described in Section 6.2, has been chosen. In Figure 6.10, which visualizes the electricity production per resource of one week, it can be observed that hydrogen, in this scenario, contributes alongside other resources to electricity generation and produces approximately the same amount as solar energy. Electricity generation from natural gas is significantly lower. Hydrogen accounted for 49.3% of the electricity supply, while solar energy contributed 37.1%. Natural gas was responsible for only 13.5% of electricity production. These statistics are derived from the data presented in Table 6.10. The following paragraph will further elaborate on the interpretation of these results.

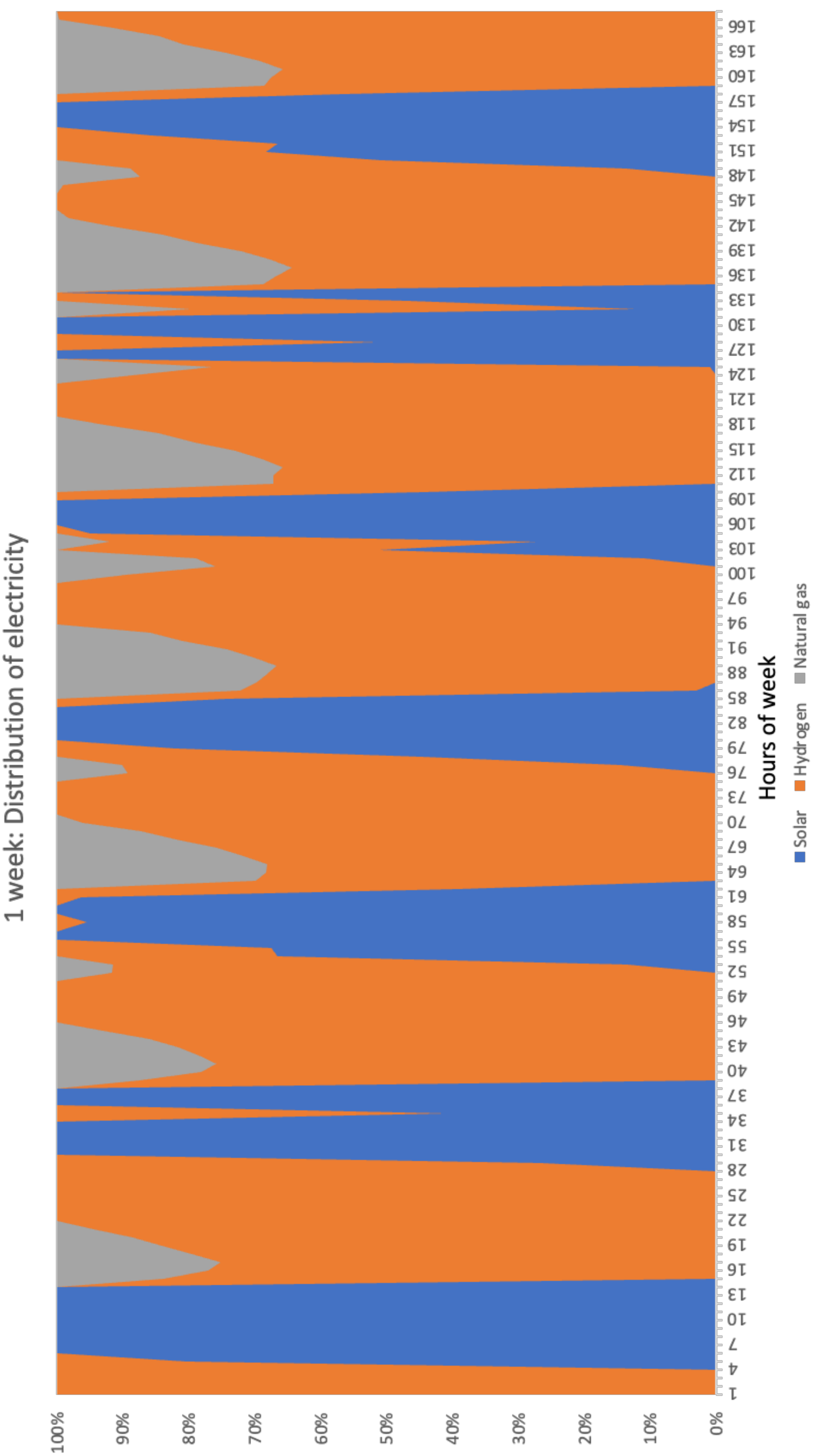


Figure 6.10: Electricity production of 1 week in % (own figure)

Table 6.10: Results of Scenario 4: Hydrogen implementation

	Hours running	MW produced	costs ($)
Solar panel	41394	410938940	3384.05
Hydrogen system	83034	546559121	437955376
Gas turbine	38571	150317279	311599.15

Interpretation of result

In this scenario, the scenario setup has been made more favorable compared to scenario 2, where the current situation of the electricity grid is tested with the implementation of a hydrogen system. The financial costs associated with hydrogen electricity have significantly decreased in this scenario, while the costs of emitting CO2 have considerably increased. The aim is to create a scenario in which hydrogen becomes a competitive resource for electricity generation, and this is reflected in the results. The following paragraphs in this section will explain how the parameter values, visualized in Table 6.11, can be interpreted and will elucidate the behavior of hydrogen consumption based on the state of the hydrogen storage over time, as visualized in Figure 6.11.

First, let's examine the hydrogen storage in Figure 6.11. It can be observed that the hydrogen storage is frequently full, but also experiences significant drops during the winter months. An explanation for this phenomenon has already been provided in scenario 3, as discussed in Section 6.3.4, and will not be reiterated here. We observe that the hydrogen storage becomes depleted six times, resulting in the fuel cells producing 5% less efficient electricity each time the fuel cell is turned off. This aspect has also been elaborated on earlier in Section 6.2.1 of Scenario 2: Hydrogen. It is worth noting that the pattern observed in the visualization roughly aligns with the visualization of the hydrogen storage of scenario 3 in Figure 6.7.

Despite the similarity in the behavior of the hydrogen storage between scenario 3 and scenario 4, the optimization of the parameters in this scenario is significantly different. This paragraph will focus on the optimized parameters in this scenario and how they influence the behavior of the strategy. Similar to scenario 2 and scenario 3, we observe that the parameters have explored the boundaries of the search space. Parameter A is set at 99%, parameter C at 2,000,000 W, and parameter E at 1000 W. Only parameter C and parameter D do not reside at the extreme ends of the search space, with parameter values of 29.9% and 1,868,058, respectively. This parameter combination yields the following results: when the fuel cells are active, they will produce 2,000,000 W until the hydrogen storage drops below 29.9%. Once the hydrogen storage falls below this threshold, the strategy dictates that the fuel cells should produce 1000 W per fuel cell until the hydrogen storage exceeds parameter A again, which is set at 99%. This explains why the hydrogen storage, as visualized in Figure 6.11, quickly replenishes after being depleted. Lastly, it is noteworthy that when solar energy generates enough electricity to meet the demand of the grid, and the fuel cells are active, they will produce 1,868,058 W.

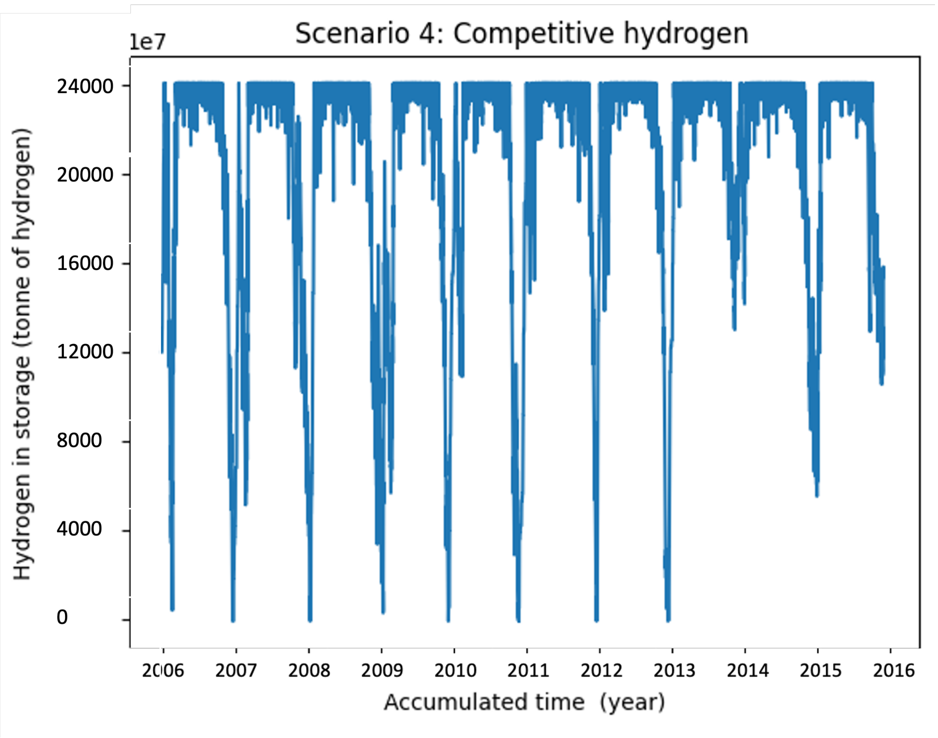


Figure 6.11: State of hydrogen storage over time (own figure)

Table 6.11: Parameter values of scenario 4 after optimization

Parameter	**Value**
A	99 %
B	2000000 Watt
C	29.9 %
D	1868058 Watt
E	1000 Watt

Particle swarm optimization

Similar to the previous scenarios, attention will be given to the optimization process executed by the particle swarm optimization algorithm. The progress of optimization in scenario 4 is visualized in Figure 6.12. This figure depicts a graph where the global best solution of the objective function is found per iteration. In each iteration, parameters A to E adapt to obtain a solution with a different configuration.

As can be observed, there is a slight improvement in the second iteration compared to the first. Then, between iteration 2 and iteration 6, the line steadily finds a better value for the global minimum and the objective function at an almost constant rate. Subsequently, further improvements are still found until the final and tenth iterations. However, the rate of improvement has significantly decreased, indicating that the minimum has been nearly reached. Consequently, the results regarding the optimized parameters also provide a good indication of the location of the global minimum within the search space.

Finally, the movement of particles throughout the iterations is documented. Figure 6.13 illustrates how the particles shift in each iteration by adjusting the parameter values. For a more detailed explanation, please refer to section 6.3.3. In this case, it can be observed that the selected particles do not change direction frequently. This indicates that for the two parameters visualized, the algorithm did not encounter many other global minima within the search space.

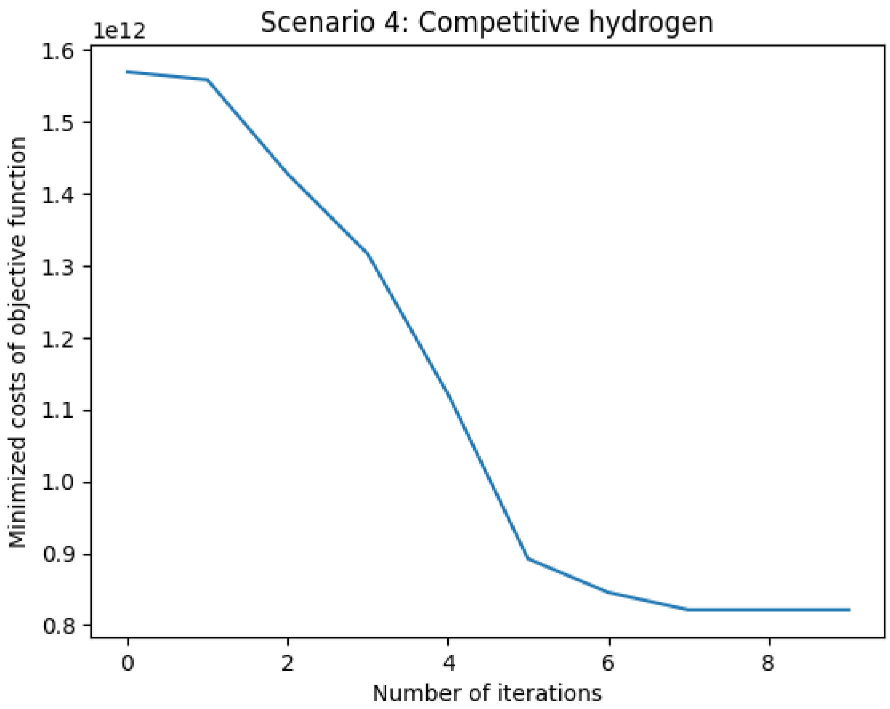


Figure 6.12: State of hydrogen storage over time (own figure)

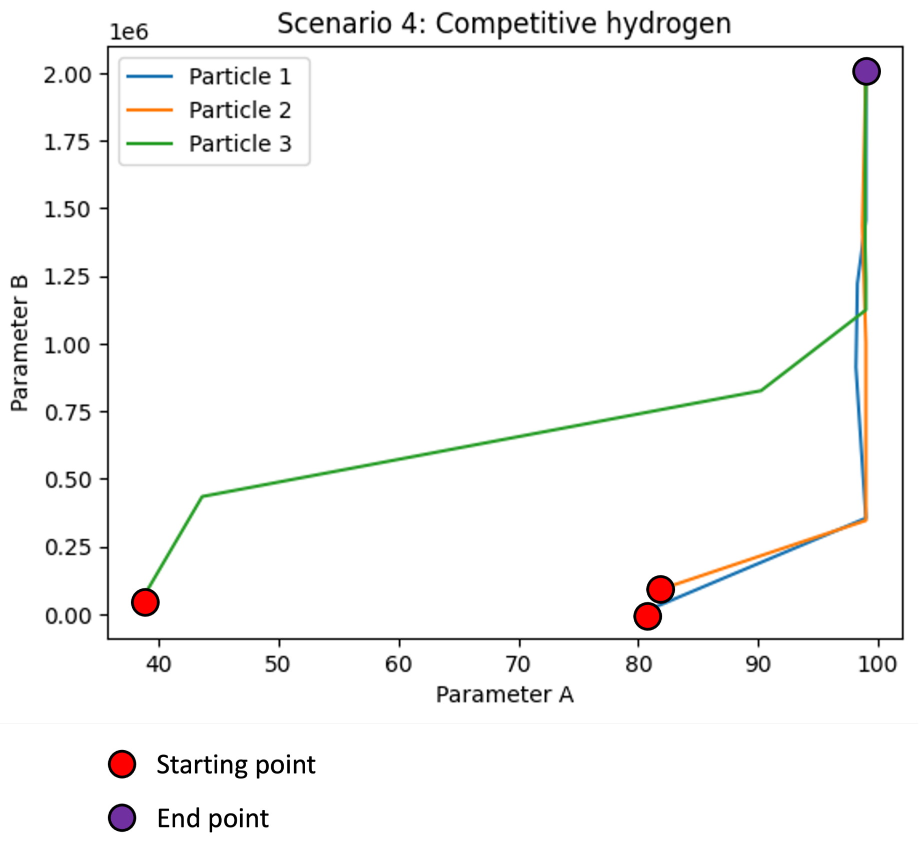


Figure 6.13: State of hydrogen storage over time (own figure)

6.4. Overview of scenarios and its results

In summary, each of the four examined scenarios yields distinct outcomes. This section will provide individual explanations for each scenario based on Table 6.12. In the subsequent chapter, namely, the Discussion (Chapter 7), these results will be further analyzed and interpreted.

In the first scenario, ”Current state,” the behavior of the model was examined without the implementation of a hydrogen system. This provides a baseline understanding of the changes observed in the other three scenarios where a hydrogen system is implemented. In this scenario, approximately 37.1% of the electricity is generated from solar energy, while approximately 62.9% is derived from natural gas. In terms of costs, the majority (96.4%) is attributed to the energy resource of natural gas, with the remaining costs associated with operating solar parks.

The second scenario, named ”Hydrogen implementation,” analyzes the behavior of the model with the implementation of a hydrogen system and an optimized operating strategy. It is notable that the optimized strategy prefers to generate minimal electricity from hydrogen. This is evident from the optimization of parameters B and E, which are set to their lowest values, specifically 1000 Watts. Parameter D deviates from this trend and produces 922177.2 Watts but does not contribute to the strategy, as explained earlier in 6.3.3. Electricity generated from hydrogen accounts for only 0.04% of the total electricity production, while the distribution of electricity from solar parks and natural gas remains largely unchanged from Scenario 1. However, there is a clear difference in costs compared to Scenario 1. It becomes apparent that the costs associated with solar parks represent only 2.4% of the total costs, while hydrogen accounts for 35.3% of the total costs. The remaining 62% of costs are attributed to natural gas. It is noteworthy that hydrogen contributes significantly less to the overall electricity generation but incurs a substantial portion of the costs. This observation will be further addressed in the subsequent chapter, the Discussion (Chapter 7).

Next, in Scenario 3, ”Sustainable priority,” the focus was on examining the behavior of the optimized strategy when the cost of hydrogen was significantly lower than that of natural gas. This investigation was motivated by the findings of Scenario 2, ”Hydrogen implementation,” which revealed that hydrogen did not contribute significantly due to its high costs in the simulation runs. In this scenario, the costs of electricity generated from hydrogen were reduced to zero. As a result, the optimized values of parameters A, B, C, and D approached their respective boundary values. Parameter A had a value of 99%, and parameter C had a value of 1%, providing information on the fill level of the hydrogen storage. Additionally, parameter B and parameter D had a maximum value of 2000000 Watts, while parameter E had a value of 535206 Watts. Parameter E indicates the amount of electricity produced when Rule 7 is executed, as explained in 5.1, and it is the only parameter that does not reach the boundary of its search field. The impact of these parameter values is reflected in the model’s output. Solar energy now accounts for only 33% of the total electricity production, while hydrogen shows a significant increase, contributing 57.4% of the total electricity generation. Furthermore, natural gas has significantly decreased, representing only 9.6% of the total electricity production.

The last scenario, ”Competitive hydrogen,” aims to explore the conditions under which hydrogen becomes a significant contributor to electricity generation in the model, considering the costs of the hydrogen system and natural gas. In this scenario, the costs of hydrogen were reduced by a factor of 10, while the costs of carbon credits were increased by the same factor. The optimized results are as follows: parameter A is set to 99%, parameter B to 2000000 Watts, and parameter E to 1000 Watts, all of which have been optimized to the boundaries of their search spaces. Additionally, parameter C has a value of 29.9%, and parameter D is set to 1868058 Watts. As a result, hydrogen accounts for 52.8% of the total electricity production, followed by solar energy at 37.1%, and natural gas at 10.1%. The costs are predominantly driven by the hydrogen system. This aspect will be further addressed in the subsequent chapter, the Discussion (Chapter 7).

Table 6.12: Overview of the scenario's results

Output		**Scenario 1: Current state**	**Scenario 2: Hydrogen implementation**	**Scenario 3: Sustainable priority**	**Scenario 4: Competitive hydrogen**
Parameters	Parameter A	-	31.2%	99%	99%
	Parameter B	-	1000 W	2000000 W	2000000 W
	Parameter C	-	7.2%	1%	29.9%
	Parameter D	-	922177.2 W	2000000 W	1868058 W
	Parameter E	-	1000 W	535206 W	1000 W
Performance variables	MW produced Solar (%)	37.1%	37.1%	33.5%%	37.1%
	MW produced Hydrogen (%)	0%	0.04%	57.4%	49.3%
	MW produced Natural gas (%)	62,90%	62.9%	9.2%	13.6%
	Financial costs Solar (%)	3.6%	2.4%	1.1%	0.01%
	Financial costs Hydrogen (%)	0	35.3%	0%	99.4%
	Financial costs Natural gas (%)	96.4%	62.4%	98.8%	0.6%

7

Discussion

7.1. Introduction

In this chapter, we will reflect on the research conducted. Firstly, we will interpret the results of the scenarios discussed in the previous chapter (Chapter 6). Additionally, we will compare these results with findings from related studies in the existing literature. Furthermore, we will reflect on the model itself and discuss its limitations. We will also review relevant literature to determine if similar observations were made regarding their models. Subsequently, we will address the limitations of the research and assess the validity of the study.

7.2. Result interpretation

In this section, the results will be further interpreted. Due to the multiple aspects analyzed in the interpretation of the results, it has been chosen to address them through the following five questions. The subsequent paragraphs dedicated to this section will aim to answer the questions formulated below.

1. Has finding the most optimized strategy for each scenario been performed correctly?
2. Why is hydrogen so expensive compared to natural gas in scenario 2, Current state? What are the cost components of hydrogen in this scenario?
3. What needs to be done to transition from scenario 2, Current state, to scenarios 3 and 4? How long will this transition take?
4. What are the limitations of the model, and how have they influenced the results (including parameter settings)?
5. What are the findings of literature that conduct similar research, and what are the similarities and differences?

7.2.1. Question 1: Optimization of operating strategy

When addressing the first question, the focus will not be on the results themselves, but rather on assessing whether the optimization process was successful for each scenario. The particle swarm optimization (PSO) technique, explained in Section 4.5.2, will be examined to determine if the obtained results are truly the optimized outcomes.

In the first scenario, Current state, no optimization was performed, so we will start by analyzing scenario 2, Hydrogen implementation, using Figure 6.4, which illustrates the optimization process. It can be observed that a saturated point is reached quite early, specifically in the fourth iteration. As discussed earlier in the previous chapter, there is a logical explanation for this, namely that the strategy performs best when the boundaries of the search space are approached.

Moving on to the third scenario, Sustainable priority, visualized in Figure 6.8, we see that the optimization process is not as rapid as in scenario 2. Until the final iteration, we observe ongoing optimization of the operating strategy. On one hand, it could be argued that the obtained operating strategy has not yet reached its optimal configuration, or that we are not certain of it at this point. To determine this, more iterations would need to be conducted until no further improvement is found for a few iterations. On the other hand, the figure shows that improvements have significantly diminished since the sixth iteration, suggesting that further optimization is unlikely to yield substantial enhancements. This claim is supported by the parameter settings provided in Table 6.8, which, similar to scenario 2, tend to approach the extremes of the search space. However, to obtain even more precise values for the optimal operating strategy in this scenario, additional iterations would be necessary.

Regarding the optimization of the last scenario, Competitive hydrogen, visualized in Figure 6.12, we observe a similar behavior to scenario 3. In this scenario as well, it takes time for the improvements to taper off, and during the last two iterations, no further enhancements are achieved. Looking at the variables in Table 6.10, we see that the parameters are positioned near the boundaries of the search space, except for parameter D, which reaches 1868058 Watt but does not quite reach 2000000 Watt. It remains unclear whether this is the optimal setting or if this parameter was converging towards 2000000 Watt. To obtain even more precise values for the optimal operating strategy in this scenario, additional iterations would be necessary.

7.2.2. Question 2: Explanation of expensive hydrogen in scenario 2, Current state

To provide a thorough answer to this question, a cost breakdown of hydrogen energy will be conducted, specifically focusing on the cost per kWh and the contribution of hydrogen storage, fuel cells, and electrolyzers. The cost distribution per kWh is presented in Table 7.1.

Table 7.1: Cost breakdown of hydrogen elecrticity

	1 kWh Hydrogen energy costs	**%**
Total costs	$0.305	100%
Hydrogen storage	$0.015	5%
Fuel cells	$0.11	36%
Electrolysers	$0.18	59%

According to the table provided, the total cost amounts to $0.305 per 1 kWh for hydrogen energy. In comparison, 1 MW generated by natural gas costs approximately $90.9 in this model. Together with the associated carbon credit costs, as explained in 5.3, this translates to approximately $0.039 per kWh, which is significantly cheaper than the cost of electricity produced from hydrogen. The costs of hydrogen are primarily attributed to fuel cells and electrolyzers. Approximately 59% of the total costs to produce 1 kWh are incurred by electrolyzers. These costs are calculated based on the assumption that it costs 6% to produce one kilogram of hydrogen. The amount of hydrogen required for 1 kWh is then determined, and the cost is calculated accordingly. Fuel cells account for 36% of the costs, followed by hydrogen storage, which contributes 5% of the costs. It should be noted that the efficiency of fuel cells may decrease over the course of the simulation run and may deviate from the values in the table above. As discussed earlier in Scenario 2: Hydrogen Implementation, the fuel cells in this study are modeled to become less efficient as they are switched on and off more frequently. In the case where a fuel cell is turned off, the costs to produce 1 kWh will increase. These costs will be reflected in the electrolyzer costs, as the electrolyzer will need to produce more hydrogen to generate 1 kWh.

This topic will be revisited in the answer to question 6, where a comparison with other literature will be made. It will be investigated whether the cost distribution, particularly the share of electrolysis, aligns with findings from other studies.

7.2.3. Question 3: Transition from scenario 2, Current state, towards Scenario 3 and 4

Now that the costs of hydrogen have been defined in the model, the question arises: What actions need to be taken to transition to a situation where hydrogen electricity is utilized? To address this question, we will examine the pathways from scenario 2, ”Current State,” to scenario 4, ”Competitive Hydrogen,” where hydrogen systems are effectively employed, based on the results from this research.

Based on the model used in this research, two approaches can be considered to make hydrogen competitive with natural gas. The first approach involves increasing the cost of carbon credits. Governments can implement policies to reduce the availability of carbon credits, creating scarcity and driving up prices. Consequently, the costs associated with natural gas electricity production would also rise. However, a drawback of this strategy is the potential increase in overall costs, which may result in electricity becoming unaffordable. Although this policy measure can incentivize a reduction in gas-based electricity generation, it also poses challenges in terms of affordability.

The second approach, albeit easier said than done, is to enhance the efficiency and cost-effectiveness of hydrogen systems. As previously discussed, the total cost of 1 kWh from hydrogen is $0.305, while that of natural gas is $0.039. This paragraph further explores the prospects of achieving cost parity between hydrogen electricity and natural gas. According to [43], it can be assumed that electrolyzers experience an annual cost reduction of approximately 3%. Although the outlook for fuel cells, as noted in [6], is less optimistic than for electrolyzers, for simplicity, we assume that fuel cells also achieve a 3% cost reduction annually. Assuming that the price of natural gas remains constant and the costs of fuel cells and electrolyzers decrease by 3% each year, it would take approximately 67 years to reach cost parity. To expedite this process, a policy measure could involve increased investment in research and development of these components required in a hydrogen system.

Considering the slow pace of development, a combination of both policies—raising carbon credit prices and intensifying research and development—seems most feasible for expediting the competitiveness of hydrogen electricity. It should be noted that optimizing the operating strategy becomes relevant only when hydrogen electricity can be produced at a lower cost and competes effectively with other resources. Until then, the primary focus should be on improving the components of the hydrogen system, such as fuel cells and electrolyzers.

Nonetheless, numerous other measures can be undertaken to promote sustainable energy or make fossil energy less appealing. For instance, consumers have the potential to decrease their electricity consumption during periods of high CO2 emissions[44]. Nowadays, a significant number of consumers lack awareness regarding the specific hours of the day when CO2 emissions are most intensive and when electricity usage is the least harmful[44]. An effective measure could be to spread awareness to the consumers about what times are the best to consume electricity, which will help hydrogen energy to be more competitive with electricity produced from natural gas.

Implementing the measure described in the paragraph above needs comprehensive research itself and is beyond the scope of this research. The two measures outlined in this study, namely, increasing price of carbon credits and more investments in research and development, have demonstrated their efficacy based on the results of scenario analyses. Consequently, this research exclusively focuses on the examination of these measures.

7.2.4. Question 4: Model limitations

The model employed in this research possesses certain limitations that have influenced the results. These limitations, along with notable findings, will be discussed in the following paragraphs to provide further context to the results.

One significant limitation of the model lies in the static values assigned to electrolyzers and fuel cells. As documented in [39] and [71], each input exhibits its own efficiency. To maintain the manageability of the study, a specific efficiency value was chosen. However, incorporating input-dependent efficiencies would undoubtedly impact the results.

Moreover, the costs associated with hydrogen storage are expressed as a percentage of the total costs, following the rationale presented in [58]. This approach implies that the costs incurred by fuel cells, electrolyzers, and inverters influence the costs of hydrogen storage. In reality, these costs cannot be determined in the same manner and are independent of the total costs. Additionally, the costs associated with turning off the fuel cell remain unclear. Despite extensive efforts to find relevant literature on this topic, no definitive value was found. Consequently, a degradation value for the fuel cell was defined (as explained in Section 6.2.1).

Furthermore, the simulation runs in the model were conducted in a controlled environment, assuming that all components function as described in the rest of the research. It remains uncertain whether these results would translate directly to the real world or if components may exhibit different behaviors than those assumed in this study.

The penultimate limitation pertains to the rules of the operating strategy. The rules dictate the actions to be taken in various situations. For this research, a set of seven rules was chosen, but they could be expanded and made more detailed. However, to ensure the feasibility of the study, only seven rules were employed. Naturally, this limitation also affects the results.

Building upon the previous paragraph, a notable result in scenario 2, ”Hydrogen implementation,” warrants further attention. As previously mentioned, the costs of hydrogen electricity play a significant role in this scenario, making the parameter adjustment of parameter D to 922177.2 Watts noteworthy. Intuitively, one would aim to minimize hydrogen production, as reflected in the other parameters. However, when the hydrogen storage is full, and Rule 5 is applied, this is not the case. To analyze why this discrepancy arises, the next paragraph will delve into the consequences of setting parameter D to its minimum value.

When this value assumes the minimum value, similar to parameters B and E, it implies that the fuel cells produce 1000 Watts, while the remaining solar energy is utilized for hydrogen production. In cases where a substantial amount of solar energy is generated and the hydrogen storage is already full, a considerable amount of solar energy is wasted in the model. It is possible that, in such situations, it becomes more cost-effective to utilize more hydrogen, thereby maximizing the utilization of solar energy for hydrogen production and minimizing wastage. Thus, the parameter adjustment of D is optimized to reduce costs.

7.2.5. Question 5: Comparing results with literature

The response to the last question will reflect on the model results and compare them with existing literature. As mentioned earlier in Section 1.2 Knowledge gap, there is limited research available that conducts similar studies. This scarcity is also evident in Table 3.2. Nonetheless, it is worthwhile to explore the similarities and differences with existing literature.

One study that has some resemblance to my research, based on my literature review, is the study performed by [98]. This study also utilizes a solar park, gas turbine, and hydrogen storage system to generate electricity. It also seeks a multi-objective operating strategy optimized for both economic costs and carbon emissions. However, despite these similarities, this research still differs significantly from the current study in terms of methodology, optimization strategies, and types of results. Consequently, a direct comparison of results is not feasible due to substantial disparities between the two studies, despite both aiming to find a strategy optimized based on a multi-objective research goal.

However, valuable insights can still be obtained from this research. In this study, it is observed that similar to this thesis, electrolyzers constitute the largest cost component. Considering the cost distribution of the hydrogen system in this research, electrolyzers account for approximately 41% and 75% of the total costs in the two examined strategies concerning electricity generation from hydrogen. Hence, despite the inherent differences between the studies regarding the costs of electrolysis, it can be asserted that it constitutes a substantial portion of the total electricity production costs from hydrogen. This finding aligns with the identified share of electrolysis in this thesis, as presented in Table 7.1. Another noteworthy observation made in [98] is that the hydrogen storage system rapidly depletes. This behavior is also evident in this research, where the hydrogen storage can quickly fill up and deplete. Finally, it is worth mentioning that many pieces of literature have employed static efficiencies for electrolyzers and fuel cells. This assumption of static efficiencies was also addressed as a limitation in Question 4. However, it is observed that this assumption of static efficiencies is also utilized in [98].

7.3. Limitations of the research

The limitations of the model are also limitations of the research itself, as discussed earlier in the section 7.2 Results Interpretation. Additionally, this thesis focuses on a fraction of the entire energy sector. Other factors such as the energy market, regulations, and societal acceptance all have an impact on the electricity market. The decision to solely focus on optimizing the operating strategy for hydrogen storage while excluding other aspects can be seen as a limitation.

Furthermore, certain boundaries were set in this research, which can be considered as limitations. For instance, only solar panels were chosen as the sustainable resource, while a large-scale electricity system typically utilizes other sustainable resources such as wind turbines, biomass, or hydro energy.

Moreover, the system described in this research and the corresponding simulation runs are conducted in a controlled environment. This means that the results of the study, in addition to the aforementioned demarcations, can also be influenced by external factors that are not present in the described system. For example, the performance of fuel cells in terms of energy production may differ on a larger scale.

7.4. Validity of the research

There are two ways to assess the validity of the research. One approach is to examine the existing literature and compare the findings of this study with other research. The other method of validation is to replicate the system in the real world and compare the results with those obtained in this research. However, the latter approach is not feasible because there is no existing system in the world with the exact properties and scale as the one described in this study. Moreover, constructing such a system would require significant costs, making this research primarily reliant on validation based on existing literature.

The model results and their comparison with the existing literature have already been addressed in Question 5 in the Results Interpretation section. As highlighted in that section and also in section 1.2 Knowledge gaps, the literature on optimizing an operating strategy in an electricity system that includes hydrogen is limited. Additionally, the studies conducted in this field have explored various electricity systems, such as systems with or without batteries or specific wind parks used for the research. Given that this research focuses on a specific electricity system (see Figure 5.1), it becomes challenging to validate the outcomes against the existing literature, which is already scarce.

8

Conclusion

8.1. Introduction

This chapter will consist of the following. First, the main research question will be introduced, followed by the answers to the sub-questions. Once these answers are provided, the main research question will be addressed. Additionally, the scientific and societal significance of the research findings will be discussed. Finally, potential avenues for future research will be suggested.

8.2. Answering research questions

The goal of this thesis is to determine an optimized operating strategy for an electricity grid incorporating hydrogen technology while considering three key performance indicators: financial costs, reliability, and sustainability. The aim is to minimize the overall cost while ensuring reliability and sustainability. To achieve this, the particle swarm optimization algorithm is employed as the chosen method to identify the most optimal operating strategies. This approach helps address the research question:

> *How can electricity demand be covered by a system of solar power, conventional power supply, and hydrogen systems, optimized for reliability, sustainability, and cost-efficiency, by adjusting the operating strategy?*

The sub-questions, as outlined in 1.5 Research question and sub-questions, have been formulated to provide a comprehensive answer to the main research question. In the subsequent paragraphs, each sub-question will be addressed, leading to the ultimate answer to the main research question. However, the answer to sub-question 6 will be presented after the main conclusion, as it entails recommendations to stakeholders, which can be determined based on the main findings.

8.2.1. Sub-question 1

> *According to the scientific literature, what are the most common approaches to finding an optimized operating strategy of an electric system including hydrogen technology?*

A comprehensive answer to this question provides a clear understanding of how the literature addresses this problem and offers more context on research conducted in this area. Firstly, it is evident that studies focusing on finding an optimal strategy are limited, with most studies primarily concentrating on economic cost reduction without incorporating environmental aspects. Secondly, the use of hourly data is prevalent in optimizing operating strategies. Thirdly, there are variations in approaches among studies, as they utilize different resources and storage methods, including solar panels, wind turbines, batteries, and others. It is worth noting that many studies employ rule-based or fuzzy logic controllers, which are rule-based approaches, to determine an optimized operating strategy. Additionally, artificial intelligence methods are often utilized for optimization purposes.

Furthermore, it is notable that a significant portion of the literature concerning electricity systems incorporating hydrogen primarily focuses on the component ratio within the electricity grid, such as the number of electrolyzers, hydrogen storage capacity, and so on, rather than finding an efficient operating strategy.

8.2.2. Sub-question 2

How should the key performance indicators in the operating strategy, referred to in 1.3 Research goal, be prioritized to conceptualize the optimal operating strategy?

In this study, the decision was made to express all key performance indicators in terms of costs, measured in euros, as explained in Chapter 5. The key performance indicator ”Cost efficiency” represents the aggregate levelized cost of the components within the electricity system. ”Sustainability” is calculated by quantifying CO2 emissions in terms of euros, considering the costs of carbon credits. Due to the significant disruptive consequences and associated high costs, ”Reliability” is not incorporated into the model. The objective function is presented in Formula 8.1.

$$Objective\ function(€) = Sustainability(€) + Reliability(€) + Financial\ efficiency(€) \tag{8.1}$$

By formulating this objective function, various strategies can be tested and compared. Furthermore, the strategies can be evaluated by examining the contribution of each key performance indicator to the total costs.

In the literature, different approaches have been taken in formulating multi-objective strategies that incorporate both economic and environmental costs in their analysis. For instance, [86] does not modify the parameters within the strategy itself but rather explores the trade-off between energy costs and CO2 emissions when sustainable resources have a greater role in the electricity system. On the other hand, [98] examines two distinct strategies that prioritize financial costs and sustainability as separate outputs of the study.

8.2.3. Sub-question 3:

According to scientific literature, which research approach, methodology, and methods are appropriate for determining an optimized operating strategy for electricity supply in the considered system?

This research utilizes discrete event simulation, where datasets on solar electricity generation and electricity demand are used, given data on an hourly basis. Similar studies in the literature, as discussed in Chapter 3, have also employed this approach, justifying its application in this study. The work by Law and Kelton (2007) offers a systematic framework that guided the chosen modeling research design [56]. Additionally, particle swarm optimization, a heuristic-based algorithm, was employed to optimize the operating strategies. This algorithm involves a swarm of particles, each representing a candidate solution to the optimization problem, which strategically adjusts its parameters to obtain the global best solution. To further enhance its efficiency, linear decay was incorporated into the algorithm. Particle swarm optimization is commonly used in similar studies, as evidenced in Table 3.2. By employing this optimization algorithm, an efficient search for the minimal objective function, and subsequently the optimal operating strategy described in the answer to sub-question 2, can be conducted.

8.2.4. Sub-question 4:

In the considered case, how can an optimal, with respect to the key performance indicators defined in sub-question 2, operating strategy be determined?

To address this sub-question, a model was developed using the Python programming language. The purpose of this model is to simulate an electricity system where electricity is generated and consumed on an hourly basis. The energy sources modeled in the system include solar electricity, energy from natural gas, and a hydrogen storage system capable of storing electricity.

The operating strategy aims to determine which energy source supplies electricity to the grid for each hour. This decision is guided by seven rules presented in Table 5.1. These rules incorporate parameters A through E, which can assume different values to define different strategies. The performance of the operating strategy is measured using the objective function mentioned in the answer to sub-question 2, and the goal is to minimize it. As mentioned in the answer to sub-question 3, the particle swarm optimization algorithm is employed to efficiently search for this optimal solution.

8.2.5. Sub-question 5:

How can the optimization model, found in sub-question 4 be used to optimize realistic future scenarios?

Chapter 6 presents the findings of the study, which includes four different scenarios designed to address the research question. Each scenario explores a different future circumstance, leading to distinct operating strategies.

The first scenario, ”Current state,” examines the scenario where no changes occur regarding the hydrogen storage system. It represents a future situation without a hydrogen system, with electricity generated solely from solar energy and natural gas. In this scenario, natural gas accounts for 63% of the electricity production, while solar panels contribute 37%.

The second scenario, ”Hydrogen implementation,” investigates the optimization of the operating strategy with the addition of a hydrogen storage system to the first scenario. The results show that electricity generated from hydrogen represents approximately 0.04% of the total electricity production, with natural gas accounting for 62.9% and solar electricity for 37.1%. The reason behind this is that electricity from hydrogen is much costlier than that from natural gas. Consequently, the optimal strategy avoids using hydrogen electricity, even though it is sourced from a sustainable resource.

The third scenario, ”Sustainable priority,” examines the optimal operating strategy when hydrogen electricity incurs no costs. This scenario explores a future situation where hydrogen electricity becomes significantly cheaper than natural gas, aiming to determine if the electricity system can consistently provide sustainable electricity to the grid. The results indicate that electricity from hydrogen accounts for approximately 57.4% of the total production, while natural gas contributes only 9.2%, and solar electricity represents 33.5%. This scenario yields the most favorable outcomes so far, as the optimal operating strategy generates a substantial portion of electricity from sustainable resources, resulting in the lowest objective function.

Lastly, the study investigates a future scenario where hydrogen electricity competes with natural gas electricity. To achieve this scenario, significant cost reductions for hydrogen electricity and a substantial increase in carbon credit prices are implemented. The results reveal that electricity from hydrogen accounts for approximately 49.3% of the total production, while natural gas contributes merely 13.6%, and solar electricity represents 37.1%. In terms of costs, solar panels account for only 0.01% of the total, while hydrogen accounts for 99.4%, and natural gas for 0.6%. Therefore, it can be concluded that in this scenario, hydrogen is utilized, and solar energy performs better compared to the previous ”Competitive hydrogen” scenario.

8.2.6. Main conclusion

In conclusion, the main research question has been addressed by examining the sub-questions and synthesizing the findings. By quantifying CO2 emissions in terms of financial costs, the key performance indicators of reliability, sustainability, and financial costs have been compared, leading to the formulation of a multi-objective function. Particle swarm optimization has been identified as a suitable method for minimizing this function and determining the optimal operating strategy.

Through the use of a simulation model, various scenarios were examined to investigate the feasibility of implementing a hydrogen storage system. The results indicate that the implementation of a hydrogen system, with the present circumstances is not economically viable. The sustainability benefits of hydrogen electricity do not outweigh the financial advantages of non-sustainable electricity. Even when considering the costs of carbon credits, the operating costs of a hydrogen system are significantly higher than those of natural gas. The main cost drivers are the high costs associated with electrolysis, followed by the costs of fuel cells.

To achieve a future scenario in which hydrogen electricity competes with natural gas, substantial cost reductions in the components of the hydrogen system are required, along with an increased price of carbon credits. These measures would enhance the economic viability of hydrogen electricity generation and create a more competitive landscape in comparison to natural gas.

8.2.7. Sub-question 6:

What are the recommendations that can be formulated for the problem's stakeholders based on the results of sub-question 5?

Based on the main conclusion, it can be determined that generating electricity from hydrogen is not currently profitable, as indicated by the model results. Assuming that the stakeholders, including energy companies and the Dutch government, desire the implementation of a hydrogen system in the electricity grid that is competitive with natural gas, two recommendations can be made.

As mentioned earlier in the section 7.2 Result interpretation, one recommendation is for the government to increase the price of carbon credits. However, a drawback of this strategy is that it would raise the overall costs and could potentially make electricity unaffordable. On the positive side, it could serve as an incentive to focus on alternative sustainable energy sources, leading us to the second recommendation.

The second recommendation is to invest more in research and development of hydrogen systems. This investment can be made by both energy companies and governments. A combination of both recommendations appears to be the best option for expediting the transition to a future where hydrogen electricity competes with natural gas electricity.

By taking these measures, stakeholders can work towards a future where hydrogen electricity becomes a viable and competitive option, contributing to a more sustainable electricity system.

8.3. Suggestions for further research

As previously mentioned in the knowledge gap section (see 1.2), there is a knowledge gap regarding efficiently operating hydrogen systems [118]. Furthermore, the literature review conducted in Chapter 3 identified a scarcity of research that considers both financial costs and environmental costs when exploring the optimal operating strategy. Although this thesis aims to address this knowledge gap, there is still ample room for further contributions on this topic. For instance, exploring electricity systems with different components, such as batteries, wind energy, etc., could be investigated.

Moreover, this research has its limitations, which can serve as inputs for further research. As discussed in the limitations of the research section (see 7.3), the model used in this study is limited to using only solar electricity. However, when supplying a national electricity grid, it is likely that other sustainable resources, such as wind turbines, would also contribute to electricity generation. Therefore, expanding the model of this research to include other sustainable resources would add value. Additionally, the strategy employed in this research is rule-based and consists of seven rules. It would be interesting to explore alternative rules or expand the existing rules to formulate a more sophisticated operating strategy.

Furthermore, as previously mentioned in the recommendations, further research is needed on the components within a hydrogen system, such as electrolyzers and fuel cells. Therefore, I would also emphasize the importance of conducting research on these components to make research on the optimal operating strategy for a hydrogen system more relevant.

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A

Dataset transformation coding

Coding for the transforming the dataset on solar irradiance

```
from google.colab import drive
import pandas as pd
import numpy as np
drive.mount('/content/gdrive')

#This line of code imports the dataset and skips the first 10 rows since this contains other
    information than the hourly data
df_pv=pd.read_csv('gdrive/My Drive/Thesis Stijn Knoop/Datasets/Timeseries_52.092_5.104
    _SA2_1kWp_crystSi_14_39deg_-1deg_2005_2020.csv', skiprows=10)

#This line of code truncates the last values of the table because these cells contain
    explainations on the column names and are not intended for the dataset
df_pv = df_pv[:-7]

#This line of code visualizes the first 20 rows of the dataset
df_pv.head(20)

#This line of code takes the 'Power column and creates a dataset of only the values of this
    column
df_time = df_pv[['time']]

#These line of codes split the column 'time' into multiple columns:Year, Month, Day, Hour.
    Also it removes the initial column time in the second line of code
df_time['Year'], df_time['Month'], df_time['Day'], df_time['Hour'] = df_time['time'].str[:4],
    df_time['time'].str[4:6],df_time['time'].str[6:8], df_time['time'].str[-4:-2] +':'+
    df_time['time'].str[-2:]
df_time = df_time[['Year', 'Month', 'Day', 'Hour']]

#This line of code takes the 'Power column and creates a dataset of only the values of this
    column
df_P = df_pv[['P']]

#This line of code merges the two datasets (the 'time dataset' and the 'power dataset')
df_pv = pd.concat([df_time, df_P], axis=1)

#This line of code visualizes the first 20 rows of the dataset
df_pv.head(20)

#This line of code creates a csv-file and stores the data in the dataframe above in the
    folder 'Modified datasets' which can be found in the 'Coding' folder
with open('gdrive/My Drive/Thesis Stijn Knoop/Coding/Modified datasets/
    Electricity_solar_dataset.csv', 'w', encoding = 'utf-8-sig') as f:
  df_pv.to_csv(f)
```

Coding for the transforming the dataset on electricity demand

```
#This line of code imports the dataset and skips the first 3 rows since this contains other
    information than the hourly data
```

```
df_demand = pd.read_excel('gdrive/My Drive/Thesis Stijn Knoop/Datasets/Monthly-hourly-load-values_2006-2015.xlsx', skiprows=3)

#This line of code filters the Dataset on the data regarding the Netherlands. All the data about other countries are dropped
df_demand = df_demand.loc[df_demand['Country'] == 'NL']

#This line of code resets the index of the table so it starts from 0 again
df_demand = df_demand.reset_index(drop = True)

#This line of code visualizes the first 20 rows of the dataset
df_demand.head(20)

#In this line of code a dataframe with empty columns is created. This dataframe will be filled with the data from the dataset 'df_demand' which is created in previous cell
df_demand_2 = pd.DataFrame(columns = ['Year', 'Month', 'Day', 'Hour', 'Demand'])

#This line is setting the variable hours_in_a_day to 24. The code below will therefore run from 0 to 23 which is needed to read the values in the columns of 'df_demand' and put them in df_demand_2
hours_in_a_day = 24

#This line of code is creating an empty list. This is needed before running the for-loop. This list will be filled with the corresponding data and will be added to 'df_demand_2'
list_to_append_to_df_demand_2 = []

#This for-loop will go through df_demand row-for-row. 'i' will be incremented for every row it reads
for i in range(len(df_demand)):

  #This line of code is keeping track of the progress how many rows have been gone through and prints every 100 rows its status.  The person running this cell is shown the progress
  if i/100 == i//100:
    print(i, ' of ',len(df_demand), ' lines have been run')

  #this for loop will produce a value for 'j' from 0 up to 23. This is needed to read the columns 0,1,3,..., 23 of the dataset df_demand
  for j in range(hours_in_a_day):

    #In the following lines of codes the Year, Month, Day, Hour and Demand are determined.
    Year = df_demand['Year'][i]
    Month = df_demand['Month'][i]
    Day = df_demand['Day'][i]

    #This if-else statement is needed to produce the correct syntax for Hour. This code makes sure the value of Hour will be (for example): '01:00' instead of '1:00'.
    if len(str(j)+':00')<5:
      Hour = '0'+ str(j)+':00'
    else:
      Hour = str(j)+':00'

    Demand = df_demand[j][i]

    #This line of code puts all the variables that have been created in the for-loop in a list
    list_to_append_to_df_demand_2 = [Year, Month, Day, Hour, Demand]

    #This line of code appends the list to the dataframe df_demand_2.
    df_demand_2.loc[len(df_demand_2)] = list_to_append_to_df_demand_2

#This line of code will let the person who runs this code know when this cell is done running
print('Finished')

#This line of code visualizes the first 20 rows of the dataset
df_demand_2.head(20)

#This line of code creates a csv-file and stores the data in the dataframe above in the folder 'Modified datasets' which can be found in the 'Coding' folder
with open('gdrive/My Drive/Thesis Stijn Knoop/Coding/Modified datasets/Demand_dataset.csv', 'w', encoding = 'utf-8-sig') as f:
```

```
df_demand_2.to_csv(f)
```

B

Model coding

Adding source code to your report/thesis is supported with the package `listings`*. An example can be found below. Files can be added using* `\lstinputlisting[language=<language>]{<filename>}`*.*

```python
def shortage_off():
  global hydrogen_storage
  global energy_match
  global i
  global solar
  global hydrogen
  global gas
  global start_up_ticker
  global A
  #global B
  global C
  global D
  global E
  global F
  global switch_on_sources

  energy_match = abs(energy_match)

 # if hydrogen_storage*100/max_hydrogen_storage < A or hydrogen_storage == 0: # below threshold A so keep fuel cell off and use gas turbine
  if hydrogen_storage == 0 :
    gas = energy_match
    energy_match = 0
    sources['gas_turbine_active'] = 'true'

  elif hydrogen_storage*100/max_hydrogen_storage >= A:   #above threshold A so start fuel cell
    if hydrogen_storage*100/max_hydrogen_storage < D:    # treshold D to determine how much Watt produced by fuel cells
      Watt_produced_fuel_cell = C
    else:
      Watt_produced_fuel_cell = E

    sources['fuel_cell_active'] = 'true'
    start_up_ticker = start_up_hours_fuel_cells #
    switch_on_sources['fuel_cell'] = switch_on_sources['fuel_cell'] +1
    #print(start_up_ticker)
    Watt_in_storage = (hydrogen_storage * (kWh_per_kg_hydrogen*1000))*(efficiency_hydrogen_tank/100)*(inverter_hydrogen_efficiency/100) #efficiencies of fuel cell/storage/inverter is already calculated here
    Max_watt_fuel_cell =  (number_of_fuel_cells * Watt_produced_fuel_cell)

    if start_up_ticker > 0:
      start_up_ticker = start_up_ticker -1
      sources['gas_turbine_active'] = 'true'
      sources['fuel_cell_active'] = 'true'
      gas = energy_match
```

```
      energy_match = 0


    elif start_up_ticker <=0: #this does not happen (if start up time of fuel cells is more than 0 hour) because ticker is just activated. However, rules made when experimenting with quick start up time
      if Max_watt_fuel_cell <= Watt_in_storage:
        if Max_watt_fuel_cell >= energy_match:
          hydrogen = energy_match
          hydrogen_storage = (Watt_in_storage -energy_match)/(kWh_per_kg_hydrogen*1000)/(efficiency_hydrogen_tank/100)/(inverter_hydrogen_efficiency/100)
          energy_match = 0
          sources['gas_turbine_active'] = 'false'
          sources['fuel_cell_active'] = 'true'

        elif Max_watt_fuel_cell < energy_match:
          hydrogen = Max_watt_fuel_cell
          energy_match = energy_match - Max_watt_fuel_cell
          gas = energy_match
          energy_match = 0
          hydrogen_storage = (Watt_in_storage - Max_watt_fuel_cell)/(kWh_per_kg_hydrogen*1000)/(efficiency_hydrogen_tank/100)/(inverter_hydrogen_efficiency/100)
          sources['gas_turbine_active'] = 'true'
          sources['fuel_cell_active'] = 'false'


      elif Max_watt_fuel_cell > Watt_in_storage:
        if Watt_in_storage >= energy_match:
          hydrogen = energy_match
          hydrogen_storage = (Watt_in_storage - energy_match)/(kWh_per_kg_hydrogen*1000)/(efficiency_hydrogen_tank/100)/(inverter_hydrogen_efficiency/100)
          energy_match = 0
          sources['gas_turbine_active'] = 'false'

        elif Watt_in_storage < energy_match:
          hydrogen = Watt_in_storage
          energy_match = energy_match - Watt_in_storage
          gas = energy_match
          energy_match = 0
          hydrogen_storage = 0
          sources['gas_turbine_active'] = 'true'
          sources['fuel_cell_active'] = 'false'
```

```
def surplus_off(): #solar panels generate enough electricity to fulfill the demand --> fuel cells are turned off and stay turned off. if gasturbine is turned on --> shut down
  global hydrogen_storage
  global energy_match
  global i
  global solar
  global hydrogen
  global gas
  global q
  #global B
  global w
  global e
  global r
  global t
  global electrolysis_list

  sources['gas_turbine_active'] = 'false'
  sources['fuel_cell_active'] = 'false'

  if energy_match > number_of_electrolysers* max_W_electrolyser:
    energy_match = number_of_electrolysers* max_W_electrolyser  #only consider the electricity that can be handled by the electrolysers. The electricity which cant be handled is wasted

  kg_produced =  energy_match * 1/(kWh_needed_for_1_kg_hydrogen*1000)
  hydrogen_storage = hydrogen_storage + kg_produced

  if hydrogen_storage > max_hydrogen_storage:
```

```
    electrolysis_list.append(electrolysis_list[-1]+hydrogen_storage - max_hydrogen_storage)
    hydrogen_storage = max_hydrogen_storage
  else:
    electrolysis_list.append(electrolysis_list[-1]+kg_produced)

  solar = (demand_dataset['Demand'][i])*1000000


  #if hydrogen_storage > max_hydrogen_storage:
  #  hydrogen_storage = max_hydrogen_storage
```

```
def surplus_on(): #keep fuel cells running, even though solar panels generate enough to fulfill the electricity demand. if gasturbine is turned on --> shut down
  global hydrogen_storage
  global energy_match
  global i
  global solar
  global hydrogen
  global gas
  global A
  #global B
  global C
  global D
  global E
  global F
  global electrolysis_list

  sources['gas_turbine_active'] = 'false'
  sources['fuel_cell_active'] = 'true'

  Watt_in_storage = (hydrogen_storage * (kWh_per_kg_hydrogen*1000))*(efficiency_hydrogen_tank/100)*(inverter_hydrogen_efficiency/100) #efficiencies of fuel cell/storage/inverter is already calculated here
  Max_watt_fuel_cell =  (number_of_fuel_cells * F)

  if Watt_in_storage >= Max_watt_fuel_cell: #if enough in hydrogen storage
    hydrogen_storage = (Watt_in_storage - Max_watt_fuel_cell)/(kWh_per_kg_hydrogen*1000)/(efficiency_hydrogen_tank/100)/(inverter_hydrogen_efficiency/100)
    energy_match = solar_dataset['P'][i]*ha_solar_park*10000 + Max_watt_fuel_cell - (demand_dataset['Demand'][i])*1000000     # 10000 meter in 1 ha.    # 1000000 to translate MW to W


    if energy_match > number_of_electrolysers* max_W_electrolyser:
      energy_match = number_of_electrolysers* max_W_electrolyser  #only consider the electricity that can be handled by the electrolysers. The electricity which cant be handled is wasted

    kg_produced =  energy_match * 1/(kWh_needed_for_1_kg_hydrogen*1000)
    hydrogen_storage = hydrogen_storage + kg_produced
    electrolysis_list.append(electrolysis_list[-1]+kg_produced)


    hydrogen = Max_watt_fuel_cell
    solar = (demand_dataset['Demand'][i])*1000000 - hydrogen


  elif Watt_in_storage < Max_watt_fuel_cell: #if not enough in hydrogen storage
    hydrogen_storage = 0
    energy_match = solar_dataset['P'][i]*ha_solar_park*10000 + Watt_in_storage - (demand_dataset['Demand'][i])*1000000     # 10000 meter in 1 ha.    # 1000000 to translate MW to W


    if energy_match > number_of_electrolysers* max_W_electrolyser:
      energy_match = number_of_electrolysers* max_W_electrolyser  #only consider the electricity that can be handled by the electrolysers. The electricity which cant be handled is wasted

    kg_produced =  energy_match * 1/(kWh_needed_for_1_kg_hydrogen*1000)
    hydrogen_storage = hydrogen_storage + kg_produced
```

```
    electrolysis_list.append(electrolysis_list[-1]+kg_produced)


    hydrogen = Watt_in_storage
    solar = (demand_dataset['Demand'][i])*1000000 - hydrogen

    sources['gas_turbine_active'] = 'false'
    sources['fuel_cell_active'] = 'false'


  if hydrogen_storage > max_hydrogen_storage:
    hydrogen_storage = max_hydrogen_storage
    electrolysis_list.append(electrolysis_list[-2]+hydrogen_storage - max_hydrogen_storage)
```

```
def shortage_on():
  global hydrogen_storage
  global energy_match
  global i
  global solar
  global hydrogen
  global gas
  global start_up_ticker
  global A
  #global B
  global C
  global D
  global E
  global F

  energy_match = abs(energy_match)


  if hydrogen_storage*100/max_hydrogen_storage >= D:   #above threshold D so  fuel cell maximum power
    Watt_produced_fuel_cell = C
  if hydrogen_storage*100/max_hydrogen_storage < D:    # treshold D to determine how much Watt produced by fuel cells
      Watt_produced_fuel_cell = E

  #print(start_up_ticker)
  Watt_in_storage = (hydrogen_storage * (kWh_per_kg_hydrogen*1000))*(efficiency_hydrogen_tank/100)*(inverter_hydrogen_efficiency/100) #efficiencies of fuel cell/storage/inverter is already calculated here
  Max_watt_fuel_cell =  (number_of_fuel_cells * Watt_produced_fuel_cell)

  if start_up_ticker > 0:
    start_up_ticker = start_up_ticker -1
    sources['gas_turbine_active'] = 'true'
    gas = energy_match
    energy_match = 0

  elif start_up_ticker <=0: #this does not happen (if start up time of fuel cells is more than 0 hour) because ticker is just activated. However, rules made when experimenting with quick start up time
    if Max_watt_fuel_cell <= Watt_in_storage:
      if Max_watt_fuel_cell >= energy_match:
        hydrogen = energy_match
        hydrogen_storage = (Watt_in_storage -energy_match)/(kWh_per_kg_hydrogen*1000)/(efficiency_hydrogen_tank/100)/(inverter_hydrogen_efficiency/100)
        energy_match = 0
        sources['gas_turbine_active'] = 'false'

      elif Max_watt_fuel_cell < energy_match:
        hydrogen = Max_watt_fuel_cell
        energy_match = energy_match - Max_watt_fuel_cell
        gas = energy_match
        energy_match = 0
        hydrogen_storage = (Watt_in_storage - Max_watt_fuel_cell)/(kWh_per_kg_hydrogen*1000)/(efficiency_hydrogen_tank/100)/(inverter_hydrogen_efficiency/100)
        sources['gas_turbine_active'] = 'true'
        sources['fuel_cell_active'] = 'true'
```

```


    elif Max_watt_fuel_cell > Watt_in_storage:
      if Watt_in_storage >= energy_match:
        hydrogen = energy_match
        hydrogen_storage = (Watt_in_storage - energy_match)/(kWh_per_kg_hydrogen*1000)/(
            efficiency_hydrogen_tank/100)/(inverter_hydrogen_efficiency/100)
        energy_match = 0
        sources['gas_turbine_active'] = 'false'

      elif Watt_in_storage < energy_match:
        hydrogen = Watt_in_storage
        energy_match = energy_match - Watt_in_storage
        gas = energy_match
        energy_match = 0
        hydrogen_storage = 0
        sources['gas_turbine_active'] = 'true'
        sources['fuel_cell_active'] = 'false'
```

C

Particle swarm optimization coding

Coding for initialising the particles.

```
def setting_particles(par):
  global global_best

  for n in range(n_particles):
    dictionary = {}
    for i in range(len(par)):

    while dictionary['position_par0'] < dictionary['position_par2']:
      dictionary['position_par0'] = random.random()*100

    model(dictionary['position_par0'], dictionary['position_par1'],dictionary['position_par2'],dictionary['position_par3'],dictionary['position_par4'])
    dictionary['personal_best_score'] = z

    if z < global_best[-1]:
      global_best = [dictionary['position_par0'], dictionary['position_par1'],dictionary['position_par2'],dictionary['position_par3'],dictionary['position_par4'],z]


    globals()['particle_%s' % n] = dictionary
    list_of_particles.append(globals()['particle_%s' % n])
```

Code for initialising a new position of the particles

```
def new_position():
    global iterations
    global p
    global list_of_particles

    for y in(range(len(par))):
       inertia = (0.4*((p-iterations)/iterations**2)+ 0.4 ) * (list_of_particles[j]['position_par{}'.format(y)] -list_of_particles[j]['position_previous_par{}'.format(y)] )

      personal = 0*(list_of_particles[j]['position_best_par{}'.format(y)] - list_of_particles[j]['position_par{}'.format(y)]  )* random.random()* ((-3*p/iterations) +3.5)
      globaal = (global_best[y] - list_of_particles[j]['position_par{}'.format(y)] )* random.random()*((3*p/iterations) +0.5)

      new = list_of_particles[j]['position_par{}'.format(y)] + round(inertia + personal + globaal,2)
      if new < par[y][0]:
        new = par[y][0]
      elif new > par[y][1]:
        new = par[y][1]

      list_of_particles[j]['position_previous_par{}'.format(y)] = list_of_particles[j]['position_par{}'.format(y)]
      list_of_particles[j]['position_par{}'.format(y)] = new
```

```

    if list_of_particles[j]['position_par0'] < list_of_particles[j]['position_par2']:
          list_of_particles[j]['position_par2'] = list_of_particles[j]['position_par0']*0.98
```

Optimizing the model with the particle swarm optimization

```
list_of_particles = []
global_best_list = []
global_best = [0,0,0,0,0,100**100000] # to make sure global best is very high starting the
    simulation
n_particles = 75
iterations = 10


if len(list_of_particles) == 0:
    setting_particles(par)

for p in tqdm(range(1, iterations +1), desc = 'Progress', leave = True):
  for j in tqdm(range(n_particles), desc = ' Progress of iteration {} '.format(p), leave =
      True):

    model(list_of_particles[j]['position_par0'], list_of_particles[j]['position_par1'],
        list_of_particles[j]['position_par2'],list_of_particles[j]['position_par3'],
        list_of_particles[j]['position_par4'])

    if z < list_of_particles[j]['personal_best_score']:
      list_of_particles[j]['personal_best_score'] = z
      for m in range(len(par)):
        list_of_particles[j]['position_best_par{}'.format(m)] = list_of_particles[j]['
            position_par{}'.format(m)]

    if z < global_best[-1]:
      print(global_best , z)
      global_best[-1] = z
      global_best[0] = list_of_particles[j]['position_par0']
      global_best[1] = list_of_particles[j]['position_par1']
      global_best[2] = list_of_particles[j]['position_par2']
      global_best[3] = list_of_particles[j]['position_par3']
      global_best[4] = list_of_particles[j]['position_par4']

    new_position()
  global_best_list.append(global_best[-1])
  print( 'iteration:', p,      'global best: ',global_best)
```