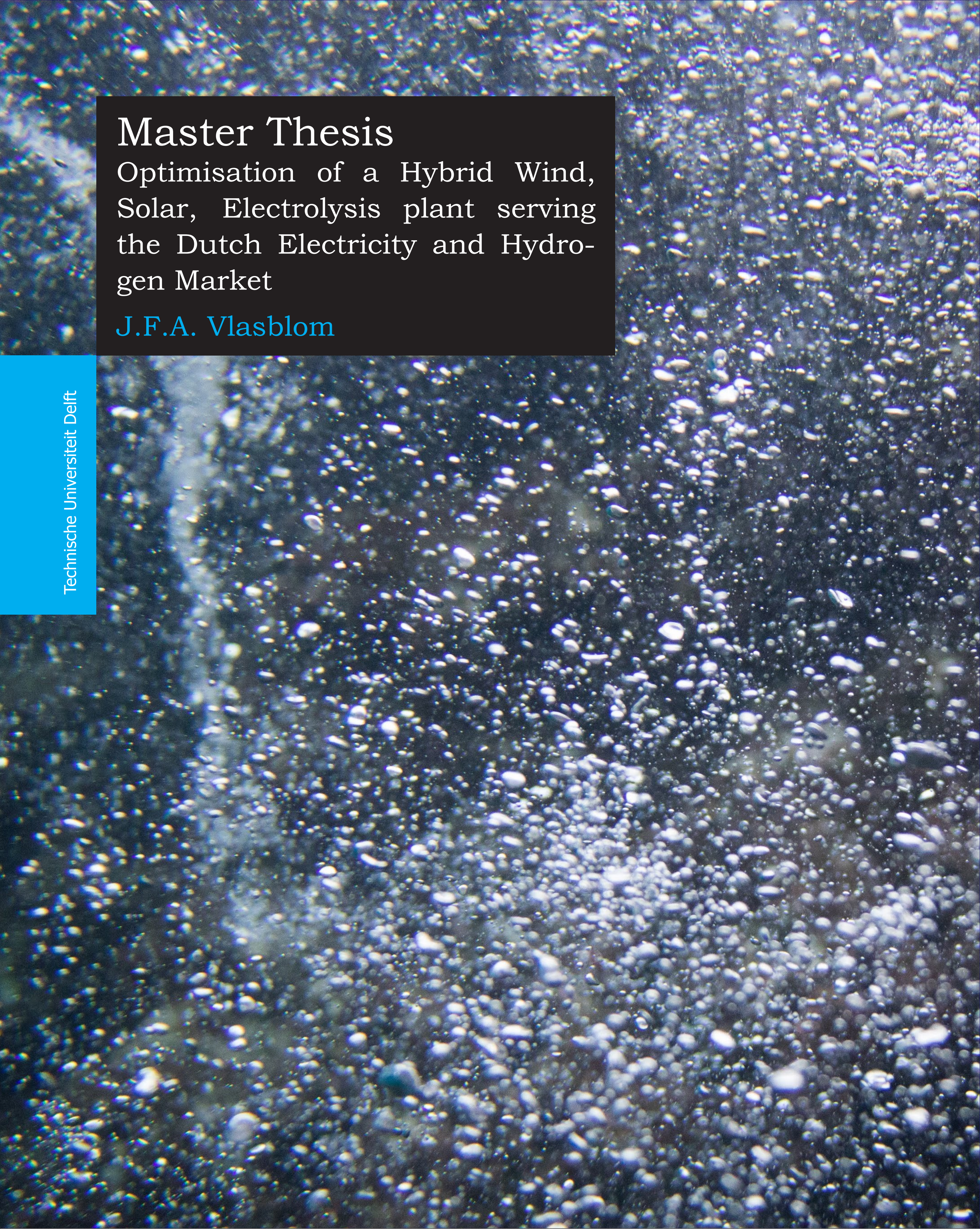

Master Thesis

Optimisation of a Hybrid Wind, Solar, Electrolysis plant serving the Dutch Electricity and Hydrogen Market

J.F.A. Vlasblom

Technische Universiteit Delft

Delft University of Technology

Challenge the future

Master Thesis

Optimisation of a Hybrid Wind, Solar, Electrolysis plant serving the Dutch Electricity and Hydrogen Market

by

J.F.A. Vlasblom

Master of Science
in Sustainable Energy technology

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Contents

List of Figures

List of Tables

Executive summary

Reason for this research

The world's energy supply is shifting towards renewable sources of energy production to reduce the adverse effects of CO2 emissions caused by fossil fuels. However, the most promising sources of renewable energy, wind and solar, have two significant drawbacks. Their energy production is weather-dependent and thus intermittent. Moreover, they are often located in rural areas or offshore, far away from the end-users. These issues cause a mismatch in supply and demand as well as an overloading of the electrical grid. The solution to these problems is the large-scale implementation of grid-connected energy storage. However, due to the lack of profitability, large-scale energy storage is not yet implemented. This research focuses mainly on hydrogen as a storage method, as it shows the most potential to be profitable in the Dutch market.

Goal & method

This research evaluates and optimises the competitiveness of a combined wind, solar, and electrolyser plant in the Dutch electricity and hydrogen market. For the electricity market, this study used the EPEX spot market, where most electricity is traded. The hydrogen market is far less transparent than the electricity market; hence, a market had to be simulated for this study. It was assumed that the price of hydrogen is set by the production cost of hydrogen through steam methane reforming, because this is by far the largest producer of hydrogen in the current market. For both markets, it was assumed that an unlimited amount of electricity and/or hydrogen could be sold at the market price at any time. The competitiveness of the hybrid plant was determined by the Net present value of the hybrid plant. This NPV was calculated for nine research scenarios placed on two axes, a climate action axis, and a time axis. The climate axis represents the amount of climate action taken by governments and industries. The time axis represents the commercial operating date, varying from 2021 until 2030; this will illustrate how the plant competitiveness evolves.

The hybrid plant optimisation model

The hybrid plant consists of an existing wind farm to which a solar pv system and a water-splitting electrolyser can be added. For the electrolyser, two technologies were evaluated; Alkaline and Proton exchange membrane (PEM). Next to the exports of electricity and hydrogen, the hybrid plant also generates revenue from subsidies on both electricity and hydrogen production.

An optimisation model was developed to optimise the hybrid plant configuration and operation to generate the maximum NPV. For this optimisation, the wind generation capacity, as well as the grid connection, are fixed. The optimisation can alter the capacity of the electrolyser and the capacity of the PV system. The optimisation also includes the operation of the hybrid plant throughout its entire system lifetime. This operation entails the electricity exchange with the grid, the amount of electricity used to create hydrogen, and the amount of generation that is curtailed.

Main findings

The main conclusion of the research is that the competitiveness of the hybrid plant is very dependent on market developments. This study concluded solar PV should always be added to a wind farm but that the electrolyser system only generates a positive NPV if drastic climate action is taken. For the other scenarios, the combination of hydrogen prices and subsidy is too low for the hybrid plant to compete. From the scenarios where the hybrid plant is competitive, we see a clear technology shift in the coming decade where the competitive advantage shifts from Alkaline technology to PEM technology. From these scenarios it is also found that the significant strength of adding an electrolyser to the hybrid plant is that it reduces the sensitivity of the hybrid plant NPV to decreasing electricity prices because hydrogen provides an alternative source of income. Finally it is confirmed that the combination of a wind farm, solar farm and electrolyser into one system is able to generate more value than the separate systems.

Recommendations for future research

This research has identified what factors influence the competitiveness of the hybrid plant and provided a valuable tool for optimising this system. Further research could take several directions. It could focus on improving the accuracy of the market predictions for both the electricity and hydrogen prices using dispatch models to quantify the effect of an increased market share of renewables on the prices. Research could also focus on expanding the understanding of the hybrid plant system. Additional sources of revenue might be derived from providing balancing and ancillary services with the hybrid plant and the sale of produced oxygen and waste heat.

1
Introduction

The use of fossil fuels has allowed the world to develop technology, industry and grow economies worldwide. Unfortunately, this progress came at the cost of unprecedented levels of CO_2 emissions causing the global climate to change. In the industrial age, the concentration of CO_2 has nearly doubled, from 280 ppm to 412 ppm, causing the average global temperature to increase by 0.7 degrees in the past century alone.[1] Further increases in CO_2 and other greenhouse gas concentrations and temperatures will cause irreversible change in the climate and render large parts of the planet inhabitable.[2]

Governments around the world have united to stop and eventually reverse the effects of climate change. This ambition to be Carbon neutral by 2050 is laid down in the Paris Agreement. One of the most important steps in reducing greenhouse gas emissions is switching from fossil fuels to renewable sources of energy production such as solar and wind. In 2018 16.2 per cent of the energy consumption was generated from renewable sources in the world. In the Netherlands, however, this number is as low as 6.4 per cent.[3, 4] Solar photovoltaics and wind turbines show the largest potential to increase the production of carbon-free renewable energy. However, they come with one major drawback: the weather dependent and the intermittent and uncontrollable nature of generation. Large scale energy storage is required to deal with this intermittency. However, implementation of large scale storage is still lacking.

This study aims to find a successful business case for storage technology to aid its large-scale implementation. Combined wind, solar and power-to-gas (Hydrogen), a promising form of energy storage, will be evaluated further as detailed in chapter 2. The electrolyser will be co-located with a wind and a solar farm also to include the benefit of co-location. For this purpose, a wind farm in the Netherlands, namely Windpark Fryslan (WPF), is chosen as a case study. WPF is currently under construction and contracted by Ventolines.

Hence, this study was done in collaboration with Ventolines. They are looking to expand their business in energy storage. With a staff of almost one hundred experts, Ventolines is a significant player in renewable energy. In the past years, it has been involved in a lead role in a large number of sustainable energy projects, with national or even European allure, in the phase of realisation or operation. Ventolines provides services in all phases of wind, solar and storage projects: in the areas of development, contracting, legal matters, system integration, construction and asset management. In addition, they provide advice on Power Purchase Agreements and the electricity market in general, stakeholder management, investment, divestment and financing transactions. Ventolines has contributed the necessary guidance, knowledge and data to make this study a success.

This Thesis is laid out as follows: in Chapter 2 a literature review is performed on energy storage technologies and the Dutch electricity markets. Furthermore, it gives an overview of the available knowledge about the competitiveness of storage technologies. The knowledge gap is identified to be the competitiveness of a combined wind, solar PV and electrolyser system serving the dutch electricity and hydrogen market. This system will be referred to as the hybrid plant. Chapter 3 formalises the knowledge gap into research questions and the approach taken to answer them. Then Chapter 4 delineates the boundaries of the hybrid plant system, which will be analysed. Furthermore, it introduces the method that will be used to evaluate and optimise the hybrid plant competitiveness. Chapter 5 details the model used to optimise the competitiveness of the hybrid plant. In chapter 6 the external influences to the hybrid plant are identified. These include market developments, technology developments, etc. A prediction is then made on how they will evolve in the future using scenarios. These scenarios are then quantified in chapter 7 using a combination of historical data and market forecasts. The results of the optimisation under the different scenarios are given in chapter 8. As the inputs to the model are subject to a large degree of uncertainty, sensitivity to these inputs is explored in chapter 9. This sensitivity analysis explores how changes in the input data influence the optimal system configuration and performance. The conclusions that are drawn from both the results as well as the sensitivity analysis are presented in chapter 10. This chapter will also provide recommendations for future research as well as recommendations for potential developers of a hybrid plant system.

2
Literature review and market analysis

This chapter will review the literature on energy storage and how they operate in energy markets. First, the need for energy storage to support a transition to renewable energy is illustrated in section 2.1. Then, how storage technology can be used to generate revenue is explained in section 2.2. Subsequently, the Dutch energy market will be analysed in section 2.3, then an overview of the different storage technologies will be given in section 2.4. Literature on the competitiveness of storage technologies is given in section 2.5. Finally, the knowledge gap is determined and underlined in section 2.7.

2.1. Renewable energy needs storage

The fastest-growing sources of renewable energy, in the Netherlands, in recent years are wind and solar photovoltaics (PV).[5] However, these sources of energy are dependent on the weather and thus intermittent. The intermittent nature of supply causes challenges in matching supply and demand. Often, renewable energy is not able to meet demand, and sometimes, renewable energy supply will exceed demand. Currently, fossil-fuel-powered plants regulate the supply to match the demand. However, variable renewable energy supply (VRES) does not share this ability. In addition, the electricity demand patterns will change as consumers shift their energy source to electricity for mobility heating etc. This will increase their demand drastically and potentially make it more variable. Therefore, a new mechanism to match supply and demand needs to be developed. One proposed mechanism is called demand response. In this method, consumers of electricity will receive a reward for reducing their consumption. An example of demand response is the industry ramping down production, but it can also be smart car chargers, which only charge vehicles when the electricity price is low.[6] Demand response could offer part of the solution. Still, even with highly elastic demand, large scale energy storage is needed to support a 100% renewable energy mix to get through periods when all VRES is zero. [7, 8]

Another problem posed by VRES is the overloading of the grid in rural areas. As VRES scale with land area, they are often placed in areas where land is inexpensive. These areas often have low population densities and low capacity grids. By unloading these grids, storing energy during peak production and releasing it during the off-peak production hours, the required grid capacity can be reduced. For such a system to work, solar and wind generation should be co-located with storage to reduce grid usage and transport losses.

It seems obvious that we should have large scale storage systems at every source of renewable energy generation from a technical point of view. However, in reality, we find that, besides pumped hydro storage, little to no large scale storage systems exist.[9, 10] This is likely caused by the fact that fossil-fuel-powered plants are still the dominant energy source. Fossil-fuel-powered plants are controllable and have inherent energy storage in their fuels. This, combined with the high CAPEX of storage systems, make it difficult to find a positive business case for a storage system. Fortunately, the market is constantly evolving, and the regulatory framework is changing as well. These changes might give energy storage the final push it needs for large scale implementation.

This study focuses on the techno-economical aspects of large scale, grid-connected energy storage. By combining knowledge about the available energy storage technologies with knowledge about the energy market and how they develop, the business case of energy storage is evaluated.

2.2. The business case of energy storage

As mentioned in chapter 1, a successful business case is important for the widespread implementation of storage technology. There are a few ways in which storage systems can both increase revenue and potentially reduce system cost.

The first principle is energy arbitrage. When a system is used for energy arbitrage, it trades energy by buying energy at low prices and selling it at high prices. Therefore, this method is not dependent on absolute energy prices but the difference between high and low prices, i.e., the price fluctuations. Energy arbitrage can also be used to reduce energy curtailment. Storing energy that can not be exported due to grid limitations and selling it at a later moment. In this case, the "low" price is zero as the power would otherwise be curtailed.[11, 12]

The second is offering grid balancing capacity in ancillary services. Such a system will offer its capacity to the balancing markets and can generate a higher income per power unit, often given in MW. For such a system, it is crucial to act and ramp its output quickly, in the order of seconds to minutes. This requirement dictates the technology choice for such a system.[13–15]

The third method explores the possibility of reducing the required grid connection capacity due to peak shaving or transporting the energy differently, such as with power-to-gas systems. In peak shaving, the generation capacity is purposely built larger than the grid connection is able to export. At peak generation, the full capacity can not be exported to the grid. This generation peak is flattened using the energy storage system. Peak shaving is likely most interesting in a combined solar and wind setup as here, the maximum power of both generations is often not reached simultaneously[11].

The fourth way to generate revenue is to sell the energy in a different form, such as a fuel or feed-stock such as hydrogen. This method works similar to energy arbitrage. The energy is bought at a low price and converted to a commodity of a higher value, and sold in a different market.[16, 17]

The methods described above can often be combined to stack their value, as a system used for energy arbitrage might also benefit from a smaller grid connection. Hence both forms of financial gain can be exploited. This "stacking" of revenue can be used to increase the system's profits and might be necessary to create a successful business case[18]. However, this is not always possible due to regulatory limitations. One of such limitations is that capacity offered for ancillary services can not be sold in other markets as this capacity needs to be reserved for the ancillary services only, regardless of whether it will be used or not. [19, 20]
In conclusion, there are a few possible methods to build a business case for energy storage. Finding the right one is a matter of matching the right technology with the right market and use case. It is especially important to match the discharge rate of the storage medium with the use case. The following sections will examine the Dutch electricity market and available storage technologies and their characteristics.

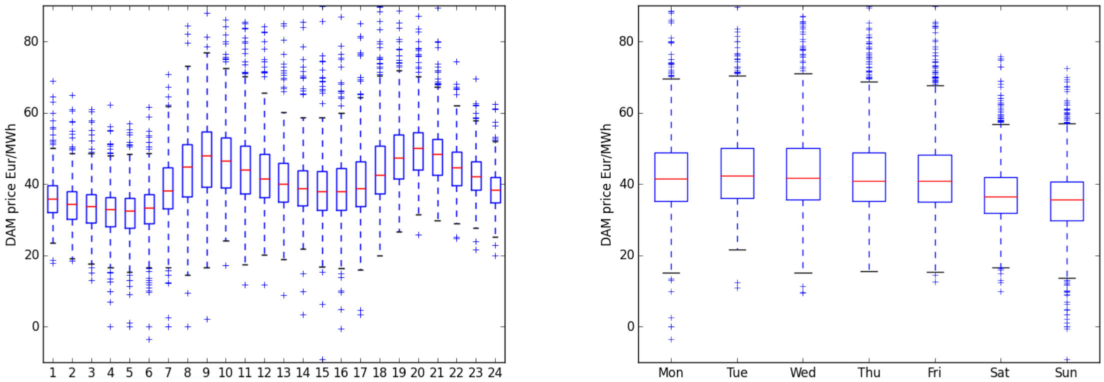
2.3. Dutch electricity markets

The Dutch power market knows several submarkets, bilateral, Day-Ahead Market, Intra Day Market and ancillary service markets, such as the Frequency containment reserve (FCR). These markets serve different purposes, from large scale energy trade over the period of years to small scale power trade over the period of seconds.

2.3.1. Wholesale markets

The largest volume of energy is traded on the Bilateral market. However, this market is not transparent, and the prices are often constant over long periods of time. Constant prices are less interesting for energy storage as the principle of energy arbitrage can no longer be applied. Furthermore, the lack of transparency makes it difficult to analyse this market. Therefore the bilateral market is less interesting for energy storage than other markets. Hence, the Bilateral market is not taken into account in this research.

The Day Ahead Market (DAM) is the largest of the wholesale markets in the Netherlands. This market is called the EPEX Spot market. On this market, suppliers and users place bids for every hour of the day, one day before delivery. The market price is set where supply meets demand, and the entire market volume is sold for this market price. This market is very volatile compared to the bilateral market, with peak prices over €121/MWh and even negative prices of €-9/MWh in 2019. As shown in fig. 2.1 The largest price differences can be seen in fluctuations throughout days and weeks. However, there is little variation over seasons. To exploit these fluctuations in price, storage duration in the order of hours or days would be required. Seasonal fluctuations are minimal,[21] reducing the margin on stored energy, and seasonal storage offers only very few charge-discharge cycles per year, meaning capital cost can only be divided over very few cycles. Another interesting fact is that the prices decreased significantly from 2018 to 2019, on average by over 20% in the Netherlands[5]. The prices decreased another 19% in 2020. However, this change was significantly impacted by the Covid-19 pandemic so that no definitive conclusions can be drawn from this price decrease regarding long-term trends [22].



(a) Dayly price variation

(b) Weekly price variations

Figure 2.1: Box plots based on DAM price data from 2019

Source:[21]

The Intra-Day Market operates similar to the DAM market, with the main difference being that the energy is sold on the day it is used. The DAM and Intra-day market prices are very similar, but the volumes traded in the intra-day market are smaller. However, the Intra-day market trading volumes are increasing rapidly as variable renewables increase their market share. This is caused by the fact that short term forecasts are more accurate than long term forecasts. This means that a more accurate prediction of the supply and demand can be made closer to the moment of delivery. With these closer to real-time insights, energy is traded on the intra-day market.[5]

2.3.2. Balancing markets (capacity market)

The Frequency Containment Reserve, FCR, is a capacity market that is activated if there is a shortage or excess of supply in the grid. A mismatch in supply can cause the grid frequency, which is normally at 50 Hz, to fluctuate. This is undesirable for a number of reasons; hence the FCR was put in place to contain the frequency.[19] This capacity market offers compensation for both the power as well as the energy delivered. Therefore, the reward per energy supplied (often expressed in MegaWatthour) is the highest out of all markets. However, the prices are very volatile, and the barrier to entry is high as the power capacity offered to the FCR can not be offered in other markets due to legislation. Compensation is only given when the energy is actually used.[19]

The Frequency Restoration Reserve, FRR, knows two submarkets, the aFRR and the mFRR. The

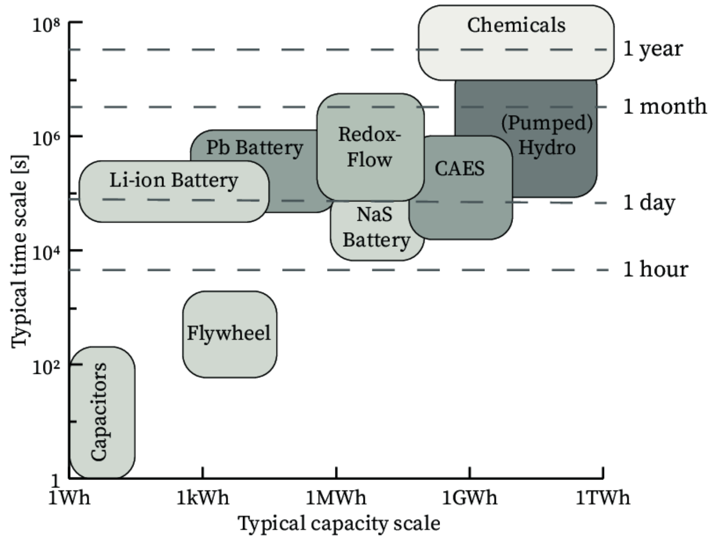


Figure 2.2: Operational time scales of several storage technologies

Source: Schlögl [23]

aFRR, automatic FRR and mFRR, the manual FRR operate similar to the FCR. However, they do not need to deploy as quickly as the FCR and operate for longer periods of time. For this reason, the prices in this market are lower, but the volumes of energy traded are higher.[20]

From this overview of the Dutch electricity markets, we can conclude that there is potential to generate revenue using storage in most time-frames. However, this revuenue should exceed the cost of storage to be viable. Next, it is investigated what storage technologies are available in section 2.4.

2.4. Overview of storage technologies

A plethora of technologies is available for energy storage. Each technology has very different characteristic making it suitable for certain applications. Therefore, it is important to match a certain technology to the market characteristics in which it operates. An important factor is the time frame for which the technology is suited to store energy, as shown in fig. 2.2. This section will describe the available storage technologies and their characteristics.

2.4.1. Pumped hydro storage

The most widely spread form of large scale grid-connected energy storage is pumped hydro storage. Pumped hydro storage uses a large dam with a lake behind it to store energy by pumping water up to a greater height. This technology accounts for over 99% of the energy storage capacity worldwide.[9] Unfortunately, pumped hydro is extremely dependent on geographical features such as large height difference and surface area to be implemented. Most suitable locations for pumped hydro storage, like large rivers with large elevation changes, are already exploited. Furthermore, the Dutch landscape's flat and densely populated nature makes it unsuitable for using pumped hydro. This study will therefore not consider Pumped hydro storage as a suitable option for the Dutch market.

2.4.2. Compressed air energy storage

A different form of mechanical energy storage is Compressed Air Energy Storage (CAES). In this technology, energy is stored by compressing air to hundreds of bars and stored in a tank or underground in geographical features such as salt caverns. CAES can also use a depleted natural gas field. However, in this case, only nitrogen should be stored as the oxygen in the air can form an explosive mixture with the natural gas. This technology is called compressed Nitrogen Energy storage (CNES). CNES loses efficiency due to the air separation, which is required to get pure Nitrogen to compress as this extra system also increases cost. Exact number for efficiency and cost of a CNES system are not available and very location dependent. CNES will likely not be a viable option in the near future[24]. Conventional CAES uses the combustion of natural gas to preheat the air before it enters the turbine. The combustion of natural gas releases CO_2 and can therefore not be considered sustainable. This can be solved by combining CAES with thermal energy storage, called Adiabatic CAES (A-CAES). In this process, excess heat from the compressed gas is stored and later reused to heat the gas before it enters the turbine. This process also increases efficiency, up to 70%, and shows great potential for large scale storage[10, 25]. The Netherlands has a lot of potential in terms of salt caverns[26]. However, due to the geographical dependence of an underground storage medium, this storage medium is difficult to co-locate with renewable energy generation as the location of the cavern might not be ideal for solar or wind generation. It is likely more suited for centralised energy storage such as the 300MW CAES plant, currently being developed at the Zuidwending in Groningen.[27] As co-location of CAES and wind and/or solar generation is often not possible, CAES will not be investigated further in this study.

2.4.3. Battery energy storage

From mechanical storage, we move to electrochemical storage, e.g., batteries. In this category, we find conventional technology such as lead-acid batteries and modern technologies such as Li-ion batteries and redox flow batteries. The advantage batteries have over mechanical storage is that they require far less to even no moving parts, allowing them to ramp up and down their power output more quickly. Furthermore, these technologies allow for higher energy and power densities both in gravimetric and volumetric terms, which makes them more suitable for mobile applications.[9, 10]

Lithium-ion batteries are being used more and more in small applications such as mobile phones and large applications such as electric vehicles and even grid-scale storage pilot projects. An example of such a pilot project is the 12 MW Project GIGA Rhino, which is to be built in the Netherlands[28, 29]. Due to this increase in production volume, Lithium-ion batteries have made a rapid drop in price over the past years, and their prices are expected to drop further in the coming years[30]. The main downsides of Li-ion batteries are their relatively short lifetimes, both in cycles as well as in calendar years, and the inability to scale the storage capacity and the power of the system independently.[12] Finally, the maximum energy capacity of Li-ion batteries is minimal, which makes them unsuitable for keeping the grid running in the order of days. [9, 10]

Redox flow batteries solve some of the disadvantages of Li-ion batteries. This is achieved by using a liquid electrolyte stored in tanks instead of inside the cathode and anode, thereby reducing stress on the material. This way, cycle life is increased to over 50000 cycles and 15+ years[10]. For this reason, redox flow batteries seem like the ideal candidate for grid-scale storage, however, the technology is still very immature, and production has not scaled up like Li-ion production has, meaning the capital cost is still very high[9, 12].

Batteries have to potential to be very useful in grid-connected energy storage. However, due to their high costs, it is uncertain whether they can generate enough revenue to cover these cost. Their operation in the market will be discussed in section 2.5

2.4.4. Chemical energy storage (Power-to-X)

The final form of energy storage is in the form of chemicals. The most widely spread of these technologies is known as power-to-gas in the form of hydrogen electrolysis. Here water is split into hydrogen and oxygen using electricity. Three types of electrolysis exist; alkaline electrolysis, PEM electrolysis and solid oxide electrolysis. Alkaline electrolysis is the most mature of the three technologies; however, it has limited capability in ramping up and down hydrogen production. PEM electrolysers are at a stage of maturity where they are starting to scale up. PEM electrolysers have better ramping performance than alkaline electrolysers and can even be switched off completely. Solid oxide electrolysers have the highest efficiency of the electrolysers, but they are still on an experimental scale, and they operate at high temperatures, so they have poor ramping performance.[31] Hydrogen can be stored and later used in a fuel cell or turbine to be converted back to electricity. Hydrogen can also be sold directly as a fuel or as a feed-stock for industry. Current developments in hydrogen technology are discussed in section 2.6

Hydrogen from water electrolysis is one of the energy storage technologies which shows the most potential, furthermore it can serve as a feed-stock in industry replacing hydrogen produced from natural gas, directly reducing CO2 emissions. Despite the promising prospects of hydrogen and high technical readiness level large scale water electrolysis is not a reality in the Netherlands.

In conclusion, CAES, Batteries and hydrogen storage can all be used in grid connected storage. The challenge is in finding a way to make their operation in the market economically viable. The next section will give an overview on what research has already been done in the field of grid-connected energy storage systems.

2.5. Literature on grid-connected energy storage systems

The use of grid-connected energy storage systems has been researched quite extensively. This section summarises the findings from this research. Finally, the technology showing the most potential is found to be power-to-gas in the form of hydrogen in combination with wind power and solar PV.

Lithium-ion batteries have been studied extensively, especially for energy arbitrage and grid balancing and a method to reduce the required grid connection capacity. Hugenholtz [12] explores the competitiveness of battery energy storage systems and concludes that even though revenue can be generated, the capital cost of Li-ion batteries is still too high to be profitable. Another important insight from this research, is the fact that capital cost is more important than system efficiency. Brouwer [11] also investigates the effect of co-location with a hybrid wind and solar plant. He concludes that Li-ion batteries are very promising but not yet profitable in the Dutch market, even with a limiting grid connection. Sijtsma [32] Also investigates co-location with an onshore wind farm and concludes that less expensive batteries are needed to be competitive.

The aforementioned research focuses mostly on the wholesale markets, but also the ancillary service markets have been studied extensively, Slooff [13] investigates the competitiveness in the Belgian capacity market and concludes that a battery storage system might be competitive in the Belgian market. However, he also mentions that the prices in the FCR are expected to fall, reducing competitiveness. Efthymiou *et al.* [15] investigates the profitability in multiple European markets and concludes that a positive Net present value (NPV) and Internal rate of return (IRR) are possible. NPV and IRR are financial terms to describe an investment's performance, positive NPV and sufficient IRR indicate that the investment is profitable and creates sufficient returns. However, their method uses a very simplistic model for battery degradation, which does not consider the battery's cycle life. Taking into account this cycle life will likely decrease the battery lifetime and reduce the profitability of the system significantly. Okur *et al.* [14] takes a decentralised approach to serving the Dutch FCR and also report that battery prices are too high to be profitable.

Finally, Visser [18] investigates the possibility of value stacking of selling to multiple markets, but he reports that this comes with little added value to regulatory constraints. All research leads to one conclusion, Li-ion batteries are promising but still too expensive. The price predictions made by Goldie-Scot [30] give hope that grid-connected energy storage might be feasible in the future, but at this moment, the market is not there yet. As plenty of research is done on batteries, and all conclude that they're not competitive yet, this technology is not chosen for this study.

Redox flow batteries show the most potential for energy arbitrage in the Dutch market Hugenholtz [12]. They have the potential to be profitable when they are operated perfectly, meaning with 100% accurate predictions of what the market will look like in the future. In reality this is not the case, reducing the revenues to non-profitable levels. Redox flow battery technology should first mature, and the capital cost should decrease, before large-scale implementation is possible.[9, 12]

Traditional compressed air energy storage is a very mature technology; the first commercial plant is in operation since 1978. These systems are mostly used for black starts and backup capacity, not for energy arbitrage.[9] The economics of CAES in combination with VRES, especially wind power, are researched extensively. Mauch *et al.* [33] investigates the profitability of a combined wind-CAES plant in the day-ahead market of the early 2010s in the US. They concluded that a wind-CAES system is unlikely to be profitable in the DAM. Ummels [34] comes to the same conclusion in the Dutch electricity system. More recent studies by Lloyd [35] concludes that Adiabatic CAES provides a good alternative for Diabatic CAES and Pumped hydro. Furthermore, it offers good integration with wind energy and shows good potential in the Netherlands.[26] However, due to the extremely location dependent nature of the storage capacity and cost, it is very difficult to co-locate with wind power generation.

Power-to-gas or, more specifically, power-to hydrogen is also seen as a good candidate for long term grid-connected energy storage. Moreover, a great demand for hydrogen already exists in the industry, producing it mostly from natural gas emitting tonnes of CO_2 . Therefore, in the current market, green hydrogen needs to compete with hydrogen made from natural gas. Several studies have been performed, analysing the profitability of power-to-hydrogen systems, especially in combination with wind power generation. Jiang *et al.* [16] investigates wind generation in combination with a PEM electrolyser, hydrogen storage and PEM fuel cell in the Nord Pool (Scandinavian) market. They conclude that in all cases, it is more profitable to sell hydrogen as is than to use a fuel cell to generate electricity from the hydrogen. An electrolyser can be used to smooth wind farm output and thus create an economic benefit this way as well. From hydrogen price of €4.3 per kg, it becomes economical to install an electrolyser in this type of system. Xiao *et al.* [17] proposes a similar wind-hydrogen system in the Danish market, similar to Jiang *et al.* [16], they concluded that profitability is very sensitive in changes to hydrogen price. Xiao *et al.* [17] also concludes that a hybrid wind-hydrogen is worth further investigation.

From the research that has been performed on grid-connected energy storage, power-to-hydrogen shows the most positive results. Policy and infrastructure changes also provide opportunities for power-to-hydorgen. This will be discussed in the next section.

2.6. Opportunities for power-to-gas in the form of hydrogen

Hydrogen is a topic which is mentioned increasingly in regards to its ability to reduce CO_2 emissions. This section will present an overview of the current hydrogen markets and how they might change in the near future. Subsequently the plans regarding hydrogen policies and infrastructure are discussed.

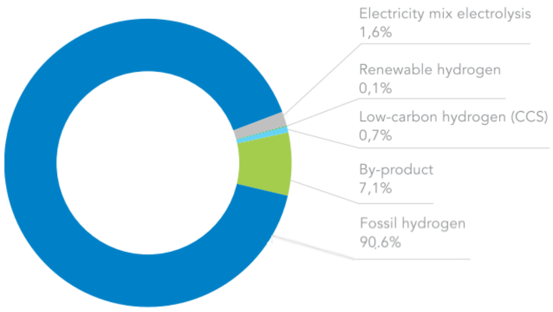
2.6.1. The current hydrogen market

A major influence on the competitiveness of the hybrid plant is the development of the hydrogen market. At the moment of writing this thesis, no wholesale Hydrogen market exists. All hydrogen is either sold bilaterally or produced on-site. This, however, does not mean that hydrogen is not used in large quantities. In the European Union, the total hydrogen use was approximately 8.3 Mt in 2018. The Netherlands contributed 14% to this Hydrogen demand, approximately 1.16 Mt of Hydrogen. As shown in fig. 2.3b, the largest share of this Hydrogen demand comes from refineries. They use 45% of all hydrogen, the second largest user of hydrogen, the ammonia industry used 34%. Another figure that stands out is that the transport sector takes up 0% of the hydrogen demand while hydrogen is often promised to be the fuel of the future.[36] This could be a sign that the demand for hydrogen will only grow.

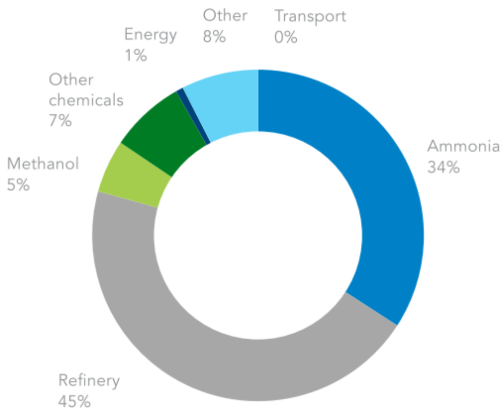
Furthermore, fig. 2.3a shows that most of this hydrogen is still sourced from fossil fuels. For 90.6 % of the Hydrogen production, the CO_2 is released into the atmosphere (grey hydrogen) and only 0.7% of hydrogen is produced with CCS, carbon capture and storage (blue hydrogen).

The hydrogen prices also vary significantly, ranging from 1.4 €/kg for large quantities and up to 30 €/kg for small quantities of very pure hydrogen. This price of hydrogen is very dependent on the cost of transport and the purity of hydrogen. The price of large volumes of hydrogen used in industry is set by hydrogen production from Steam methane reforming (SMR). [36] An electrolyser producing hydrogen will therefore have to compete with SMR installations.

The production cost of hydrogen through SMR is dependent on many factors, the most important ones being the price of CO_2 emissions rights and natural gas prices. This is because SMR uses natural gas to create hydrogen, releasing CO_2 in the process. Next to these variable costs, the fixed costs also affect the final cost of hydrogen. Mulder *et al.* [37] studies the future of the Dutch hydrogen market and creates a relation between natural gas, CO_2 and Hydrogen prices for grey Blue and Green (from green natural gas) hydrogen. This relation can then be combined with the predictions for natural gas and CO_2 prices to forecast the Hydrogen price in the future.



(a) Hydrogen supply sorted by production type.
Source: Hydrogen Europe



(b) Hydrogen demand demand sorted by en user type.
Source: Hydrogen Europe

Figure 2.3: Hydrogen supply and demand data in the European Union.

Source:Hydrogen Europe [36]

2.6.2. Industry shifts towards hydrogen

Besides the existing industries working with hydrogen, new users of hydrogen are also emerging. Hydrogen is seen as one of the most important energy carriers of the future. It has the potential to revolutionise several sectors, including energy-intensive industry and transport.

The steel industry

A great example of a potential major user of hydrogen in the steel industry. Responsible for 4% of the CO_2 emissions in Europe and 9% worldwide, it is one of the most polluting industries.[38] The steel industry could replace a large amount of coal used with hydrogen from renewable sources. This could reduce the carbon footprint of the steel industry significantly. The technology required to do this is already largely understood, and pilot plants are being set up.[38] Therefore, it is likely that the demand for hydrogen from the steel industry will increase in the near future.

The transport industry

The transport sector is also thought to be a major contributor to the hydrogen demand. Hydrogen can play a key role in nearly all forms of transportation. In the future, hydrogen will both be used as a fuel directly and as a feed-stock to create more energy-dense fuels.

Energy density is one of the most important aspects when choosing an energy source in the transportation sector. Two distinct kinds of energy density can be identified; gravimetric energy density and volumetric energy density. The gravimetric energy density, formally referred to as specific energy, is the amount of energy contained in a substance or device (batteries etc.) for a certain mass. The volumetric energy density indicates the amount of energy contained in a certain volume of a substance or device. Specific energy is often given in $\mathrm{kW\,h\,kg^{-1}}$, the (volumetric) energy density is often given in $\mathrm{kW\,h\,m^{-3}}$. In transport, a higher energy density will allow the vehicle to transport more payload as less volume and/or mass is occupied by the fuel.

Hydrogen has an extremely high specific energy with a higher heating value of $141.80\,\mathrm{MJ\,kg^{-1}}$ this makes it suitable for many transportation applications. However, hydrogen has a relatively low volumetric energy density. Hydrogen can be used directly in road, rail and small maritime transport. It is, however, not suitable for aviation and long-distance shipping due to the low volumetric energy density

In road transport, hydrogen mostly plays a role in heavy transport such as busses and lorries. In small road transport such as passenger cars, batteries offer sufficient energy density. Still, for larger, heavier transport, hydrogen is a better option as it allows these vehicles to have a longer range and carry more load. [39]

In the maritime industry, hydrogen can be used as a fuel for small and medium-sized shipping. Ammonia, which can be derived from hydrogen, can be used for long-distance freight shipping. [40]

Besides the steel industry and the transport sector, many other industries are also looking to shift their energy demand to hydrogen. This indicates that the demand for hydrogen will only grow, potentially increasing the price for hydrogen.[36] This could increase the profitability of an electrolyser significantly.

2.6.3. Hydrogen infrastructure developments - Hydrogen Backbone

At the time of writing, no infrastructure is available yet for the large scale transportation of hydrogen. This is likely part of the reason no wholesale hydrogen market exists either. However, there are plans for large scale Hydrogen infrastructure in the Netherlands.

In 2019 the Dutch transmission system operators Gasunie and Tennet presented an outlook on the Dutch energy infrastructure. This report shows that hydrogen will play a major role as an energy carrier in the Netherlands[41]. Then in Mid 2020 a collective of European gas infrastructure companies, including the Dutch Gasunie, presented the "European Hydrogen Backbone"[42]. This report details their plans to roll out a network of Hydrogen pipelines throughout Europe. This network will consist of a mix of re-purposed natural gas pipelines as well as new hydrogen pipelines. This will ensure the system can already be partially operational in the mid-2020s [42]. Gasunie aims to have a regional backbone operational by 2026, a national backbone by 2028 and a connection to international Hydrogen infrastructure by 2030[41]. These investments in infrastructure will help the hydrogen economy grow and allow a more liquid hydrogen market to form.

The Netherlands is one of the leading countries in the field of hydrogen according to the "Clean Hydrogen Monitor 2020" by Hydrogen Europe [36] due to the ambitious policies surrounding hydrogen. The SDE++, "subsidie Stimulering duurzame energieproductie en klimaattransitie", presented in 2020 offers a subsidy for the production of hydrogen through electrolysis. This subsidy offers a premium on the market price of hydrogen to increase its competitiveness with hydrogen produced from natural gas[43].

2.6.4. Electricity market developments

How the electricity market develops is a key factor is the development of grid-connected energy storage as well as power-to-hydrogen systems. This is caused by the fact that hydrogen production is very energy intensive. The production cost of green hydrogen is directly related to the cost of electricity. The price of electricity should be sufficiently low in order to offer a competitive hydrogen price.[37]

The electricity market is inherently challenging to predict. The "klimaat en energie-verkenning", which will be referred to as KEV, provides price predictions for electricity and other energy sources.[44] This report is a joint effort from several Dutch government organisations to describe the Dutch greenhouse gas emissions and the energy system for developers. From this report, it becomes evident that many factors play a role in setting the price of electricity.

The first effect on electricity prices is the increased fuel prices. Increased fuel prices cause higher marginal costs of electricity production, which mean higher bids. These higher bids will cause the electricity price to increase. Especially the price of natural gas has a significant effect on the price of electricity in the Netherlands as natural gas-fired power plants are often the price-setting technology.[5]

The second effect is caused by the increased prices of CO_2 emissions. Similar to increased fuel prices, increase CO_2 prices will increase marginal costs. The increased marginal cost will again increase the overall electricity price.[37, 44]

The third effect is caused by the increased penetration of variable renewable energy supply on the market. Variable renewable sources such as solar and wind energy have a marginal cost of close to zero. Therefore renewable energy supplier offer energy to the spot market at a price which is practically zero. This means that the supply curve will shift to lower prices, thus decreasing the resulting market price.[5]

The fourth and final effect is the increase in energy efficiency by various systems. An increase in efficiency will cause a decrease in the energy demand. This decrease in demand will shift the demand curve to meet the supply curve at a lower market price.[5]

The way the electricity price develops in the coming years is very important for the competitiveness of an electrolyser and PV system. These developments and the uncertainties in these price developments will therefor be taken into account in this study. It is unclear which effect, mentioned in this section, will take the upper hand. This causes a large amount of uncertainty regarding electricity prices. The KEV gives forecasts of the wholesale electricity prices, which contain a bandwidth to account for this uncertainty. Both this prediction and the band width of the KEV are used to evaluate the hybrid plant system is this study. The KEV will also be used for predictions regarding the natural gas and CO_2 emissions prices.

2.6.5. Potential benefits of co-located renewable energy generation and electrolyser

Next to the developments in the market, an additional benefit can be gained from the co-location of a wind farm, solar farm, and electrolyser system. In other words, the combined system has greater value than the sum of its parts.

As mentioned in section 2.1, the electrical grid is getting more and more congested. This congestion causes a number of issues, including curtailment of renewable energy and limits on the expansion of renewable energy projects. Co-location of a wind solar and electrolyser plant could resolve some of these issues. A wind farm only uses its grid connection when it is producing electricity. Assuming the farm has a capacity factor of 0.4, meaning the wind farm only runs at 40% of its maximum capacity on average, the connection is not used for the majority of the time. The addition of a solar farm and an electrolyser could make use of this unused grid capacity.

When a large solar PV farm is added to a wind farm, some energy will likely still need to be curtailed when the solar and wind farm reach their peak generation at the same time. However due to the seasonal nature of both, wind is mostly available in winter and solar is available mostly during the summer, this will likely not happen frequently. If excessive curtailment does occur this can be counteracted by the electrolyser.

The added electrolyser can use excess energy, which would otherwise be curtailed, to produce hydrogen at low cost. In theory this should allow more PV to be added to the system without excessive curtailment. This will in term make the PV system more profitable. Next to reducing curtailment the electrolyser can also use the grid connection to import electricity to create hydrogen allowing it to be used more frequently.

Finally, Co-locating a wind and solar farm with an electrolyser could reduce this uncertainty by providing an alternative source of income through hydrogen sales. The hydrogen produced by the electrolyser can likely be sold for a more stable price.

2.7. Knowledge gap

Hydrogen can be considered as one of the most promising 'green' energy carriers of the future. Using electrolysis to produce hydrogen would allow for long-term, bulk storage of variable renewable energy, allowing further integration of wind and solar power. From the literature, we can conclude that there is potential for a successful business case for Hydrogen production from electrolysis. This is because there is an already large and growing hydrogen market, the infrastructure for hydrogen is being built and policies are put in place to support green hydrogen production.

There is little research regarding the optimal operation of an electrolyser in the Dutch market. Moreover, there is no research on combining a wind farm with a solar farm and electrolyser in the optimal configuration. This combination should in theory be more competitive than the sum of its parts. Therefore, this thesis will evaluate and optimise the competitiveness of a combined wind and solar farm with an electrolyser, serving the Dutch electricity and hydrogen market.

The results from this research can be used as a guide for developers to build and operate this hybrid plant. It will also highlight the improvements that are needed in electrolyser technology to be more competitive. Furthermore, if a successful business case can be found, this could serve to increase the scale and quantity of hydrogen electrolyser and solar PV systems in the Netherlands. This could help accelerate the energy transition.

3

Research question & approach

This chapter presents the research objective as well as the research questions. Each question is first presented in section 3.1 and then elaborated in section 3.2.

3.1. Research objective and the main question

This study aims to develop a method to evaluate and optimise the competitiveness of a hybrid plant in the Dutch market. This hybrid plant system consists of the following components;

- A wind farm that can use the wind to generate electricity
- A solar PV farm that can use the incoming solar radiation to generate electricity
- An electrolyser which can convert electricity and water into hydrogen, using electricity
- A grid connection through which electricity can be exported to and imported from the electricity market
- A connection to a hydrogen infrastructure through which hydrogen can be exported

This system will be able to serve both the electricity as well as the hydrogen market. It has the ability to switch between hydrogen production and the direct sale of electricity to maximise Net Present Value. The system will also be able to import electricity to produce hydrogen.

The main question this thesis aims to answer is the following:
Q. *What is the most economically competitive configuration of a PV system and/or an electrolyser added to an existing wind farm, trading on the Dutch electricity and hydrogen market under different scenarios?*

To answer the main question, the following sub-questions are formed:

1. How can the competitiveness of a hybrid plant be accurately modelled
2. How can the configuration of a PV system and an electrolyser added to a wind farm be optimised?
3. Which external factors influence the optimal system configuration and competitiveness?
4. How will the markets, and system parameters develop under different scenarios?
5. How sensitive is the optimal system to changes in the markets and system parameters and other assumptions?

These questions are chosen to create a better understanding of the problem and main question. Furthermore, answering these sub-questions will provide the data to answer the main question. The next section will discuss the relevance and approach that will be taken to answer each sub-question. The combination of a wind farm, solar farm and electrolyser will be called a hybrid plant.

3.2. Research approach

The relevance of each sub-question and the approach is taken to answer it are set out in this section.

3.2.1. How can the competitiveness of a hybrid plant be accurately modelled

To evaluate and optimise the competitiveness, it needs to be identified how the hybrid plant functions. To do this, the assets of the hybrid plant need to be determined and their characteristics identified. Then the operation of the hybrid plant can be analysed by evaluating the sources of revenue and costs.

The approach to defining competitiveness will take place in three steps. Firstly the stakeholder, as well as the consumer values, will be defined. From this, the important figures such as financial returns and reduction in CO_2 can be defined. Secondly, the competitors will be identified, and an image of the competitive environment created. For an electrolyser, these competitors include other methods for the production of hydrogen. Finally, the markets in which the hybrid plant operates will be investigated. The electricity market and hydrogen market are analysed to identify how they might change in the future and alter the competitiveness of the hybrid plant.

3.2.2. How can the configuration of a PV system and an electrolyser added to a wind farm be optimised?

To find the most competitive configuration for the hybrid plant, the configuration needs to be optimised. The hybrid plant will have a fixed wind generation capacity and grid connection. The optimal configuration consists of three things; electrolyser technology, the electrolyser and PV capacity, and the optimal operation of the plant. An optimisation model is made to optimise the sizing and operation of the system throughout its entire lifetime to generate maximum Net Present Value.

To chose the optimal electrolyser technology, all possibilities are identified and compared. As mentioned in section 2.4, the three main technologies are alkaline, PEM and solid oxide. Alkaline and PEM will both be optimised and compared as choosing between the two can not be done qualitatively. Solid oxide electrolysers are not evaluated as they are not suited for an intermittent operation like the hybrid plant demands.

The electrolyser capacity and solar PV capacity will be optimised using cost projections and revenue projections as well as a case study. This case study will be used to get realistic data for these capacities as well as realistic generation data for the wind and solar farm. Ventolines will provide this data. The model will optimise for NPV considering revenues from electricity and hydrogen and costs from the electrolyser and PV system. It will do this by changing the size of the electrolyser and PV system as well as the way it is operated.

The hybrid plant is able to use electricity to create hydrogen and export it, export and import the electricity to and from the grid, or curtail electricity generation. The optimisation is able to optimise these actions using electricity and hydrogen price data and solar and wind generation data. The results of this daily operation will give an indication of how the system should be operated and at what moments hydrogen should be produced.

The parameters which are optimised are internal parameters that can be controlled by the design and the operation of the hybrid plant. However, the competitiveness of the hybrid plant is dependent on many factors which can not be controlled, and these will are addressed in section 3.2.3.

3.2.3. Which external factors influence the optimal system configuration and competitiveness?

The hybrid plant operates in several markets and consists of a number of assets that incur costs. To evaluate the competitiveness of the hybrid plant, these external factors need to be identified and quantified. These external parameters can then be used as inputs to the optimisation model to find the optimal sizing and operation for the set of external parameters.

As there are many external parameters that can all take different values, analysing all combinations is impossible. Therefore, scenarios are made to create consistent sets of inputs to run the optimisation model.

3.2.4. How will the markets and system parameters develop under different scenarios?

The optimisation model requires a large amount of data, electricity prices, hydrogen prices, electrolyser cost, etc. This data is based on forecasts which are in turn based on assumptions. These assumptions can then be connected to the scenarios discussed in section 3.2.3.

Using a combination of historical data and market and cost forecasts, data for future markets can be generated. This data can then be used combined with forecasted solar PV and electrolyser parameters to run the optimisation model for years in the future. This can then indicate how the competitiveness of the added PV system and electrolyser change over time.

3.2.5. How sensitive is the optimal system to changes in the markets and system parameters, and other assumptions?

A large number of assumptions need to be taken in order to create the scenarios and run the optimisation. Some of these might not be valid; therefore, it is essential to analyse the sensitivity of the optimum to these assumptions.

Finding the parameters to which the system is most sensitive will aid in identifying where more research is necessary. This research could be aimed improving electrolyser technology in terms of efficiency, cost etc. But it could also be directed at improving the understanding of the market and thus improving market forecasts.

The questions in presented in this chapter will form the basis for the rest of this report. Each following chapter will aim to answer one of the questions presented above.

4
Research method

This chapter presents a detailed description of the hybrid plant assets and operation. This way it aims to answer the sub-question: *How does the hybrid plant function and operate in the market?*. Then the competitive environment in which the hybrid plant operates is evaluated and the reasoning for optimising the NPV of the hybrid plant presented in section 4.2. The optimisation model used to optimse the hybrid plant is introduced in section 4.3. The data which is required to run the optimisation of the hybrid plant is set out in section 4.4. Finally section 4.5 will explain how the tools presented in this chapter will be used to answer the research questions presented in chapter 3.

4.1. Description of the hybrid plant

The idea of the Hybrid plant is to take an existing wind farm with an existing grid connection and add to this a solar PV farm and water-splitting electrolyser to produce hydrogen. This method can be applied to all onshore, near shore and offshore wind farms, provided that floating PV can be installed. In this thesis Wind Park Fryslân is chosen as a case study to evaluate such a system. All components of the Hybrid plant are set out in section 4.1.1 and the way the hybrid plant is operated to generate profit is set out in section 4.1.2.

4.1.1. Assets of the hybrid plant

A schematic overview of the hybrid plant is given in fig. 4.1. The hybrid plant consists of 3 main parts, wind farm, solar PV farm and electrolyser. These parts are connected to a transformer station which converts the power to the right voltage and frequency to be exported to the grid. This transformer station can also be used to redirect the power from the solar and/or wind farm to the electrolyser. Next to export the transformer station can be used to import energy from the grid to run the electrolyser or control the wind turbines while idling.

The electrolyser can be divided into two parts, the electrolyser stack and the Balance-of-plant (BOP). The stack contains the membranes at which water is split into Hydrogen and Oxygen. The BOP is everything needed to keep the stack running within its operational window. The most important parts of the BOP are the water purification system, the gas liquid separators, heat-exchangers and power electronics. These make sure the electrolyser stack does not get contaminated, hydrogen and oxygen are extracted and the stack operates at the right temperature, potential and current density.

4.1.2. Operation of the hybrid plant

The hybrid plant can be operated in many ways and has many potential sources of revenue. The wind and solar farm can generate a certain amount of electricity based on the weather, when the wind blows the wind turbines can generate electricity and when the sun shines the solar PV panels can generate electricity. This generation can also be curtailed to allow for some control over the energy output. However this curtailment can only reduce the generation and not increase it.

The generated electricity then has 2 ways to go, it can either go directly to the grid where its is sold on the EPEX spot market for the spot price at that moment. Or the electricity can be sent to the electrolyser where it will be used to split water into hydrogen and oxygen.

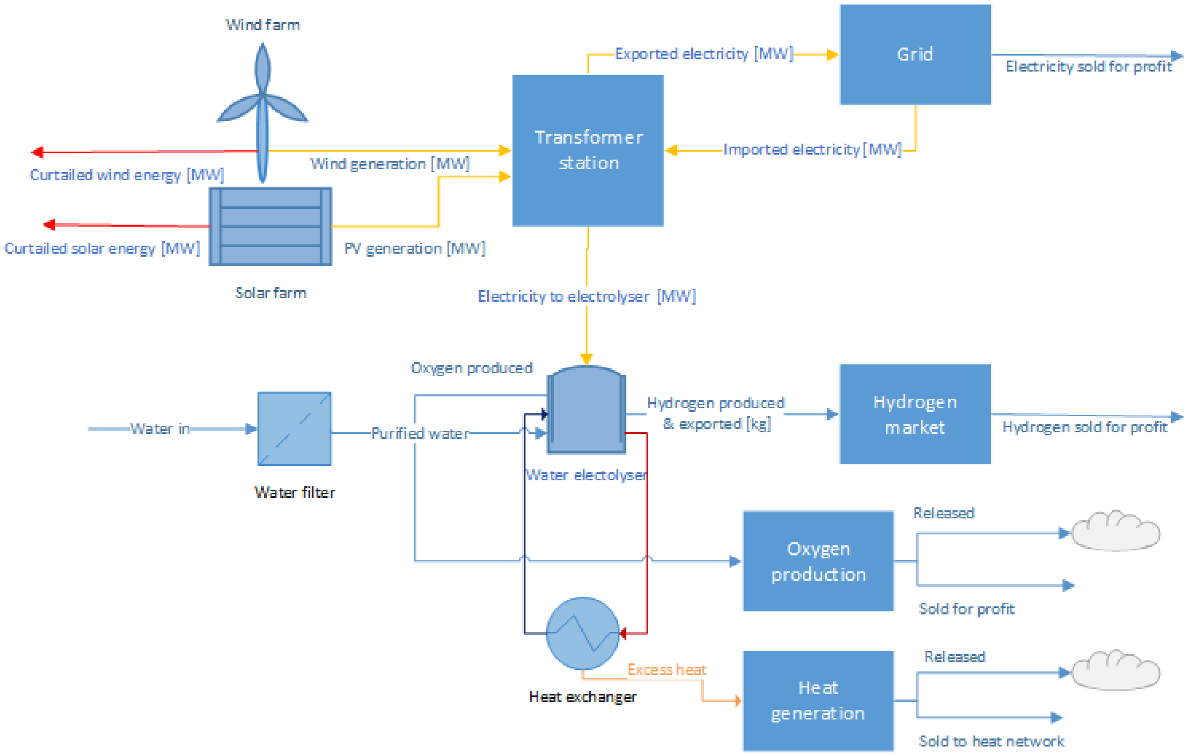


Figure 4.1: Hybrid plant assets and operation

The electrolyser receives electricity from the wind and solar farm or imported from the grid. The electrolyser has 3 outputs, Hydrogen, Oxygen and heat. Hydrogen can be sold via a hydrogen pipeline or other form of transportation to the consumer. Oxygen can either be sold, similar to hydrogen or be released into the atmosphere. Finally the heat could be exported to a heat network and used for heating the residential or commercial sector. The final way in which the electrolyser can create a revenue is by using it to balance the output of the hybrid plant to the grid, reducing imbalance cost.

The sales of oxygen and heat are extremely location dependent and as such not taken into account as a form of revenue in this study. Furthermore the balancing properties of the electrolyser are not taken into account as a source of revenue. It is assumed the oxygen and heat produced by the hybrid plant are released into the atmosphere.

4.1.3. Dealing with internal and external variables

The complexity of the hybrid plant causes its performance to be dependent on many variables. Some of these can be controlled such as the sizing and operation of the hybrid plant while others are uncontrollable, like the market parameters. Both types of variables are dealt with differently. The internal, and thus controllable variables are optimised to generate the maximum NPV as explained in section 4.2.4 and section 4.3. The system will be optimised for a set op external and thus uncontrollable variables. The external variables are simulated using historical data, market forecasts and research scenarios. The external data which is required and the method used to obtain this data are detailed in section 4.4.

4.2. Definition of competitiveness

No universal definition of competitiveness exists, therefore it needs to be defined how competitiveness is evaluated in this study. Rainer Feurer and Kazem Chaharbaghi [45] states that in order to be competitive an organisation has to cater both to customer as well as shareholder values.

4.2.1. Customer values

A customer values an organisation based on benefit and price as shown in eq. (4.1). An organisation is considered competitive if it is able to offer more customer value. This can be achieved either by offering the same benefit at a lower price or by justifying a higher cost with more benefit.[45]

In the framework of the Hybrid plant, the organisation offers 2 products, Electricity and Hydrogen. Electricity can be considered a homogeneous good as one kW h of electricity is no different from any other kW h. For Hydrogen this is not necessarily true as there are multiple specs for the purity of hydrogen which can have a different value. In this thesis it is assumed that hydrogen will be sold to industry for which does not require highly pure hydrogen, therefore the added benefit of extremely pure hydrogen is neglected. Currently the dominant technology for Hydrogen production is steam methane reforming (SMR), as the benefit of the Hydrogen sold by the Hybrid plant is the same as the hydrogen from SMR it is assumed that the price should also be the same as SMR.[45] More information on the Hydrogen market and how it is expected to develop can be found in section 2.6.1

One way in which both hydrogen and could be considered a heterogeneous good is in the field of negative externalities to the environment. Many forms of electricity production as well as for hydrogen production through SMR, CO_2 and other greenhouse gasses are emitted into the atmosphere, changing the climate. Two methods are used to indirectly value these externalities. The first one is in the form of the European Emissions trading system which adds a cost to every ton of CO_2 emitted.[46] The second is in the form of a subsidy for renewable energy and Hydrogen production from electrolysis in the SDE++.[43] The ETS price increases the price of hydrogen produced by competitors while the SDE++ subsidy add extra revenue to the hybrid plant to increase its profitability.

$$customerValue = \frac{Benefit}{Cost} \tag{4.1}$$

4.2.2. Shareholder values

Next to creating customer value, an organisation should also be able to generate shareholder value in order to be competitive. As Rainer Feurer and Kazem Chaharbaghi [45] describes it; ”An organization is competitive in the eyes of its shareholder if it is able to provide a satisfactory return on investment in the short, medium and long terms.” Another important factor for the assessment of shareholder value is the risk associated to the expected profits. A more risky investment will require a larger return than a more certain investment. Hence, the competitiveness of the Hybrid plant is defined as the ability of the hybrid plant to generate profit and a return on investment throughout its lifetime.

Financial returns and risk are not the only factors which play a role in shareholder decision making. Technological development which can generate a profit in the more distant future can be a deciding factor for project with a low expected return.Rainer Feurer and Kazem Chaharbaghi [45] This value of the hybrid plant is not taken into account in this study.

To account both for the financial return and the risks associated with the Hybrid plant the Net Present Value of the system was chosen as the measure of competitiveness. More on the risks and why NPV is used in section 4.2.3 and 4.2.4 respectively. To give the hybrid plant the best chance of success the sizing and operation of the system are optimised for Net Present Value. The way this optimisation is performed is set out in chapter 4.

4.2.3. Risks

The financial risk related to the Hybrid plant can be split in 2 parts, the costs of the hybrid plant and the revenues of the hybrid plant. Investment risk, such as devlopment risks are not taken into account in this study.

The hybrid plant generates electricity from solar and wind energy both of these do not use fuels and thus do not add variable cost to the system. The electrolyser uses water to operate, this water is only an extremely small fraction of the cost and can therefore be assumed as negligible. The only uncertain cost which remains for the hybrid plant is the cost of maintenance to the assets of the Hybrid plant.

The risks related to the revenues generated by the hybrid plant are far greater. The Hybrid plant is able to generate profit in 2 ways, by the sales of electricity to the dutch EPEX spot market and by using this electricity to produce hydrogen which can then be sold as a product. The 2 risks are therefore the electricity and hydrogen market price. Both these prices affect the revenue of the hybrid plant directly.

One of the major benefits of the Hybrid plant is its flexibility to switch between the 2 streams of revenue. If the electricity price is low the system can switch to producing more hydrogen and when the electricity price is high the system can produce less hydrogen. The same holds for a low hydrogen price, which will cause the system to decrease hydrogen production. The same would happen is the hydrogen demand were to drop suddenly. The way these markets are expected to develop is set out in chapter 7

4.2.4. Net present value

The method of Net present value allows the for the evaluation of investments based on their expected cashflows and risks. Equation (4.2) is used to calculate the NPV. The net future cashflows (NCF) are discounted to the moment of investment using a set discount rate (d). This discount rate is dependent on the risk related to the project, riskier projects will have a higher discount rate. The net cashflows consist of the income form the exports of electricity and hydrogen minus the costs of the system operation and maintenance and the cost of imported electricity.

$$NPV = \sum_{t=0}^{n} \frac{NCF_t}{(1+d)^t} \tag{4.2}$$

A NPV of zero indicated that the internal rate of return of the project is exactly equal to the discount rate. A positive NPV (NPV > 0) indicates that the project outperforms the discount rate. A negative NPV (NPV < 0) indicates that the returns of a project are less than the discount rate.

The NPV is not an absolute measure of competitiveness but it can be used in 2 ways. If a single investment is considered the investment should be made if the NPV > 0 as this increases the value of the organisation. Alternatively if several options are considered the NPV is used to compare the options, and the option with the highest NPV is chosen. In this case a negative NPV might be acceptable as other options are more negative. When comparing NPV it is important to compare options on a level playing-field as external factors will affect the NPV. [47]

In the context of the Hybrid plant there are many factors which can affect the NPV of the Hybrid plant. Both internal and external factors have a major impact on the hybrid plant performance. The external factors are summarised in chapter 7, sets of these external factors are compiled into 9 research scenarios in section 6.5. The major internal/control-able factors affecting the competitiveness of the Hybrid plant are the sizing of the PV system and the electrolyser system, and the operation of the hybrid plant. Therefore both the sizing of the hybrid plant as well as the operation throughout its lifetime are optimised for NPV. This way for each scenario the most competitive configuration and operation of the hybrid plant is determined.

Comparing the competitiveness for the systems between scenarios more difficult as the NPV of the wind farm will also change between scenarios. As the wind farm is fixed it is not part of the decision. Therefore the NPV of the wind farm will be subtracted from to total NPV to determine the NPV of the electrolyser and solar PV system. Comparing this NPV for different scenarios will give insight in how the different scenarios affect the competitiveness of the electrolyser and PV system.

The discount rate has a major effect on the NPV of a project, therefore it is important to choose the right discount rate. A method which can be used for projects with lower risk is setting the discount rate equal to the risk free rate of return.[48] However, for investments involving more risk, the discount rate should be higher. In the case of renewable energy projects a discount rate of 5% is more appropriate according to experts at Ventolines.

4.3. Optimisation model

An optimisation model is developed to optimise the net present value of the hybrid plant for a given set of external variables. The optimisation model runs over the entire lifetime of the electrolyser to capture all fluctuations and long term price trends. The optimisation model is free to optimise sizing of the hybrid plant components and the daily operation of the hybrid plant. The sizing consists of the size of the PV system and the electrolyser system, the size of the wind farm and grid connection are fixed. The operational parameters consist of a time-series of per hour data for the entire lifetime of the system. The optimisation is able to chose the amount of energy which is used to create hydrogen, exported to and imported form the grid and the amount of energy which is curtailed. This decision is made for every hour in the lifetime of the electrolyser system.

The generated income will be calculated by multiplying the amount of electricity and hydrogen with the instantaneous price of electricity and Hydrogen. The cost of the electrolyser system can be calculated from the electrolyser capacity and technology. The cost of the PV system is calculated in a similar manner. The optimisation runs over the entire lifetime of the electrolyser, however this is shorter than the lifetime of the PV system, therefore for the PV system the annual depeciation is taken instead of the total cost of the PV system. The lead time of the system is assumed to be one year, meaning there is one year between the investment and first year of operation of the system.

The optimisation model described is compiled in to a linear programming optimisation. This linear program is written in Python, usin the Pyomo optimisation library. A detailed description of the objective, bounds and constraints of the optimisation model and the software used is given in chapter 5.

4.3.1. Key assumptions

In order to limit the complexity of the optimisation model a few assumptions have to be made. This section will discuss these assumptions and their justification and implications.

1. Hydrogen is sold to the hydrogen market instantaneously.
   This assumption limit the need for an on site storage facility which would also need to be optimised therefore simplifying the model. This assumption simulates that the hybrid plant is connected to the hydrogen backbone or receives payout at the moment of exporting the Hydrogen to a tank truck at on location. [42]

2. The hydrogen price is set by the production cost of steam methane reforming.
   A transparent wholesale hydrogen market does not exist in the Netherlands yet, an alternative method was chosen to value the Hydrogen produced by the Hybrid plant. As it is assumed that the hybrid plant will sell to industry it is assumed to compete with hydrogen produced through steam methane reforming (SMR). This leads to the assumption that the hybrid plant will sell hydrogen at an equivalent cost to hydrogen produced through SMR. The cost of hydrogen through SMR is dependent on the natural gas and CO_2 emissions price.

3. The efficiency of the electrolyser is constant.
   A non constant efficiency would cause the system to become non-linear drastically increasing the computational intensity of the optimisation. In reality the efficiency the cell voltage and thus the efficiency varies linearly with the current density, mostly due to Ohmic losses.[31] To account for this a more conservative estimate for the efficiency was taken as the system will mostly run at full load when it decides to produce hydrogen.

4. Electricity can be exported and imported at the day ahead market price.
   The electricity produced by the hybrid plant can be sold and bought at the EPEX market price. no electricity will be traded with other markets. Electricity can both be imported and exported to allow the hybrid plant to operate as optimally using the cheapest energy available.

5. The cost of water for electrolysis can be neglected.
   Tap water in the Netherlands costs €0.79/m^3 or €0.00079/kg [49]. This comes down to approximately €0.00632/kg of Hydrogen, which is negligible. This assumption simplifies the optimisation model as the variable cost of water does not need to be programmed in.

6. Electrolyser lifetime of the electrolyser is independent of the operation of the hybrid plant.
   The lifetime of the electrolyser is assumed to be a certain number of hours depending on the state of electrolyser R&D. This number is assumed to be independent on the operation of the electrolyser. The number of full load operating hours is thus less than the lifetime of the system even though most literature lists the lifetime of an electrolyser as a number of operating hours.[31] However the intermittent operation of the electrolyser could have an effect on the lifetime.[50] The effect of operation on electrolyser lifetime is an interesting subject for future research but is left beyond the scope of this research.

7. The electrolyser is not used to perform balancing and ancillary services.
   An electrolyser could potentially be used to provide ancillary services by ramping the electrolyser up in case of an excess in supply or ramping it down in case of a shortage of supply. The additional benefit of using an electrolyser to provide grid balancing services is beyond the scope of this research.

8. The production of oxygen and heat create no extra value for the hybrid plant.
   It is assumed that the oxygen and heat produced in the electrolyser are released into the atmosphere and no benefit can be gained from selling them.

9. It is assumed that the total Hybrid plant should not be a net consumer of electricity.
   The purpose of the hybrid plant is to produce a combination of electricity and hydrogen, not to a dedicated hydrogen factory. This means that on an annual basis the amount of exported electricity should be greater than the imported electricity.

4.4. Required data

The data which is required to run the model consists of the market data and the hybrid plant data these are discussed in section 4.4.4 and section 4.4.6 respectively. Due to the large amount of data and the uncertainty connected to this data, a number of scenarios were made to analyse the system. The method used for this scenario building is explained in section 4.4.1

4.4.1. Use of scenarios

The focus of this study is to analyse the competitiveness of the hybrid plant in the future. This is done by optimising the hybrid plant over its entire lifetime. To do this, data from the future is required. For this market forecasts are used including the "Klimaat en energie-verkenning"[44] to forecast market developments and Schmidt *et al.* [51] for the development of electrolysers. However this data is subject to a large amount of uncertainty. Analysing all possible combinations of parameters separately requires a massive amount of work and is not useful as not all combinations are realistic. Scenarios are created to create consistent sets of variables which correspond to realistic possible futures. Scenarios building can be a valuable tool for decision making, if done right.[52] Due to the large number of variables, a scenario-axes technique is used to cover the uncertainty connected to the market forecasts.[52] These scenarios consist of a set of possible future based on the moment when the investment is made and the amount of climate action which is undertaken by governments. Based on qualitative assessment of how the energy market will develop over time 9 scenarios are created with predictions of prices for electricity and hydrogen. A full explanation of the scenarios building process is given insection 6.5.

4.4.2. Electrolyser

The electrolyser is the part of the Hybrid plant which splits water into hydrogen and oxygen. The levelised cost of Hydrogen consists of 2 parts, the fixed cost and variable cost. The electrolyser itself is the main contributor to the fixed costs while the efficiency and operational limits have a large impact on the variable cost. The most important characteristics of the electrolyser are therefore the CAPEX, lifetime, efficiency and operational limits. How these parameters will develop will be based on literature investigating the development of electrolysers under different R&D scenarios.[51]

4.4.3. PV system

The PV system will generate electricity based on the available sun. The data required for the solar PV system are the cost of the PV system and the electricity generated by the PV system. The cost of the PV system will be based on literature. The generated solar power will be based on the Photovoltaic Geographical Information System (PVGIS) tool.[53]

4.4.4. Market data

As two markets are evaluated, the Dutch electricity market and hydrogen market, data from both markets is required.

Electricity market

The future electricity market is based on market forecasts combined with historical data. Data from the EPEX spot market is used to find the trends of the market data. This data is retrieved from Entso-e[21]. Data from 1st of January until the 31st of December 2019 are used as this is the last full year of data available. These fluctuations are then combined with forecast data from the "klimaat en energie-verkenning"[44] to generate future price data.

Hydrogen market

The price of hydrogen is assumed to be equal to the cost of hydrogen production through steam

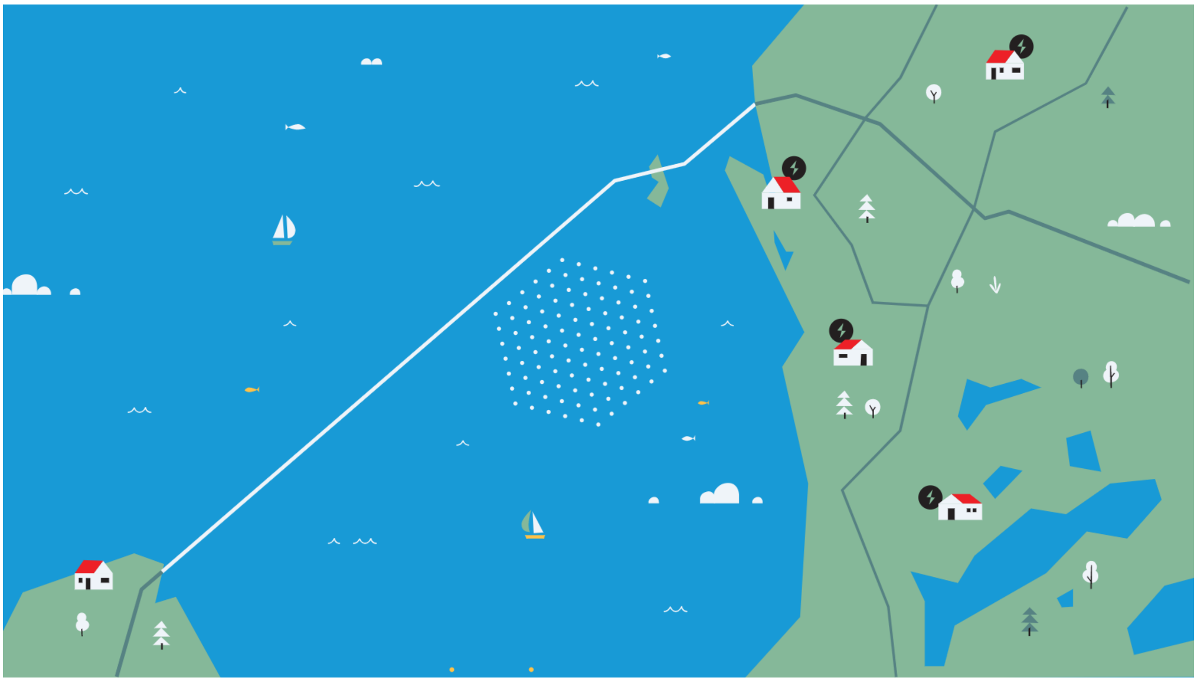


Figure 4.2: Sketch of Windpark Fryslân and its location on the IJsselmeer

Source: windparkfryslan.nl

methane reforming. Using Mulder *et al.* [37] this cost can be related to the cost of natural gas and CO_2 emissions. A combination of historical Natural gas price data and CO_2 data is combined with forecast data from the "klimaat en energie-verkenning"[44] to simulate a future hydrogen market.

4.4.5. Government support/subsidy data

The subsidised price is based on the SDE++ subisdy[43]. The SDE++ will provide subsidy for the produced electricity by the solar farm as well as subsidy for the production of hydrogen by the electrolyser. The SDE++ can not be combined with other subsidies and is therefore the only for of subsidy which will be investigated.

4.4.6. Hybrid plant data - case study

In order to have a good baseline to run the model a case study is used. For this case study an existing wind farm in the Netherlands is chosen. For this Purpose Windpark Fryslan (WPF) is chosen, a near shore wind farm under construction in the Ijsselmeer in the north of the Netherlands. WPF is contracted by Ventolines and consists of 89 turbines delivering a nominal power of 382.7 MW. This location also has the possibility of adding solar generation and an electrolyser system. Furthermore it is placed relatively close to the foreseen hydrogen backbone[42]. As construction of the wind farm is finished the wind farm generation data will consist of simulated generation data.

4.5. Data processing and sensitivity analysis

The optimisation model will output a time-series of the system operation, the system sizing and NPV. The NPV will be corrected to portray the NPV of the electrolyser and PV system exclusively. This is done by subtracting the NPV of the wind farm if it were to sell all electricity to the grid directly. This allows different scenarios to be compared. Another interesting factor in the competitiveness is the sizing of the PV and Electrolyser system. If their optimal size is equal to zero this indicates that their NPV is below 0.

One criteria for competitiveness is the ability to react[45]. This combined with the fact that the markets are constantly changing[5, 44], make the analysis of the sensitivity of the hybrid plant very important. The scenarios cover most external variability to the hybrid plant. For the other factors a sensitivity analysis will be performed with respect to the electricity price, subsidy height, subsidy coverage and the energy generation of the wind farm.

Finally by comparing the different scenarios and analysing the system sensitivity, it can be determined what is required to make the hybrid plant competitive.

This chapter presented has presented what the hybrid plant entails, how it functions and what markets it operates in. Furthermore it sketched a method of how the hybrid plant will be optimised for net present value and evaluated. The subsequent chapter will go into more detail on the optimisation model which is used to optimise the hybrid plant.

5

Optimisation model

This chapter will explain everything about the optimisation model used to optimise the hybrid plant. This way, it aims to answer the question: *How can the configuration of a PV system and an electrolyser added to a wind farm be optimised?* The purpose of the optimisation model is to find optimal internal/controllable parameters for a given set of external parameters. These sets of external parameters are based on the scenarios described in chapter 7. First, the definition of what the model will do is given, then these are translated into the mathematical expressions of the optimisation model. The implementation of the model in the programming language of Python is discussed, and finally, the functioning of the model is verified.

5.1. Definition of the optimisation model

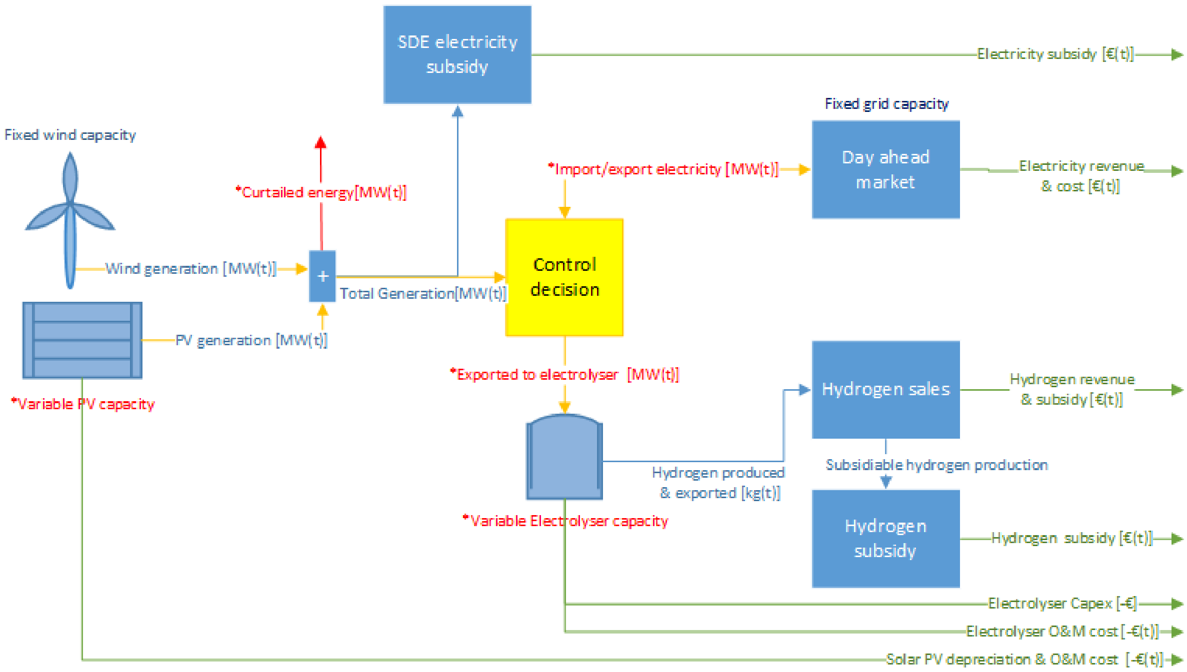
The optimisation model is a linear programming optimisation model. It consists of an objective, decision variables and constraints. This model is a tool to optimise the hybrid plant, which can be used to answer the subquestions posed in chapter 3. A graphical representation of the model is given in fig. 5.1.

The model can be subdivided into the technical model and the financial model. The technical model, displayed in fig. 5.1a, contains the physical relations between the system's components. The decision variables are also located in this part of the model as the decision is made for the physical size of the system and the electricity streams controlled by the transformer station. The second part of the model, displayed in fig. 5.1b, contains the financial part of the model. This translates all the revenue streams into annual cash-flows, which are then discounted to calculate the NPV of the hybrid plant. The financial part of the model contains the objective of the optimisation, the NPV. The combination of the technical model and financial model into one optimisation enables it to find the optimal configuration and operation of the hybrid plant. A more detailed description of the model, including all the objective, bounds and constraints in mathematical expressions, is given in section 5.2.

Linear programming is a method that optimises an objective function by changing decision variables within certain constraints. Large linear programming problems can be run significantly quicker than non-linear optimisation problems. This allows the model to optimise for the entire lifetime of the hybrid plant instead of just a single year without excessive computational effort. The major downside of linear programming is the fact that the problem needs to be linear. For the optimisation of the hybrid plant, this meant that some assumptions needed to be made to keep the problem linear. These assumptions include the constant electrolyser efficiency as well as the assumption that the system cost scales linearly with the PV and electrolyser capacity.

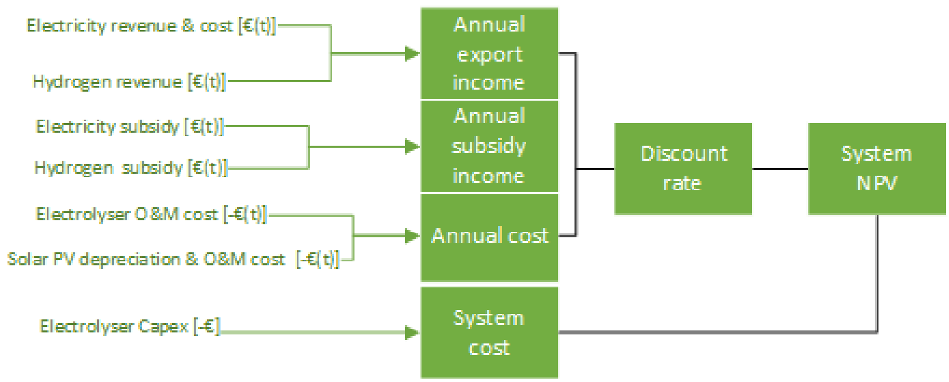
5.2. Mathematical description of the model

This section will provide a detailed explanation of the objective, bounds and constraints used in the optimisation model. Furthermore, this section will provide mathematical expressions for these relations. An overview of the variables used in the optimisation model is given in table 5.1. These variables are divided into constants, time-dependent variables and annual variables. The constants remain



(a) schematic of system components, energy stream, costs and revenues

Time series are indicated with (t). Decision variables are given in the red text with an asterisk [*]. Electricity streams are given in orange arrows. Revenue and cost are given in green arrows. The objective function is indicated with "Objective:"



(b) Calculation of NPV from incomes streams and expenses

Figure 5.1: Visualisation of the optimisation model.

constant throughout the entire operation of the hybrid plant and thus the optimisation model. The time-dependent variables are time-series with the length of the system lifetime in hours (T). These variables can take a different value for every time t. The annual variables are series with the length of the system lifetime in years. These variables can take a different value for every year y. The decision variables are presented in section 5.2.2; other variables are either inputs or intermediate variables which are used to come to the system NPV.

Symbol	Unit	Variable
constants		
η_{H2}	-	Electrolyser efficiency
Cap_{H2}	MW	Electrolyser capacity
$Cap_{H2,max}$	MW	Maximum allowed electrolyser capacity
$Cost_{H2}$	€/MW	Electrolyser cost
HHV_{H2}	kWh/kg	Higher heating value Hydrogen
Cap_{grid}	MW	Grid export/import capacity
Cap_{PV}	MWp	PV capacity
Cap_{PV}	MWp	Maximum allowed PV capacity
$Cost_{PV}$	€/MWp	PV cost
min_{H2}	-	Minimum operating point electrolyser
$H2_{ramp}$	h^{-1}	Electrolyser ramping rate
$pr_{submission}$	€/ MWh	SDE++ PV subsidy submission price
pr_{base}	€/ MWh	SDE++ PV subsidy submission price
d	-	Discount rate
BOL	year	Begin of life, first year of operation
EOL	year	End of life, last year of operation
T	h	System lifetime is hours
Time dependent variables		
t	-	Hour of system lifetime
$E_{wind}(t)$	MWh	Power generated by wind farm at t
$E_{PV}(t)$	MWh	Power generated by solar PV farm at t
$I_{PV}(t)$	MWh/MWp	Power generation potential by solar PV farm at t
$E_{total}(t)$	MWh	Power generated by complete farm at t
$E_{curt}(t)$	MWh	Power curtailed at t
$E_{Ex}(t)$	MWh	Power exported to the grid at t
$E_{H2}(t)$	MWh	Power to electrolyser at t
$H2_{kg}(t)$	kg	Hydrogen produced by electrolyser at t
$pr_{El}(t)$	€/MWh	Electricity price at t
$pr_{H2}(t)$	€/kg	Hydrogen price at t
$S_{PV}(t)$	€/Mwh	PV subsidy height at t
Annual variables		
y	-	Year
$t_{start}(y)$	hour	First hour of year y
$t_{end}(y)$	hour	Last hour of year y
$R_{total}(y)$	€	Annual revenue
$S_{total}(y)$	€	Annual total subsidy income
$S_{H2}(y)$	€	Annual hydrogen subsidy income
$H2_{subkg}(y)$	kg	Subsidised Hydrogen production
$H2_{FLH}$	hour/year	Subsidised full load hours

Table 5.1: Variables used in optimisation model

5.2.1. Objective: maximise the net present value

The objective of the model is to optimise the Net Present Value (NPV) of the Hybrid plant. The NPV is a good method for comparing the profitability of investments. In the objective function, all costs and revenues are discounted to the year of investment using a discount rate of 5% annually. The optimisation will run over the entire lifetime of the electrolyser.

$$max : NPV = \sum_{y=BOL}^{EOL} \Big[(R_{total}(y) + S_{total}(y))\,(1+d)^{-(y-BOL)} - Cap_{PV} \cdot Cost_{PV} \Big] - Cap_{H2} \cdot Cost_{H2} \quad (5.1)$$

$$R_{total}(y) = \sum_{t=t_{start}(y)}^{t_{end}(y)} \big(E_{El}(t) \cdot pr_{Ex}(t) + H2_{kg}(t) \cdot pr_{H2}(t) \big) - Cost_{OM} \cdot Cap_{H2} \quad (5.2)$$

$$S_{total}(y) = H2_{subkg}(y) \cdot H2_{subsidy}(y) + \sum_{t=t_{start}(y)}^{t_{end}(y)} (E_{PV}(t) \cdot S_{PV}(t)) \quad (5.3)$$

5.2.2. Decision variables: hybrid plant sizing and operation

The optimisation model is free to optimise the sizing and operation of the hybrid plant. However, the wind farm capacity and grid connection are fixed and can therefore not be altered by the optimisation model. The operation of the hybrid plant consists of the electricity streams; these include the electricity exchange with the grid, electricity use in the electrolyser and energy curtailment. The sizing variables are bounded by the maximum sizing for the system. This maximum sizing is based on the available space for the systems. The values assigned to these maximums are based on the case study in section 4.4.6.

$$0 \le Cap_{H2} \le Cap_{H2,max} \quad (5.4a)$$

$$0 \le Cap_{PV} \le Cap_{PV,max} \quad (5.4b)$$

5.2.3. Energy flows and curtailment

The optimisation optimises both the sizing and operation of the hybrid plant. In operation, the system is able to optimise the amount of electricity that is sold directly, imported, used to produce hydrogen, and curtailed. The total energy generation and net energy use are given in eq. (5.5) and eq. (5.6) respectively. The curtailment of energy is given in eq. (5.7). Curtailment can not be lower than zero as this would mean that energy appears out of nothing. The generation of the PV system is given in eq. (5.8), the PV generation is calculated by multiplying the capacity of the PV system (in Mega Watt peak) by the unit generation per capacity (in Mega Watt hour per Mega Watt peak).

$$E_{total}(t) = E_{wind}(t) + E_{PV}(t) \quad (5.5)$$

$$E_{total}(t) = E_{Ex}(t) + E_{H2}(t) \quad (5.6)$$

$$E_{curt}(t) \ge 0 \quad (5.7)$$

$$E_{PV}(t) = I_{PV}(t) \cdot Cap_{PV} - E_{curt}(t) \quad (5.8)$$

5.2.4. Grid connection

The hybrid plant is connected to the Dutch electricity grid. This connection is assumed to be fixed and can thus not be increased or decreased by the optimisation. The grid connection both be used to export and import electricity.

$$- Cap_{grid} \le E_{Ex}(t) \le -Cap_{grid} \quad (5.9)$$

5.2.5. Hydrogen production

The hydrogen production for each hour t is calculated using eq. (5.10), 5.10 and 5.12. The production of hydrogen is calculated using a fixed efficiency based on the scenarios. In reality, the efficiency varies slightly with current density due to ohmic losses[31], this effect was neglected as it adds unnecessary complexity to the model. The power sent to the electrolyser is limited by the capacity of the electrolyser and the minimum load at which the electrolyser can operate. The capacity of the electrolyser is optimised by the solver. The minimum load of the electrolyser is a fixed value based on the type of electrolyser used. For Alkaline electrolysers this value is taken to be 15% of the electrolyser capacity based on values used in industry[54]. For PEM electrolysers it is assumed that they can go all the way down to 0%.

$$H2_{kg}(t) = E_{H2}(t) \cdot \frac{\eta_{H2}}{HHV_{H2}} \tag{5.10}$$

$$E_{H2}(t) \leq Cap_{H2} \tag{5.11}$$

$$E_{H2}(t) \geq min_{H2} \cdot Cap_{H2} \tag{5.12}$$

5.2.6. Hydrogen subsidy

Since 2020 the Netherlands has introduced a subsidy for the production of green Hydrogen through electrolysis. This subsidy is part of the SDE++ program and offers a compensation for a reduction in CO_2 emissions.[43] This CO_2 reduction price is recalculated to a per kg price for Hydrogen from electrolysis in section 7.4. The subsidy is only available for 2000 full load hours per year. This means that only 2000 hours of production will be subsidised, the remaining hydrogen production will not be subsidised. The hydrogen production which is eligible for subsidy each year is defined by $H2_{subkg}(y)$ and calculated in eq. (5.13).

$$H2_{subkg}(y) <= H2_{FLH} \cdot Cap_{H2} \cdot \frac{\eta_{H2}}{HHV_{H2}} \tag{5.13a}$$

$$H2_{subkg}(y) <= \sum_{t=t_{start}(y)}^{t_{end}(y)} H2_{kg}(t) \tag{5.13b}$$

5.2.7. Electricity subsidy

The subsidy on electricity production is dependent on the electricity price. The SDE++ subsidy consists of a submission price and base price. The submission price is, as the name implies, submitted by the energy generator and can be approved by the Netherlands enterprise agency (RVO). The RVO also set a base price, if the price drops below this base price only the difference between the base price and submission price is rewarded. If the market price is above the submission price, nos subsidy is rewarded. [43] These rules are summarised in eq. (5.14).

$$pr_{El}(t) \leq pr_{base} \Rightarrow S_{PV}(t) = pr_{submission} - pr_{base} - pr_{El}(t) \tag{5.14a}$$

$$pr_{base} < pr_{El}(t) \leq pr_{submission} \Rightarrow S_{PV}(t) = pr_{submission} - pr_{El}(t) \tag{5.14b}$$

$$pr_{El}(t) > pr_{submission} \Rightarrow S_{PV}(t) = pr_{submission} - pr_{El}(t) \tag{5.14c}$$

5.3. Implementation of the model

The model is programmed using the Python programming language. Python is a free to use yet very powerful programming language. Furthermore python has many libraries which can be used to for free. For this project Python version 3.8 was used in the "Anaconda individual edition" environment.[55, 56] The libraries which were used and their uses are listed below.

- Spyder[57]
  The Spyder interface was used to program the optimisation model. Spyder has clever features such as the variable explorer which allow for quick debugging of code.
- Numpy[58]
  The Numpy library is used is many computing applications it allows easy and quick calculations using arrays and matrices.
- Matplotlib[59]
  Matplotlib is a library full of plotting and other visualisation tools. Matplotlib was used to plot the results from the optimisation model.

- Pandas[60, 61]
  Pandas is a Python library specifically designed to handle large amounts of data. Pandas was used to import and export data from the model to and from save files. Moreover Pandas dataframes were used to handle all timeseries in the preparation of the optimisation model.

- Pyomo[62, 63]
  The Pyomo library is an open source optimisation library in python. The main benefit of Pyomo over other optimisation libraries is the readability of the objectives, constraints and bounds in the Pyomo language. The optimisation model is compiled in Pyomo but solved in a lower level programming language which allows it to run far quicker.

- GLPK[64]
  The solver which was used to solve the optimisation is called ”GNU Linear Programming Kit” (GLPK). This solver is intended for large scale linear programming and thus ideal for the optimisation of the hybrid plant. This solver is also fully supported by Pyomo making it easy to implement.

5.4. Verification of the model

In order to guarantee credibility of the result, verification is an important step. This section will discuss the process of verification used to verify the optimisation model. This method consists of a series of tests on both the different units of the model and finally on the model as a whole using data with a trivial outcome.

5.4.1. Unit testing

Unit tests were used to test each new addition to the model, these include new constraints bounds etc. The model was systematically and incrementally expanded to increase its complexity. The full list of model versions and unit tests used to verify the model can be found in table A.1. This section will give a brief overview of the 4 main versions of the model and how they were progressively built to the final optimisation model. Each new addition to the model was first tested and verified before the next functionality was added.

Version 1.0 - 1.8 single year of operation

Version 1 of the model created the basic optimisation model for a single year of operation of the hybrid plant. This year of operation was based on historical market data and simulated generation data from the same time period. First the operations optimisation was implemented using fixed system sizing and constant hydrogen prices. Then optimisation of the electrolyser and PV system were added ass well as a finite grid connection. Finally the hydrogen subsidy was added and tested.

Version 2.0 - 2.2

Version 2 of the model was made for a different type of hybrid plant operation. It assumed on site use of hydrogen and a hydrogen storage system. however this model was not used in the end.

Version 3.0 - 3.2 Introducing research scenarios

Version 3 of the model is a cleaned up version of model version 1 allowing for easier changing of the inputs. Furthermore it added the use of electrolyser scenarios and to include or exclude the hydrogen subsidy. Version 3.1NPV was used to test the implementation of NPV in one year, this was done by discounting months instead of years. The NPV was first tested on a shorter timescale to limit the computational effort for the test. Finally version 3.2 was used to add the solar PV subsidy, again version 3 was used instead of 4 to reduce the computational effort.

Version 4.0 - 4.5 Multi year optimisation

Version 4 of the model expanded version 3 to a multi year optimisation over the entire electrolyser lifetime. The first iteration still optimised for total profit. This was then expanded to work with the research scenarios. Finally the obejective was converted to optimise for NPV and then the solar subsidy was implemented, after testing the implementation using version 3.2.

5.4.2. Result verification & validation

The results of the scenario runs also serve in the verification of the model and method as a whole. This will be done by comparing the results to results from different studies as well as to the trends shown in the market. Since no large scale electrolysis plants are operational in the Netherlands as of now, the hypothesis is that the Hybrid plant concept is not competitive in the current market and therefore also not in the business as usual scenarios.

This chapter has provided a detailed description of the optimisation model used to optimise the hybrid plant. The subsequent chapter will identify the important inputs to the optimisation model, identify why they are important and create scenarios to evaluate the hybrid plant. These scenarios are then quantified in chapter 7.

6

External factors & scenarios

This chapter describes the competitive environment in which the Hybrid plant will operate, what defines the hybrid plant competitiveness and what external factor might influence the competitiveness. This chapter aim to answer the question: *Which external factors influence the optimal system configuration and competitiveness?* The hybrid plant's performance is influenced by many factors, too many to analyse them all individually. Therefore, this chapter presents 9 research scenarios and the hybrid plant will be optimised and evaluated for each. More on the optimisation can be found in chapter 5.

The costs and revenues of the Hybrid plant depend on many external factors. Each external factor has a different impact on the system. The external influences to the hybrid plant can be identified by analysing the inputs to the optimisation model. The inputs to the optimisation model are the following:

- Electrolyser: CAPEX, Efficiency, Lifetime, O&M cost, Minimum load
- Solar PV system: CAPEX, Efficiency, Lifetime, O&M cost
- Electricity market: Mean price, Price volatility
- Hydrogen market: Natural Gas price, CO_2 price, Hydrogen infrastructure
- Government support: Subsidy on electricity production, subsidy on hydrogen production

This chapter will identify all factors and discuss how they affect the hybrid plant. These factors are subject to change, how they change is analysed quantitatively. Finally internally consistent sets of external factors are combined into 9 research scenarios. The way these scenarios are set up is described in section 6.5. The scenarios, which are set up in this chapter, will be quantified in chapter 7.

6.1. Hybrid plant asset parameters

The assets of the hybrid plant are discussed in section 4.1.1. For the optimisation model only the electrolyser and PV system are of interest as the rest of the hybrid plant is not subject to change because the wind farm and grid connection are fixed. To determine the optimal configuration of the hybrid plant, both the cost and operational parameters related to these systems are required. These are determined in this section.

6.1.1. Electrolyser parameters

The crucial parameters of the electrolyser to the hybrid plant performance are the CAPEX, Lifetime, O&M cost, Efficiency and Minimum load. This section will underline the importance of these parameters and their influence. Finally a projection is presented on how these parameters are expected to develop in the different scenarios, based on literature.

Electrolyser cost and lifetime

The fixed cost of hydrogen production consist of two parts, the Capital expenditure, (CAPEX) and the operation and maintenance cost (O&M). The CAPEX is closely related to the lifetime of the system. This is because a longer lifetime allows the electrolyser to operate for longer, thus producing more hydrogen. In this way, the cost of the electrolyser can be spread over a larger volume of hydrogen production, reducing the unit cost.

Cost breakdown

The CAPEX can be split into 2 main components, the electrolyser stack and the Balance of plant (BOP), the part which regulates and controls the electrolyser. The BOP can be further split up in the mechanical and electrical BOP. Both for Alkaline and PEM electrolysers the largest contributors to the cost are the electrical BOP and the stack. Fortunately these are also the components where the largest cost reduction is expected in the coming years, creating a significant price decrease for the electrolyser as a whole.[51]

Lifetime

The lifetime of alkaline electrolysers ran in the range of 60 000 to 90 000 hours in 2016. For PEM electrolysers this range was 20 000 to 60 000 hrs in 2016. For alkaline electrolysers these values are expected to stay at this level in the future as this is an already mature technology. The lifetime of PEM electrolysers is expected to increase up to 60 000 to 90 000 by 2030, similar to Alkaline electrolysers nowadays. These improvements are expected due to ongoing research is electrode stability but also in improved water purification etc.[51]. These increasing lifetimes improve the competitiveness of the Hybrid plant as it allows for the system to spread the capex over a larger volume of hydrogen production, thus lowering the levelised cost of hydrogen.

O&M

The final fixed cost is in the form of the annual operating and maintenance cost. These O&M costs are assumed to be related to the CAPEX. Predicting unplanned maintenance cost is not possible, therefore the O&M cast was assumed to be 5% of the total CAPEX of the system annually. 5% is a conservative value which is most often used in similar research.[16]

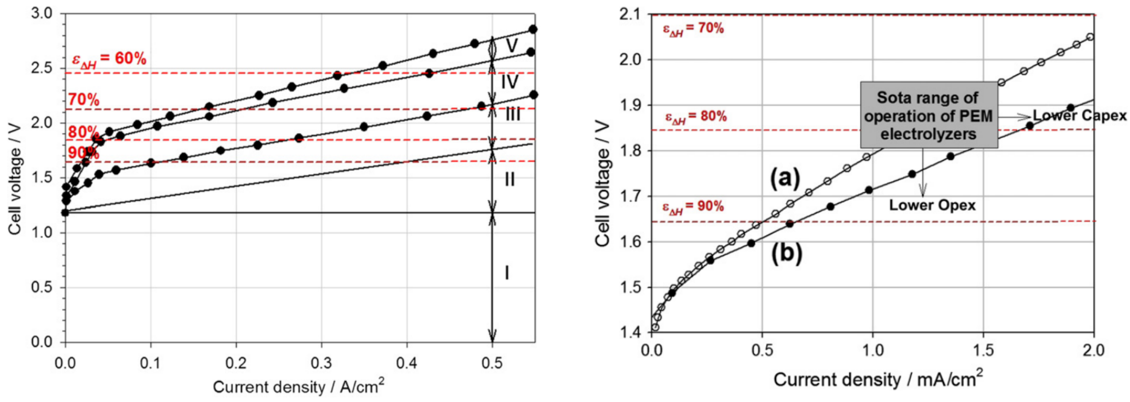
Efficiency & operational limits

The most important factors affecting the variable costs of hydrogen production are the efficiency and operational limits of the electrolyser. The efficiency is the ratio between the higher heating value of the produced hydrogen and the electricity used to make it: $\eta = \frac{E_{h2out,HHV}}{E_{Electric}}$. The efficiency of the electrolyser thus dictates how much electricity is required to produce a certain quantity of hydrogen. Because this electricity comes at a cost, the amount of electricity used dictates the hydrogen cost. The cost of electricity is the opportunity cost of selling the electricity to the market, or the cost of importing this electricity from the market.

The efficiency of an electrolyser depends on many factors. The splitting of water into hydrogen and oxygen is an electro-chemical reaction, also known as redox reaction. In such reactions electrons are transferred from the oxidant to the reductant. This reaction can create an electrical current or be driven using an electrical current. In the case of electrolysis the reaction in driven by the electrical current. Inefficiencies occur mostly in the form of electrical losses due to electronic resistance. These losses are called ohmic losses. The conversion of H_2O into H_2 and O_2 always requires 2 electrons. This means a certain current will always produce the same amount of hydrogen. Since the energy input into the system is equal to the current multiplied with the potential, the only thing that can change the efficiency is therefore the potential.[31]

The potential at which water can be split is 1.4 V, so in theory using a potential of 1.4 over the electrolysis cell would yield a near 100% efficiency. However, in reality the current and thus the hydrogen production at this potential is nearly zero. To improve the production rate, an over-potential is therefore applied. The larger the over-potential, the higher the current but the lower the efficiency. Figure 6.1 shows this relationship between current density and cell voltage for both Alkaline (6.1a) and PEM (6.1b) electrolysers.[31]

The over-potential and current density can be tuned to find the right balance between fixed and variable



(a) Alkaline

(b) PEM

Figure 6.1: Cell voltage as a function of current density

Source: Millet and Grigoriev [31]

costs. Larger current densities reduce the required electrode area for the electrolysers, this way a smaller electrolyser can produce the same amount of hydrogen. Reducing the size of the electrolyser in this way reduces the fixed costs. On the contrary, increasing the current density by applying a larger over-potential increases the electricity usage and thus the variable costs. This is a result of the lower efficiency experienced at higher over-potentials. An optimum should therefore be found between fixed and variable costs, based on the market in which the electrolyser operates. For this research a constant efficiency is used as the focus is on the optimisation of the entire hybrid plant, not the optimal over-potential to be applied.

Next to the losses in the process of water splitting, other losses can also be identified. These losses are mostly related to the Balance-of-plant of the electrolyser. They include the losses due to the systems which keep the electrolyser running such as the power electronics, water purification and electrolyser cooling systems, but also the post processing of the hydrogen such as the compression and purification of hydrogen to the desired specifications. [65]

Minimum load

The minimum load at which the electrolyser should operate is also an important factor for its competitiveness. The is caused by the fact that the minimum load of the electrolyser reduces its flexibility to operate. The flexibility allows the electrolyser to chose ar what moment the markets are beneficial to produce hydrogen. Less flexibility thus means higher hydrogen production costs.

The minimum load is one area where Alkaline and PEM electrolysers differ most. Using the electrolyser at very low cell potentials can cause the electrodes to degrade, reducing the lifetime of the electrolyser. The membranes in PEM electrolysers are coated with a Platinum and Iridium catalysts, these metals are very stable and will therefore not degrade at low cell potentials. Alkaline electrolysers on the other hand, use non noble metals as electrode materials.[31] These metals can be corroded by the electrolyte when to little potential is applied reducing the lifetime of the electrolyser. For this reason a minimum load of 15% of the maximum load is used for alkaline electrolysers.[54]

Ramping ability

The final important parameter for the electrolyser is the rate at which it can ramp up and down it's power. Alkaline electrolysers are traditionally known to have relatively slow ramping rates while PEM electrolysers have high ramp rates.[51] Quick ramp rates are beneficial as they allow the electrolyser to be used for balancing of the power output of the hybrid plant. When the power output of the farm is higher than expected, the electrolyser can be ramped up to counteract the imbalance. Similarly when the output is lower than expected the electrolyser could be ramped down.

The ability to ramp up or down quickly can also have a value in the balancing market in the Netherlands, the FCR, and FRR, as discussed in section 2.3.2. The electrolyser is not able to generate electricity but it could be used as a dump for access electricity, in case supply exceeds demand. It could also be used to combat a shortage in supply by ramping down. This study will focus only on the use of an electrolyser in the day-ahead market to limit complexity. Operating an electrolyser in the balancing markets is therefore not taken into account.

Little information is publicly available about the ramping rates of commercial electrolysers. Furthermore, it is very dependent on the design of the electrolyser. A conservative estimate is 10%/min for alkaline electrolysers and ever quicker for PEM electrolysers, hence it can easily ramp up or down 100% within an hour, the resolution at which energy is sold in the DAM. For this reason ramp rates are not modelled in the optimisation.[66]

Electrolyser technology developments

The focus of electrolyser research and development is mainly on lowering the production cost of hydrogen. This translates into three main area's of research; Lowering of electrolyser manufacturing cost, increasing of electrolyser lifetime, and increasing current density.

Lowering of the manufacturing cost can be split in to lowering the stack cost and BOP cost. Both the stack and electrical BOP are expected to see significant cost reductions through economies of scale. Next to economies of scale other improvements in the manufacturing process such as reducing the platinum loading on PEM electrolyser membranes are expected to reduce cost.[51, 67]

Increasing the lifetime of electrolysers is another point of focus for research and development. As discussed in section 6.1.1, by elongating the lifetime of the electrolyser the cost of hydrogen can be reduced. Alkaline electrolysers only expect minor improvements in lifetime because this technology is already very mature. Some improvements can be made in the stability of the electrodes and reduction of impurities, these can be made both in manufacturing as well as in the purification of water used in the electrolysis. For PEM electrolysers, far greater lifetime improvements are expected. These improvements are also expected to come from improvements in electrode stability and reduction in impurities.[51]

Increasing current density in the electrolysis cells is also an important factor in reducing the cost of hydrogen. By increasing current density the same amount of electrode area will produce more hydrogen. This indirectly decreases the capex per unit of hydrogen. Increasing current density does come with the drawback of decreased efficiency therefore is can not be increased indefinitely. Some improvements in efficiency are expected in other areas but this is not the main focus of the R&D efforts.[51]

Based on these the expected developments and an expert study[51] the assumptions for the alkaline and PEM electrolysers are given in table B.1 and B.2 respectively.

6.1.2. Solar PV parameters

Next to the electrolyser a solar PV farm can also be added to the hybrid plant. This PV system will also be optimised for maximum NPV of the hybrid plant.

In recent years the price of solar photovoltaics has dropped drastically. A cost reduction of approximately 90% was realised between 2009 and 2019. These cost reductions were achieved not only through manufacturing of scale and experience, even though these contributed significantly. Cost reductions were also achieved through optimisation of manufacturing and new cell architectures, bringing on efficiency improvements.[68] In contrast to electrolysers, efficiency improvement do bring forth cost reductions as they reduce the cost of the balance-of-systems as well as reducing the required land mass to place the PV modules.

The price of solar PV varies significantly from region to region and between applications. Like in most technologies economies of scale also play a role in solar PV, hence residential PV systems are more costly than commercial plants. The cost also varies between regions due to cost of installation and costs related to land use. The cheapest being India at 618 USD/kWp and the most expensive the Russian federation at 2117 USD/kWp in 2019. The Netherlands is not mentioned in the study by International Renewable Energy Agency [68], therefore the price of Germany, the closest neighbor to the Netherlands, is taken for the Hybrid plant. In Germany the total installed cost of solar PV averaged at 1130 USD/kWp for commercial systems in 2019.

The total installed cost of solar PV is expected to keep decreasing in the coming years. To account for this price decrease a learning curve was fitted to the historical PV costs. Using this learning curve the future PV costs were extrapolated. This fit and extrapolation was done using a power law , as this is the method most commonly used and it gave a good fit for the data.[69] Both the historical PV cost data and the learning curve are given in fig. 6.2. The dollar values in International Renewable Energy

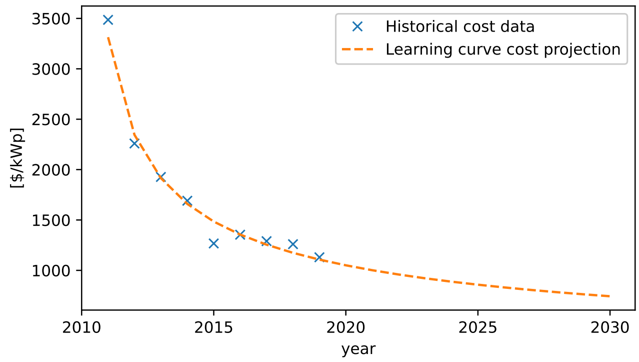


Figure 6.2: Historical PV cost data and learning curve extrapolation

Agency [68] were converted to euros using the average conversion rate in 2019.[70] The resulting PV cost for every scenario is given in table B.3

6.2. Electricity market

The price of electricity is key to the performance of all parts of the hybrid plant. The revenue generated by the wind and solar farm are directly related to the electricity price. This is because the electricity they generate can be sold directly for this price. High prices will thus increase the NPV of the wind and solar farm and lower prices will decrease their NPV.

The relation between the electricity price and the electrolyser is slightly more complex. The electrolyser uses electricity to produce hydrogen, which is then sold to the market. This electricity has a value based on the electricity market, therefore the electricity dictates the marginal hydrogen production cost. If this marginal hydrogen cost is below the hydrogen price, the electrolyser can make a profit. If not, the electrolyser can not make a profit and no hydrogen will be produced. Therefore the relation between the electricity price and hydrogen price is key to the electrolyser competitiveness.

The price volatility of electricity also plays an important role in the competitiveness of the electrolyser. The hybrid plant has the flexibility to produce hydrogen at the optimal times, meaning it will only produce hydrogen during periods of low electricity prices. The price at these lows is dependent on the mean price as well as the price volatility. Highly volatile prices would create higher highs and lower lows. This is beneficial for the electrolyser because it means the electrolyser will operate only during the lows. Therefore, it will effectively operate at lower prices.

To take into account both the mean prices and price volatility in the optimisation, wholesale price forecasts are combined with price volatility, from historical data. The method used to create this market data is discussed in section 7.2.

6.3. Hydrogen Market

The hydrogen market is very important for the competitiveness of the electrolyser as hydrogen forms it's main source of income. In this study, the hybrid plant is assumed to be a price taker. This means that the hydrogen market dictates the price of hydrogen, and therefore, the income generated from the export of hydrogen produced by the electrolyser. If the price of hydrogen is too low it will not be able to cover the costs of producing hydrogen through electrolysis. As mentioned in section 6.1, the cost of hydrogen production can be divided into fixed and variable costs. The fixed costs are related to the capex, o&m cost etc. The variable cost are related to the cost of the electricity used in hydrogen production, hence they are related to the electrolyser efficiency and the electricity price.

As of right now no transparent hydrogen market exist, like the EPEX spot market for electricity. Instead a market needs to be simulated to get an idea of how hydrogen prices develop and fluctuate. In order to do this it is assumed that the price of hydrogen is set by the production price of steam methane reforming, as discussed in section 2.6.1. In this way the price of hydrogen can be calculated using the price of natural gas and CO_2 emissions, for which transparent price data is available. This method of determining the hydrogen prices will be discussed in section 7.3. The price of hydrogen is also dependent on the colour of the hydrogen. The colour relates to the carbon intensity of the hydrogen, green being the least carbon intensive and grey being the most carbon intensive. It is then assumed that the carbon intensity of hydrogen will decrease over time and with climate action from governments. The price of hydrogen then follows from the "colour" of hydrogen as explained in section 7.3.

Developments in the market could increase the demand for hydrogen to a point where steam methane reforming can no longer supply the demand. The electrolysers would likely fill the gap between supply and demand, and a higher market price will be set. Assuming the market price to be set by hydrogen produced from SMR can therefore be seen as a conservative estimate.

6.4. Government support - subsidies

In order to aid in the energy transition the Dutch Government has introduced the SDE++ subsidy (Stimulering Duurzame Energie).[43] Among others this subsidy support the production of hydrogen through electrolysis and the production of electricity through solar PV. The wind farm will also receive a subsidy but this is not taken into account in the optimisation because this does not influence the decision of the electrolyser and PV sizing.

The subsidy offers and additional income to the electrolyser or the PV farm. For the electrolyser this effectively changes the relationship between the hydrogen price and the electricity price by offering a "bonus" for hydrogen production. This will make it beneficial to produce hydrogen more often, increasing the competitiveness of the electrolyser. For the PV system the additional income allows the system to recoup the capex more quickly, increasing its competitiveness.

The height of the subsidy is expected to decrease over time. As the technology improves, the price will decrease and subsidy is no longer necessary. This is in line with the trends of the past years.[43] Moreover it is expected that the subsidy will be higher if governments prioritise mitigating climate change. The Height and exact working of the subsidy will be discussed in section 7.4.

6.5. Research scenarios

There are many parameters which affect the hybrid plant performance. All these parameters can take on an infinite amount of values which creates an infinite amount of possible outcomes of the optimisation. It is therefore impossible to evaluate every combination of the parameters. Moreover, it is not useful to evaluate every combination as many of them are unrealistic. Therefore it was chosen to create a number of scenarios for which to performance of the hybrid plant is evaluated. These scenarios form internally consistent possible futures based on qualitative assessment of the market developments. The scenarios are not forecasts but instead possible future pathways. A scenario-axes technique was applied to reduce the large amount of variables to scenario axes.[52] These scenarios are positioned on two axes "climate action" axis and a time axis. The reasoning behind these specific axes and their effect on the market prices are set out in this section.

6.5.1. Scenario axes

Most parameters related to the hybrid plant follow a certain trend to the future combined with a level of uncertainty. This can be viewed as different paths which the parameters follow. For example the trend of CAPEX for electrolysers is expected to go down, however the amount by which it goes down is dependent on the amount of research and development. The 2 axes are then used to choose a path and determine the position on that path. The climate action axis serves the purpose of determining the path on which the scenario is placed. The time axis determines the specific place on that specific path. As illustrated in fig. 6.3, for each axis 3 locations are chosen creating a total of 9 scenarios for which the system is evaluated.

climate action axis

The climate action axis represents the amount of action taken by governments and industry to reduce carbon emissions and thus their harmful impact on the environment. This climate action has effect

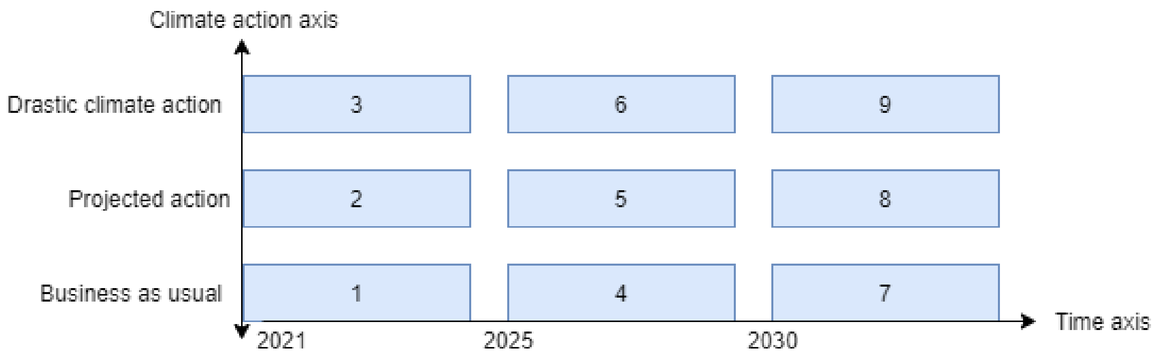


Figure 6.3: Visualisation of scenarios on axis system

on the policies and legislation put in place by governments. These policies affect how the prices of carbon and fossil fuels progress over the coming years. The climate action axis was chosen such that it resembles anything from a worst, to a best case scenario for the electrolyser competitiveness. Note that the level of climate action taken corresponds to a price path not a fixed price. Furthermore, the level of climate action can also affect the price volatility of electricity as VRES enters the market.

The lowest level of climate action, called the ”business as usual” scenarios, assumes little to no action is taken to reduce emissions. In these scenarios the price of CO_2 emissions increases only very slightly as a large number of credits are still issued by the EU. The low emissions prices do not provide an incentive for utility companies to close their coal fired power-plants and thus the market share of gas fired plants does not increase. Due to this relatively low natural gas demand the price of gas also follows the low path of the KEV[44]. Investment in the R&D of electrolyser technology is low, resulting in a limited increase in lifetime and decrease in cost following the R&D 1x scenario in Schmidt *et al.* [51]. Finally subsidies for hydrogen production through electrolysis are low and decrease rapidly[43]. Subsidies for solar PV are low and remain at this low level until 2030.

The middle level, called the ”business as projected” scenarios, assumes the current plans to reduce greenhouse gas emissions are continued. Prices for both the CO_2 emissions as well as natural gas follow the middle line set by the KEV[44]. The development of the electrolyser follows the R&D 2x scenario set by Schmidt *et al.* [51] and subsidies are in the middle of the range presented in 2020[43]. Subsidies for solar PV are at a medium level and remain at this level until 2030.

The highest level of climate action is found in the ”drastic climate action” scenarios. These scenarios represent a future in which far more action in taken to reduce climate change. CO_2 emissions prices therefore increase rapidly due to a quick decrease in issued credits. This caused coal fired plants to lose their competitive edge and gas fired plants to take their place, causing gas prices to increase rapidly. Both follow the high line on the KEV[44]. Large investments are made both in the R&D as wel as the deployment of electrolyser, thus the electrolyser cost and lifetime developments follow the RD&D 10x scenario[51]. Finally the subsidy for hydrogen production is high. Subsidies for solar PV are at a high level and remain at this level until 2030.

Time axis

The time axis represents the commercial operating date (COD) of the electrolyser. This means that for the 2021 scenarios, the commercial operating date is the 1st of January 2021, 2025 and 2030. Analysing for several commercial operating dates, makes sure that not only the market developments, but also the technology developments are taken into account. The cost and other parameters of the electrolyser and PV system are set at the COD and remain for the lifetime of the system. The market, and thus the prices of electricity and hydrogen, will change during the system lifetime. This method allows insight to how the competitive position of an electrolyser changes over time. Perhaps the electrolyser is not competitive at this moment but it becomes a viable technology in the future. The three point in time are 2021, the year this thesis is written, 2025 and 2030. Going beyond 2030 does not make sense as there are no forecasts for the markets and electrolyser technology beyond that point. There are a number of reasons why electrolyser competitiveness is likely to increase over time.

The first reason is the fact that research and development of electrolysers is decreasing the cost and increasing the lifetime of electrolysers as mentioned in section 2.6.1.

The second reason is the development of the market, according to the KEV the price of both natural gas and CO_2 emissions will both increase over time, regardless of the climate action. A higher gas and CO_2 price will result in a higher SMR hydrogen price, resulting in an increased competitiveness for the electrolyser.

The third reason is the development of infrastructure for the transport of hydrogen. This increase in infrastructure is likely to increase the demand for hydrogen as it allows it to be used in more applications.

In this chapter scenarios were created to optimise and evaluate the hybrid plant, based on a qualitative assessment of the markets and technologies. These scenarios will be quantified into inputs for the optimisation model in the next chapter.

7

Input data & Case study

This chapter describes how the input data to the optimisation model is generated base on the different scenarios and the case study of WPF. This way it aims to answer the question: *How will the markets, and system parameters develop under different scenarios?* First the historical price data for electricity, gas and CO_2 price data and their sources are analysed. Secondly the future electricity prices are generated using a combination of price forecasts and historical prices volatility trends. Third is the simulation of a wholesale hydrogen market based on SMR production prices using the natural gas and CO_2 markets. subsequently the government support in the form of subsidy is explained and finally the case study of Windpark Fryslân is presented.

7.1. Market data

The Hybrid plant will operate in the dutch market, hence it will be optimised for the characteristics of this market. The optimal configuration and competitiveness of the hybrid plant is dependent on the market data, therefore it is important to use accurate market data. Inaccurate data will cause the result to be less useful.

7.1.1. Importance of time series data

The optimisation of the hybrid plant is based on both the sizing as well as the operation of the hybrid plant. In order to optimise the operation of the hybrid plant time series data is required. This is due to the instantaneous nature of electricity and the fluctuations of electricity price. A watt that is generated now needs to be used now. Therefore for every moment in the hybrid plant lifetime, the electricity price and hydrogen price at that exact moment need to be known in order to make a decision. Figure 7.1 shows this relation between electricity price and equivalent hydrogen price. At moments when the hydrogen line is above the electricity, line hydrogen should be produced and at the moments when the electricity price is higher, electricity should be sold directly. The same holds for the generation data, there it is very important to take into account the simultaneity of solar and wind generation as these together form the total generation. When the total generation is larger than the grid capacity and electrolyser, energy needs to be curtailed and potential profits are lost.

7.1.2. Electricity market data - EPEX spot NL

For the electricity price, data from the EPEX spot NL market is used. The EPEX is the European power exchange, many European countries have markets within the EPEX, including the UK, Germany, France and Scandinavian countries. The EPEX NL is the dutch part of this market. Energy in the EPEX spot NL is traded in quantities of MWh per hour. Both suppliers and consumers of electricity submit their bids for energy one day before delivery. The market price is then set at the point where supply meets demand. The data from this market is made publicly available by ENTSO-E, the European Network of Transmission System Operators for Electricity[21]. Price data from 2015 up to the present is available.

For the evaluation of the Hybrid plant it was chosen to use the data from 2019 as a reference. This year was chosen as it is the most recent year with "normal" price data. in light of the Covid-19 pandemic the 2020 data could not be used as the demand pattern was altered significantly. Due to the

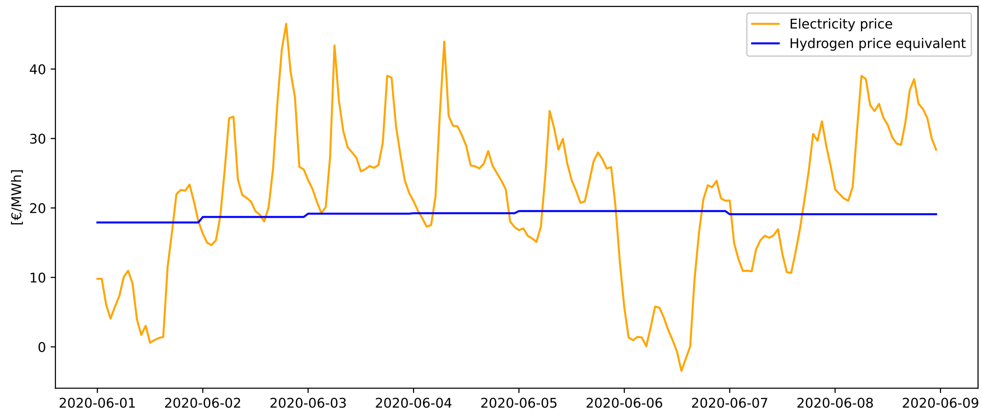


Figure 7.1: Relative electricity price and equivalent hydrogen price, based on simulated hydrogen price and electrolyser efficiency

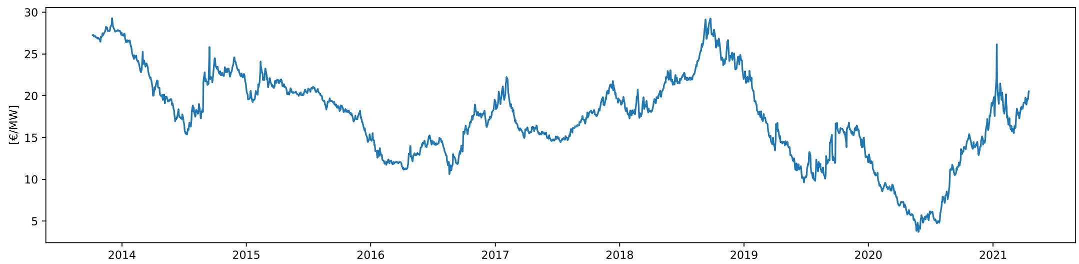


Figure 7.2: ICE Endex gas futures 2014 until 2021

pandemic people worked from home more frequently and thus the demand for energy and as such the price of electricity was significantly lower. [22] 2020 is therefore not seen as a representative year for the Dutch electricity market. The data from 2019 is not used directly but used to create a prediction for the future electricity prices in section 7.2.

7.1.3. Gas price data - ICE Endex gas futures

For the historical gas price data the ICE Endex Dutch TTF Gas Futures price data is used. This data was retrieved from the wiki continuous futures using a Quandl time series API.[71] The ICE is a digital trading platform for energy markets including natural gas, crude oil, coal and emissions rights worldwide. The Endex is the european branch of the ICE. The TTF Gas Futures are contracts for the physical delivery of natural gas per month. This is achieved through the transfer of rights to natural gas delivery at the Title Transfer Facility (TTF). This virtual trading point is operated by Gasunie transport services, the natural gas transmission system operator in the Netherlands.[72] The resulting prices are displayed in fig. 7.2.

Similar to the electricity price the gas price is not used directly but as a method to find how the gas prices fluctuate and then used in conjunction with gas price predictions from the KEV[44] to get a prediction for future prices. as it was also done for the electricity prices, the gas prices of 2020 were taken as a reference to limit the influence of the COVID-19 pandemic on the prices.

7.1.4. Carbon dioxide emissions pricing

The CO_2 emissions allowance prices is based on the European emissions trading system (EU ETS). The EU ETS was set up in 2005 to combat climate change through CO_2 emissions. This system was the first international emissions trading system in the world. Besides CO_2 , this system also covers emissions of Nitrous Oxide (NO_2) and perfluorocarbons (PFCs) but these do not apply to power generation or

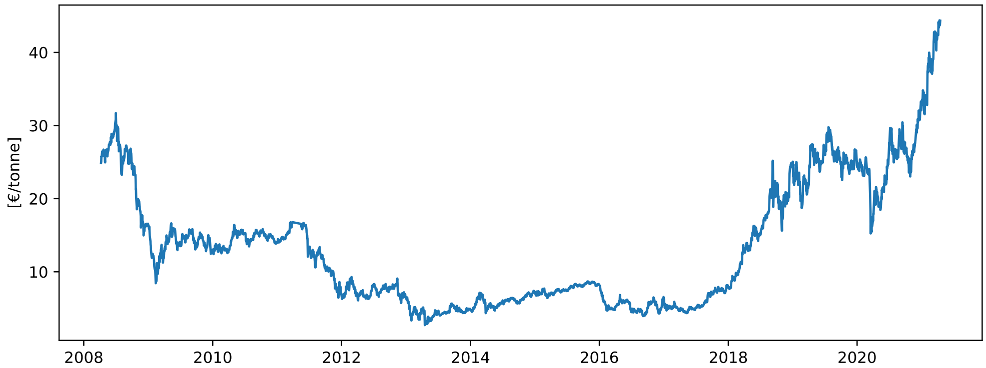


Figure 7.3: EUA futures prices from 2008 until April 2021

hydrogen production. [46]

The EU ETS CO_2 emissions allowances are traded on the EUA Futures market, operated by ICE.[73] Volumes of CO_2 emissions are traded per metric tonne. Since 2005 the price has ranged between €3.19 t^{-1} in April 2013 up to €44 t^{-1} in April 2021. The prices are displayed in fig. 7.3. A clear trend can be seen from 2018 onwards, the price had been increasing in an almost linear fashion with the exception of a dip in price in 2020, likely caused by a decrease in demand due to the COVID-19 pandemic. The increase in price is in line with the predictions made by the KEV[44]. Next to this the EUA price shows no intra year fluctuations so for the future prices a constant price through the year is assumed.

7.2. Future electricity price

As mentioned in section 7.1.1 it is important to have a good time series to run the optimisation model. However these time series only exist as historical data. Future price predictions only exist for wholesale prices. By combining the wholesale market price predictions with trends from historical data a reasonable prediction of a future time series can be made. However this process is not straight forward and caution should be used as not to over-fit the data to the historical data.

7.2.1. Mean price development

The development of the mean price is based on the Klimaat- en Energieverkenning 2020 (KEV)[44]. The KEV provides an estimate on how the electricity price will develop until 2030. It provides an expected path with a wide band-with as shown in fig. 7.4. In this study the lower bound on the bandwidth, the expected path and the upper bound are all taken into account as the ”Low”, ”Mid”, and ”High” price path. The KEV only forecasts prices until 2030, however many of the scenarios run far past 2030. Fortunately the forecasts follow a close to linear path, hence for 2031 and onwards the KEV price data is extrapolated linearly to get the expected price.

One major shortcoming of the KEV is that it only provides wholesale price forecasts. In order to run the optimisation a time series for every year is required. For this the fluctuations in energy prices were identified and added to the wholesale price to create a time-series.

7.2.2. Price fluctuations

The price trends of the electricity were categorised in 4 kinds of price fluctuations, diurnal fluctuation, Weekly fluctuations, annual fluctuations and fluctuations caused by VRES. Diurnal, weekly and annual fluctuations are mostly caused by changes is demand, while the VRES fluctuations are supply based.

Diurnal price fluctuations

Diurnal price fluctuations are caused by human behaviour, people are mostly active during the day and sleeping at night. A peak in price can be seen in the morning when people get up and in the evening when people get home from work or other activities.

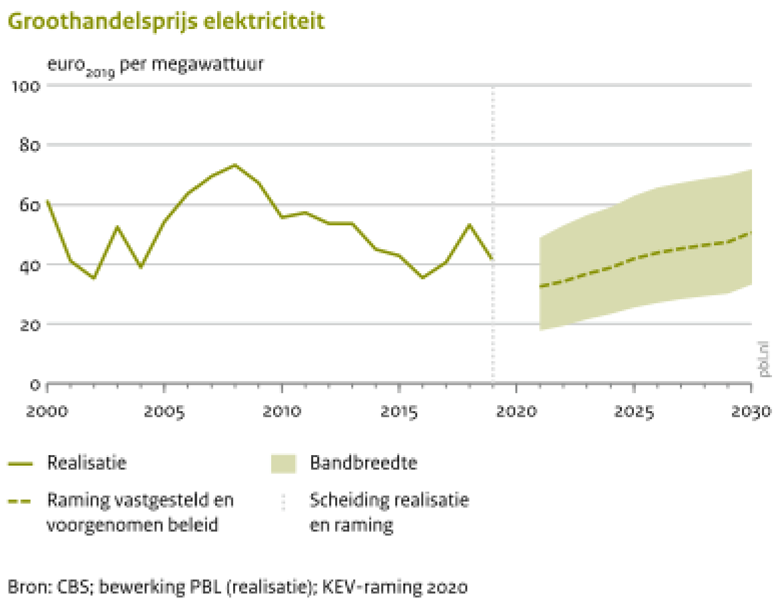


Figure 7.4: Expected electricity prices according to KEV

Source: Planbureau voor de Leefomgeving [44]

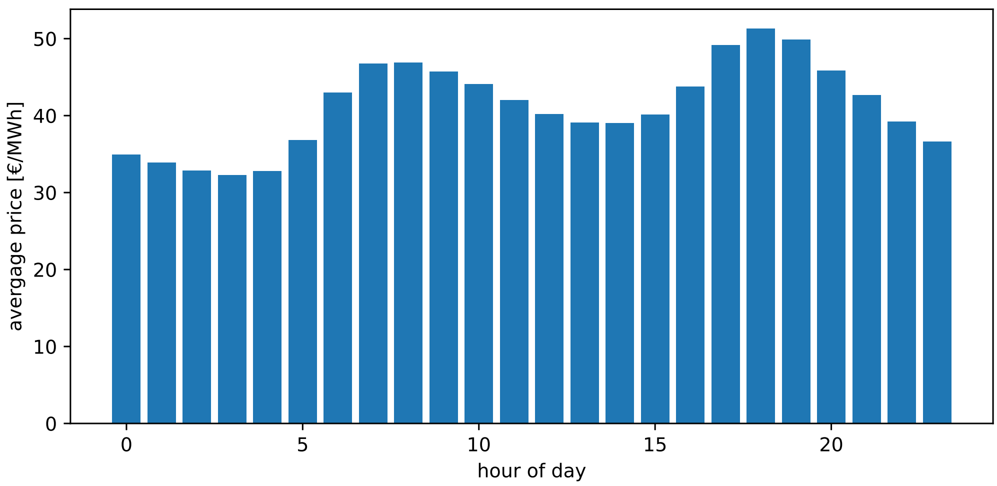


Figure 7.5: Average energy prices in 2019 as a function of hour in the day

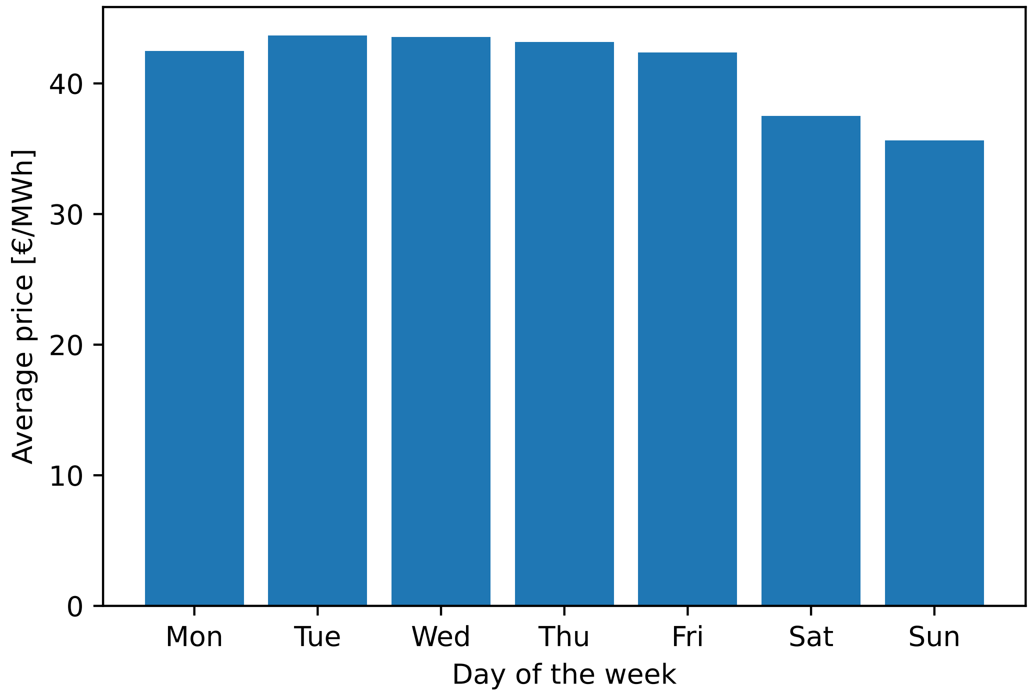


Figure 7.6: Average energy prices in 2019 as a function of day in the week

Weekly price fluctuations

Weekly price variation show mostly a difference between work days, Monday until Friday, and weekend days, Saturday and Sunday. During work days most people are, as the name suggests, working. This means they are on average using more electricity than during the weekend. This difference is shown in fig. 7.6.

Monthly price fluctuations

Monthly price fluctuations are the price changes between month averages. These fluctuations are likely caused by the seasons as the price of electricity is slightly higher in winter as shown in fig. 7.7. This change could be explained by an increase in demand during the winter months. Another possible explanation could be an increase in the natural gas price during the winter.

Effect of Variable renewable energy supply on price volatility

Finally the effect of variable renewable energy supply on the electricity price should be identified. Unfortunately this effect has not been studied in the Netherlands, however a study by Rintamäki *et al.* [74] performed in Denmark and Germany shows some interesting results. The paper researches the effect of both solar and wind generation on the price volatility in Denmark and Germany. They conclude that both solar and wind generation have a significant effect on Day ahead prices in both regions.

Wind power shows opposing effects in the two regions; it increases daily price volatility in Germany while decreasing volatility in Denmark. The likely cause for these contrasting results is the fact that Denmark has access to large hydro storage facilities in Scandinavia, while Germany's cross border capacity is very limited.[74] The Netherlands also has a cross border connection with Scandinavia, Norned a 700MW interconnection with Norway. Denmark has a far greater interconnection capacity with Norway at 1700 MW and 740 MW + 1700 MW with Sweden (DK1->SE3 + DK2->SE4)[75]. This allows Denmark significantly more cross border flows then the Netherlands, it is therefore assumed that the Dutch market resembles the German market more closely than the Danish market.

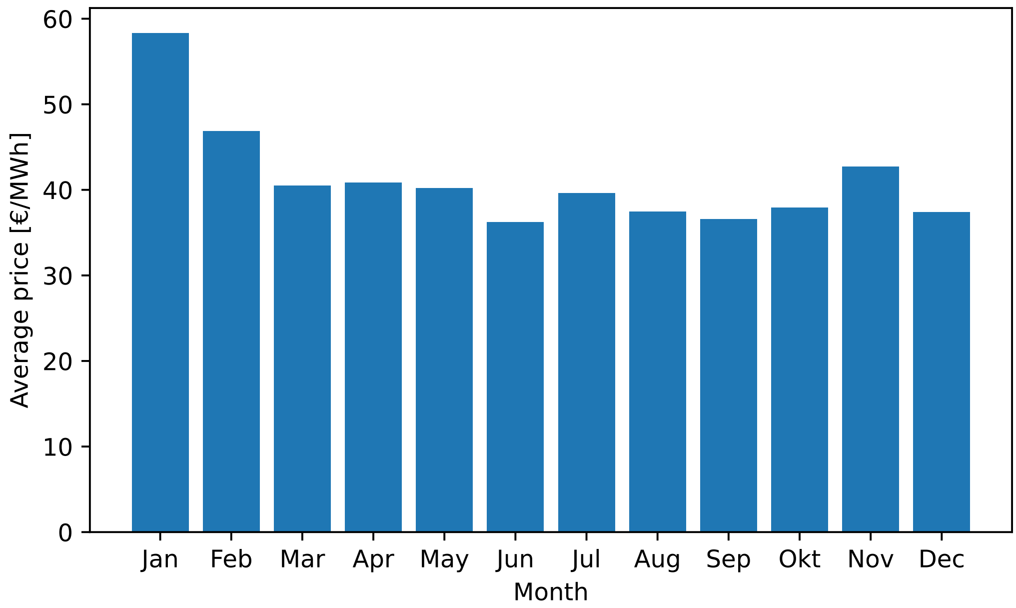


Figure 7.7: Average energy prices in 2019 as a function of Month in the year

Solar power has the same effect on the daily price volatility in both the Danish and German market. Increased solar power reduces daily price volatility. The production of solar power takes place during peak hours, reducing peak prices and thus decreasing volatility. [74]

The weekly price volatility is increased for both the Danish and German market when VRES increases. This is caused by large day-to-day changes in solar and wind generation. [74]

The total effect an increased penetration of variable renewable energy supply will have on the energy prices in unclear and impossible to quantify. Therefore the effect is not taken into consideration. Instead the price fluctuations are dependent on the height of the electricity price. This is further explained in section 7.2.3.

7.2.3. Combining fluctuations to create new data

After identifying the trends in price fluctuations these were used to generate new prices data which is dependent on the historical data but not the exact same. Two methods were used to generate this new data. To understand this method, the format of the data must first be understood. The historical data set with data from 2019 is a data set of 8760 price points p_t consisting of the price "p" and the index "t". The index "t" is a time stamp. This time stamp can be used to extract the hour, date, day of the week etc. For this method the hour (h), day (d), weekday (wd), week (w), and month (m) are used, these are denoted as t.hour, t.day etc. Using these identifiers the data-set is split into set with the same time variable as denoted in eq. (7.1).

$$p_h(h) = \{p_t | t.hour = h\} \tag{7.1a}$$

$$p_d(d) = \{p_t | t.day = d\} \tag{7.1b}$$

$$p_{wd}(wd) = \{p_t | t.weekday = wd\} \tag{7.1c}$$

$$p_{week}(week) = \{p_t | t.week = week\} \tag{7.1d}$$

$$p_m(m) = \{p_t | t.month = m\} \tag{7.1e}$$

for 1 < h < 24, 1 < d < 365, 1 < wd < 7,

The first method uses the absolute difference of the instantaneous price with the average price. This way the delta for the time units hour, weekday and month are calculated. Using these deltas the new price data can be generated by adding the deltas to the new annual average price which is based on the KEV forecast. This way a this way a data-set similar to the historical data set is created. The equations used for this method are given in eq. (7.2). Mean prices are indicated with a bar ($\bar{p}$).

$$p_{new}(t = \{h, wd, m\}) = \bar{p} + \Delta p_h(h) + \Delta p_{wd}(wd) + \Delta p_m(m) \tag{7.2a}$$

$$\Delta p_h(h) = \{mean(p_h(h) - \bar{p})|1 < h < 24\} \tag{7.2b}$$

$$\Delta p_{wd}(wd) = mean(p_{wd}(wd) - \bar{p}) \tag{7.2c}$$

$$\Delta p_m(m) = mean(p_m(m) - \bar{p}) \tag{7.2d}$$

The second method uses factors by which the new annual mean is multiplied. These factors are calculated using eq. (7.3). For example the hourly factor is calculated as follows; first the daily mean, $\bar{p_d}$, is calculated. Each hour data set then has the daily mean subtracted and is divide by the daily mean. This creates a data set with the hourly factors for every hour and every day of the year, averaging the hourly factors over the days of the year then creates the final hourly factors. Mean prices are indicated with a bar ($\bar{p}$).

$$p_{new}(t = \{h, wd, m\}) = \bar{p_{yr}} \cdot f_h(h) \cdot f_{wd}(wd) \cdot f_m(m) \tag{7.3a}$$

$$f_h = mean(\frac{p_h - \bar{p_d}}{\bar{p_d}})|0 < d < 365\&0 < h < 24 \tag{7.3b}$$

$$f_h(h) = \frac{\sum_{d=1}^{365} \frac{p_h(h)}{\bar{p_d}(d)}}{365} \tag{7.3c}$$

$$f_{wd}(wd) = \frac{\sum_{week=1}^{52} \frac{p_{wd}}{\bar{p_{week}}(week)}}{52} \tag{7.3d}$$

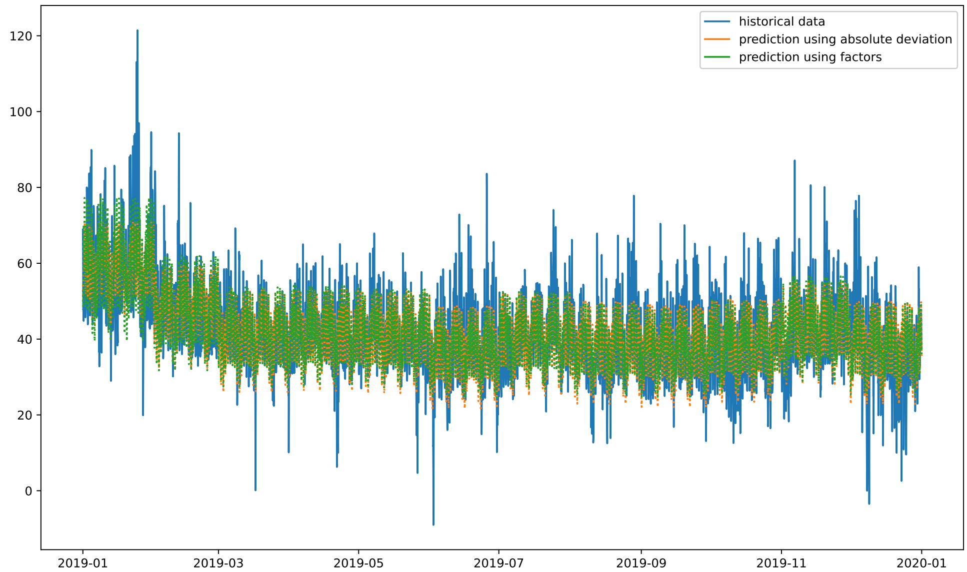
$$f_m(m) = mean(p_m(m)/\bar{p}) \tag{7.3e}$$

The resulting price predictions for both methods are given in fig. 7.8. In these figure it can be seen that the 2 methods are very closely related, however the method using the factors matched the larger price fluctuations found at higher electricity prices better. This can most clearly be seen in January 2019 as shown in fig. 7.8b. For this reason the factor method is used in generating the electricity price data.

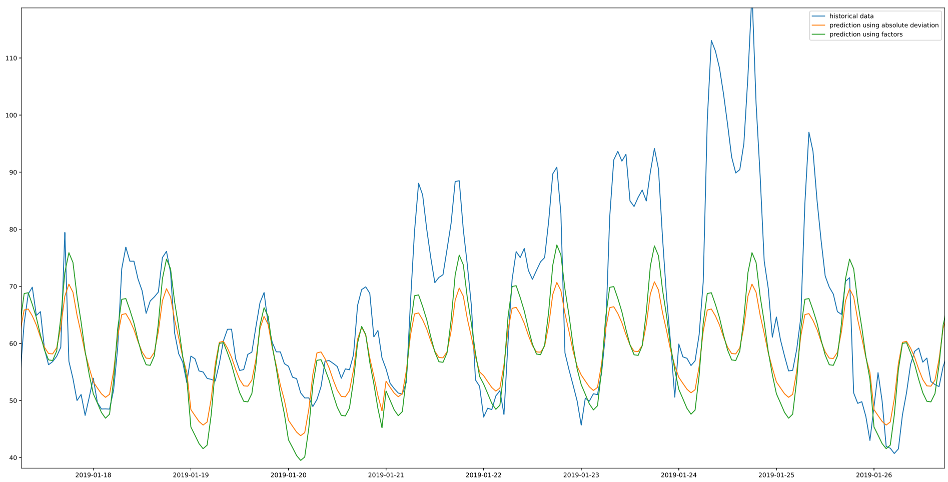
The method of averaging fluctuations has one major drawback, which is that the fluctuations are far less pronounced than in the historical data, this can very clearly be seen in fig. 7.8b. To battle this a noise function was added to the price data. By dividing the historical data by the predicted value, the "noise" in the original data set could be identified. Plotting this "noise" in a histogram, it becomes clear that this data follows a normal distribution quite nicely. Therefore a normal distrubution is fitted to the noise data and new noise data is generated using the same standard deviation. This new noise function is the added to the prediction data to get the final simulated market data. Figure 7.9 shows the new data including the noise.

7.3. Hydrogen price data

The optimisation model needs to be able to decide between hydrogen production or sales of electricity to the grid. In order to do this a time series for the hydrogen price is required. As mentioned in section 2.6.1, no wholesale hydrogen market exist and thus nu historical data of hydrogen prices exist. Most hydrogen is sold bilaterally which also causes a lack of transparency in the hydrogen prices. It was therefore assumed that the price of hydrogen is set by the cost of hydrogen production through steam methane reforming.



(a) Entire year 2019



(b) Zoomed in on January

Figure 7.8: Prices predictions using absolute deviations and factors vs historical data

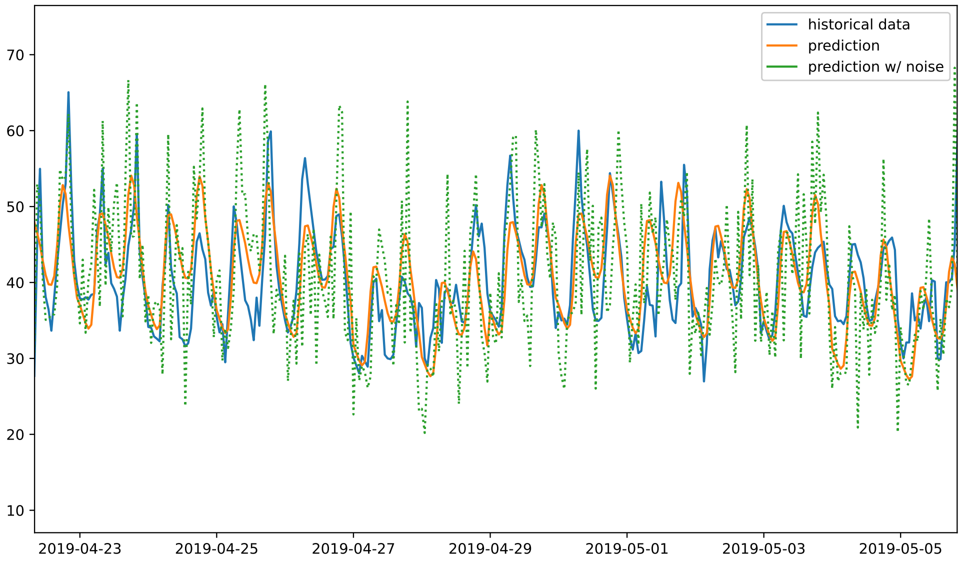
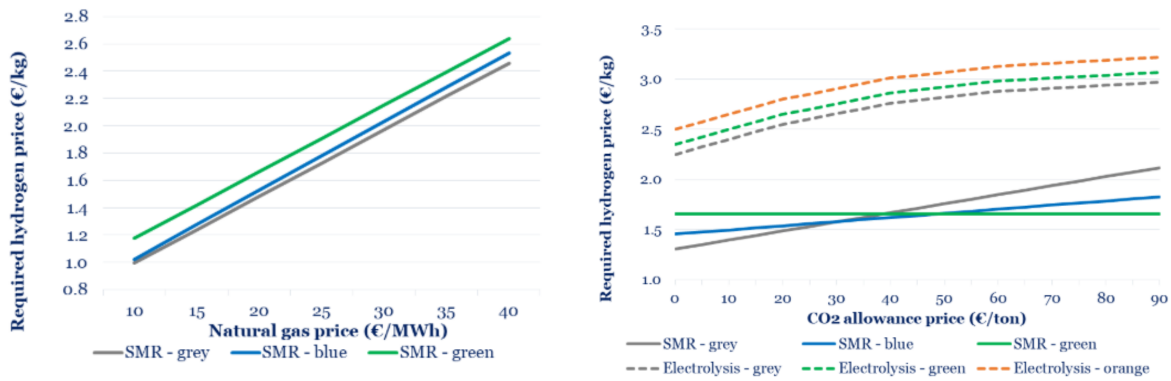


Figure 7.9: Predicted data including noise

7.3.1. The cost of steam methane reforming

The cost of hydrogen through steam methane reforming is dependent on many factors including the depreciation of the machinery used, the price of natural gas and the price of CO_2 emissions. A study Mulder *et al.* [37] predicts the cost of hydrogen through SMR based on these factors. The results of these calculations are presented in fig. 7.10. The relations between the hydrogen price and both natural gas and CO_2 price are linear. Using these linear trends the required hydrogen price can be calculated as a function of the natural gas and CO_2 price. The resulting equations from this extrapolation for grey, blue and green hydrogen are given in eq. (7.4). The meaning of these colors is explained in section 2.6.1, in this case the green hydrogen indicates that the natural gas comes from renewable sources such as biomass.[37]



(a) Required hydrogen price as a function of natural gas price with a CO_2 price of €15 /tonne

(b) Required hydrogen price as a function of CO_2 emissions

Figure 7.10: Results of hydrogen cost calculations

Source: Mulder *et al.* [37]

$$H2_{SMR,grey} = 0.0486 \cdot p_{gas} + 0.0091 \cdot p_{CO2} + 0.3635 \tag{7.4a}$$

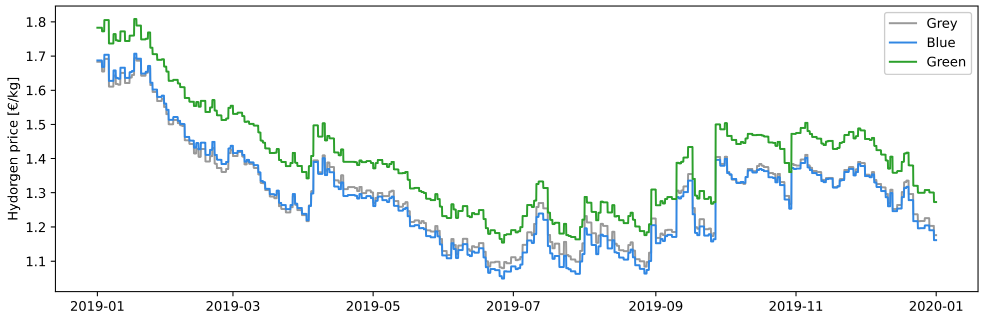


Figure 7.11: Simulated hydrogen prices in 2019 based on natural gas and CO_2 prices

$$H2_{SMR,blue} = 0.0504 \cdot p_{gas} + 0.0042 \cdot p_{CO2} + 0.4495 \tag{7.4b}$$

$$H2_{SMR,green} = 0.0489 \cdot p_{gas} + 0.6839 \tag{7.4c}$$

7.3.2. Simulating a historical hydrogen market

Using the relation between the required hydrogen price and the natural gas and CO_2 price a hydrogen wholesale market can be simulated. The natural gas price is based on the TTF gas futures discussed in section 7.1.3 and the CO_2 emission price is based on the European emissions trading system, discussed in section 7.1.4. The gas price has a resolution of one day meaning the price is set every day, the CO_2 emissions price also has a resolution of one day. Using eq. (7.4), the cost of grey, blue and green hydrogen can then be calculated for every day of the year. The results of this simulated market in 2019 are given in fig. 7.11. In 2019 these simulated price range from €1.1/kg up to €1.7/kg. According to the clean hydrogen monitor 2020[36] the price of hydrogen at volumes over 10 000 tonne is €1.4/kg which is exactly in the middle of this simulated range. It is therefore reasonable to assume that the simulated cost is close to the real price of hydrogen.

7.3.3. Simulating a future hydrogen market

Similar to the electricity price discussed in section 7.2 a time series for the hydrogen price is required for hydrogen. The development of the natural gas price and CO_2 emissions price are based on the ”klimaat- en energieverkenning” [44]. The hydrogen price predictions based on this report are shown in fig. 7.12. The 3 colours indicate the colour of hydrogen produced, note that the green hydrogen is produced through SMR using green natural gas. Furthermore there are 3 sets of price predictions from 2021 onwards, these are based on the different forecasts for the future natural gas and CO_2 prices. The lowest line assumes the lower end of the bandwidth from the KEV, the middle line shows the average and the top line the higher end of the bandwidth. [44]

The predictions shown in fig. 7.12 only give a prediction of the annual average prices, these therefore need to be transformed back into a time-series. In section 7.1.3 and section 7.1.4 it was concluded that there is an annual fluctuation in the gas price but no recognisable annual trend in CO_2 price. Therefore it was chosen to only apply the seasonal fluctuation of the natural gas market to the time series and keep the CO_2 price constant throughout the year.

7.4. Government support & subsidy structure

The subsidy mentioned in section 6.4 the Dutch government offers a subsidy for hydrogen production through electrolysis and electricity production through solar PV. This section gives the height of the subsidy under different scenarios.

7.4.1. Hydrogen production subsidy

The SDE++ subsidy offers a subsidy for hydrogen production through electrolysis. This subsidy is offered in 4 phases, these phases offer an incrementally larger compensation. The chance of getting the subsidy rewarded is larger for the first phases.[43] The subsidy offers a reward for produced

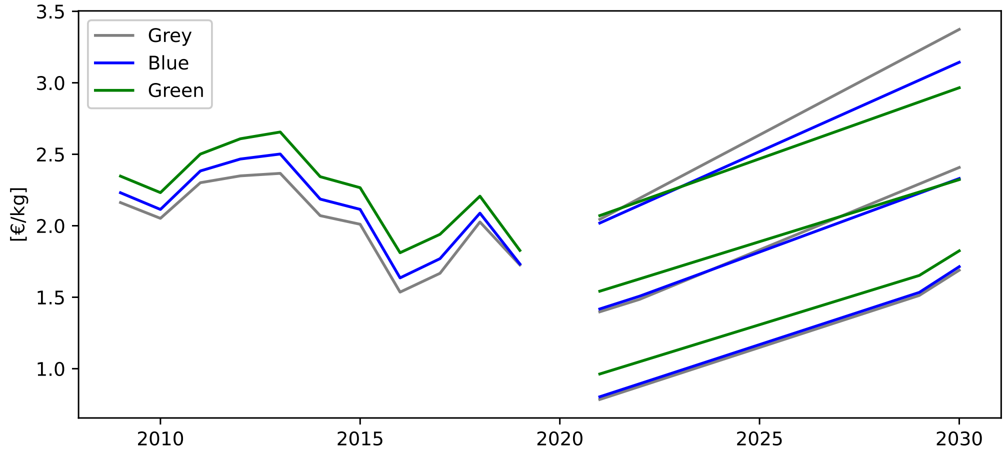


Figure 7.12: Simulated hydrogen prices based on the KEV

predictions for the future show the expected path and and upper and lower bound based on the upper and lower bound of the gas and CO_2 price combined

Table 7.1: SDE Hydrogen amounts 2020

	Max. phase amount			
Unit	1	2	3	4
€/MWh$_{HHV,H2}$	51.2	55.6	76.4	103
€/kg H_2	2.02	2.19	3.00	4.05

hydrogen per kWh of produced hydrogen. Using the higher heating value of hydrogen this value can be converted to a per kg subsidy for the produced hydrogen. The heights of the different phases is given in table 7.1. In the research scenarios the highest amount of subsidy is rewarded to the drastic climate action scenarios. Furthermore next to this the subsidy also decreases over time. The resulting subsidies are given in table B.3.

7.4.2. PV subsidy

This SDE++ solar PV subsidy offers a feed in tariff for electricity generated through various renewable energy sources, including solar PV. The subsidy essentially "tops up" the market remuneration to the submission amount as displayed in fig. 7.13. However if the market remuneration will drop below the base energy price, only the difference between the base energy price and the submission amount will be provided. [43]

The base energy price and submission amount are both set when the subsidy is approved. These prices are then fixed for 15 years, which is the run time of the subsidy. The prices for 2020 are given in table 7.2.

Table 7.2: SDE solar amounts 2020

	Max. phase amount [€/Mwh]				Base energy price [€/Mwh]	
PV type	1	2	3	4	Grid supply	Non-grid supply
Building-mounted	69.4	73.1	74	74	29	51
Ground-mounted	59.5	63.2	69	69	29	51
Ground-mounted tracking	59.5	63.2	69	69	29	51
Floating	59.5	63.2	80	80	29	51
Floating tracking	59.5	63.2	80	80	29	51

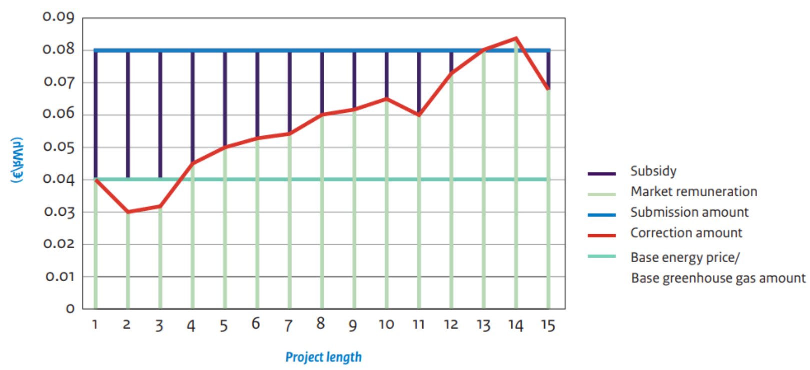


Figure 7.13: Graphical representation of SDE++ subsidy regulations. Source:RVO

7.5. Case study WPF

Windpark Fryslân (WPF) is the subject of the case study for this study. WPF is located in the North of the Ijsselmeer near the afsluitdijk. WPF consists of 89 turbines, each able to produce a nominal power of 4.3 MW, this brings the peak power of the wind farm to 382.7 MW. [76] The wind farm can be expanded with a floating PV farm. The possible configurations this solar farm could take on in given in fig. 7.14. Each layout is able to generate 200 MWp, it is therefore assumed that a maximum of 400 MWp forms a reasonable addition.

The grid connection of WPF has a peak capacity of 440 MV A, this cable is routed underground over a long distance to the connection with the Tennet grid. It is therefore assumed that the grid capacity can not be increased.

7.6. Power generation data

The generation data is predicted based on historical weather data. A data set of 10 years was used to minimise the effect of specific years on the result of the optimisation. The weather data was taken from the start of 2007 until the end of 2016. When the length of the scenario is longer than 10 years the generation data is set to repeat itself. The data for the solar power and wind speed are taken from the same data set to include the correlation between wind and solar power and to include the effect of their simultaneity.

7.6.1. Wind

The wind power generation data is generated using the predicted power curve of WPF and historical wind data. The power curve of WPF relates the power generated by WPF to the local wind speed. The power curve is given in fig. 7.15. The wind speed data is part of the TMY data (Typical meteorological year) of the PVGIS tools used to calculate the solar generation. This tool is discussed in more detail in section 7.6.2. The resulting annual wind power is given in fig. 7.16, this shows a large annual difference in wind power generation. The effect of this difference in wind power is investigated in the sensitivity analysis in section 9.7.

7.6.2. Solar

The tool which was used to generate the PV generation data is called PVGIS, or Photovoltaic Geographical Information System. PVGIS is a web application developed by the EU Science Hub to calculate the possible PV generation at almost any geographical location and for various technologies. This calculation is based on a data base of historical solar radiation data. [53] The PV modules were assumed to be south facing crystalline silicon modules at an angle of 30°. A unit of 1 kW was used for the size of the PV system, the data is then divided by the peak power and used as a unit generation in order to optimise the PV size. The unit of the PV generation data is thus Watt per Watt-peak. The resulting solar data is given in fig. 7.17.

This chapter has presented the data which will be used to run the optimisation model. The results

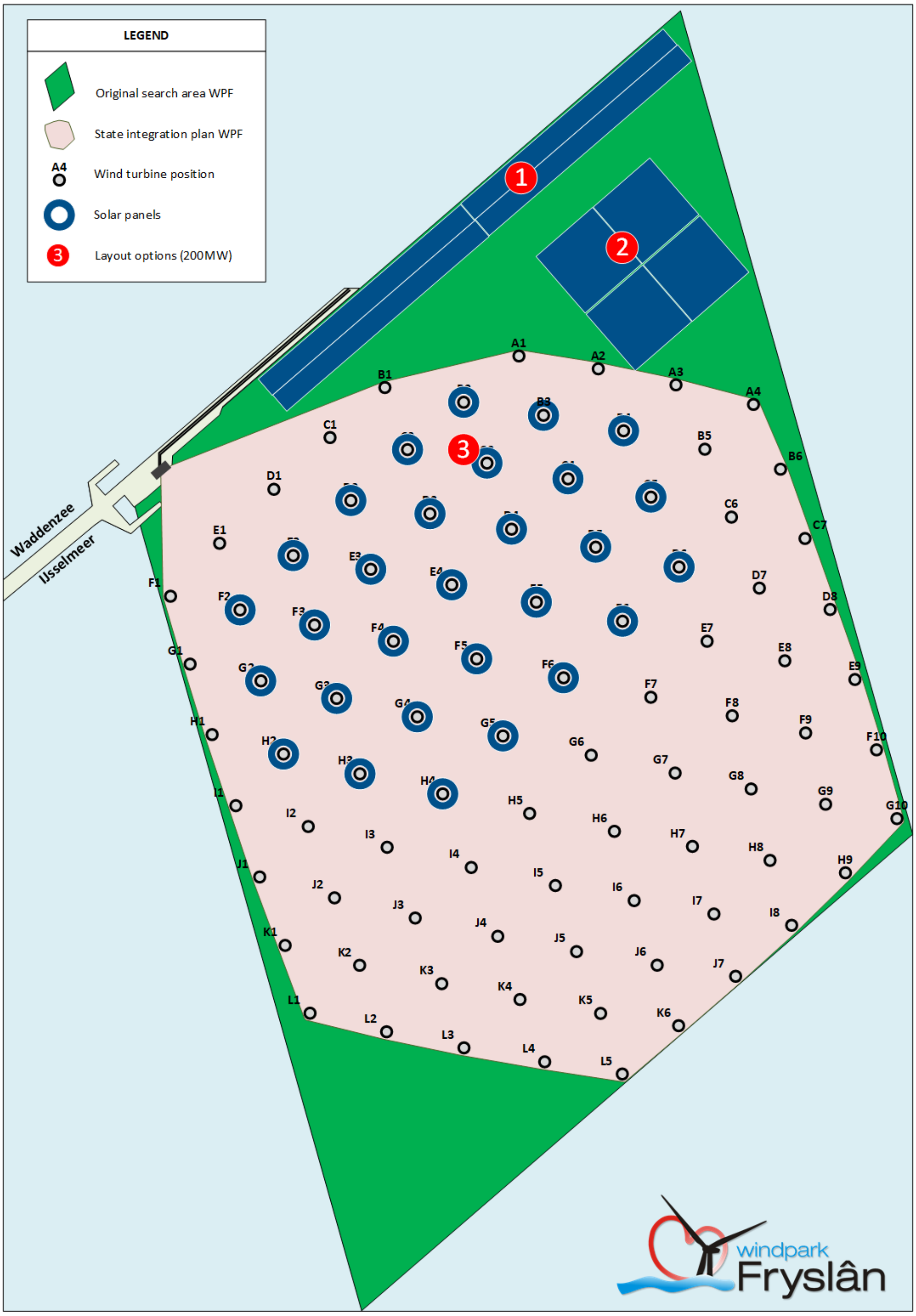


Figure 7.14: Possible layout for floating solar PV

Image provided by Ventolines

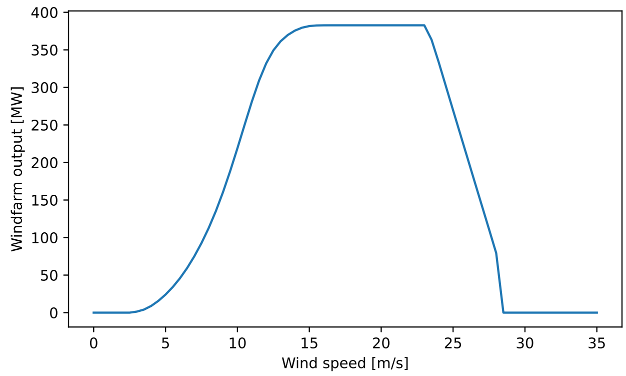


Figure 7.15: Windpark Fryslan powercurve

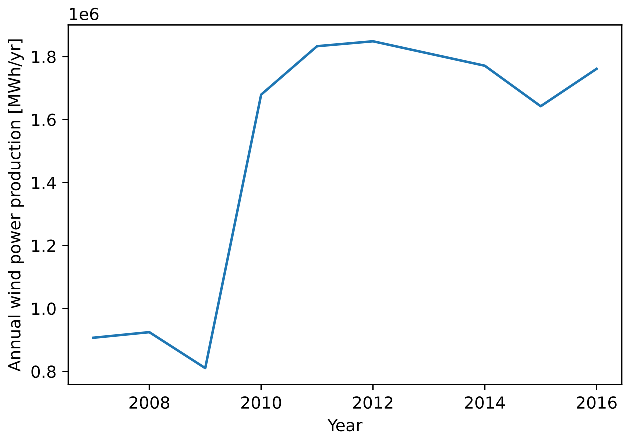


Figure 7.16: Annual wind power generation

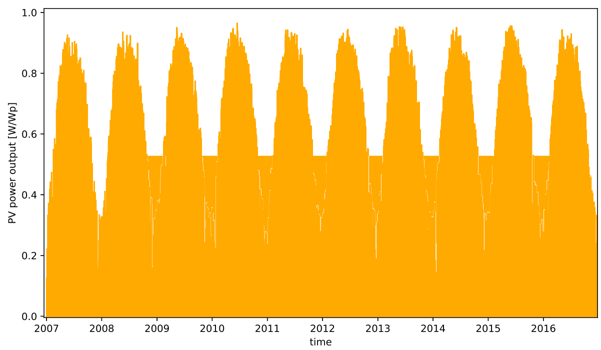


Figure 7.17: PV system unit generation data

of these optimisations will be presented in the next chapter.

8

Optimisation results & discussion

This chapter contains the results of the optimisation of the hybrid plant under the different research scenarios. Firstly the NPV of the hybrid plant for all scenarios is discussed in section 8.1. Then the optimal sizing of the electrolyser and PV system under different scenarios are discussed in section 8.2. As the results of the optimisation are highly sensitive to the inputs, a thorough sensitivity analysis of the results is performed in chapter 9.

8.1. NPV results

The NPV of the hybrid plant under every scenario is given in fig. 8.1. The data was corrected by subtracting the NPV of the wind farm without the solar PV or electrolyser system from the total NPV of the hybrid plant. The result is the NPV of exclusively the PV and electrolyser system (the added NPV). It is found that the electrolyser and/or PV system only create a positive NPV in all scenarios. The NPV is much higher in the drastic climate action scenarios than in the projected and BAU scenarios. The BAU and Projected scenarios are very similar for scenarios starting at the same time. In those scenarios, only a PV system is added, which will sell its energy at the same price. The NPV is slightly higher in scenario 2 as compared to 1 because the subsidy for solar energy is slightly higher in this scenario. An electrolyser is only added in the drastic climate action scenario; this indicates that the electrolyser has a negative NPV in the Projected and BAU scenarios. More details about the sizing of the PV and electrolysers system are given in section 8.2.

One interesting trend, which can clearly be seen in fig. 8.1, is the shift in competitive advantage between Alkaline and PEM electrolyser technology. In scenario 3, the NPV of the Alkaline system is €270 million while the PEM NPV is only €107 Million, a factor 2 difference. However, in scenario 9, the roles have completely reversed. Here the alkaline system has an NPV of €109 Million while the PEM system has an NPV of €207 Million. Several effects can explain the competitive shift from alkaline to PEM. At first, the cost of an Alkaline electrolyser is significantly lower than the cost of a PEM electrolyser, and the lifetime of the alkaline electrolyser is far longer than the PEM electrolyser. This causes the alkaline electrolyser to be more competitive than the PEM electrolyser. However, over time the R&D and thus the prices and lifetime of the PEM electrolysers catch up to the Alkaline electrolysers. For this reason, the marginal cost of hydrogen production becomes more important. Since PEM electrolysers are more flexible in their operation than Alkaline electrolysers, this allows them to operate at moments of low marginal costs only. Hence, PEM technology becomes more competitive. To confirm the suspicion that lifetime plays a large role in the competitiveness between alkaline and PEM electrolysers, a sensitivity analysis with respect to system lifetime is performed in section 9.6.

8.2. Optimal sizing

A good indicator of the competitiveness of the Hybrid plant electrolyser and PV system is the optimal sizing. The optimisation model optimises for NPV. NPV is taken as the indicator for competitiveness; hence the system with the highest NPV is the most competitive system given that scenario. Hence, the larger the optimal size of the system, the more "competitive" the technology is. If the optimisation

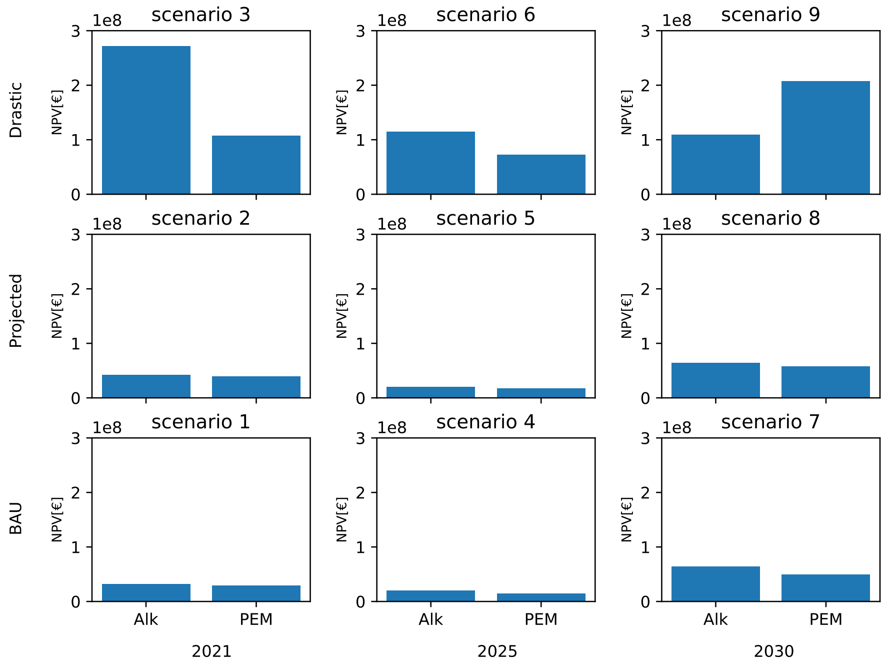


Figure 8.1: NPV of the PV and electrolyser system for each scenario

sets a certain system's size to zero, it has more net present value if the system is not built. However, it does not mean that the system is not profitable. Instead, it means that the profits are not enough to justify the investment.

8.2.1. Electrolyser system sizing

The sizing of the electrolyser of all 9 scenarios is given in fig. 8.2. In this figure, we can clearly see that the projected and business as usual paths do not create a positive NPV. For the drastic climate action pathway, a very large electrolyser is optimal.

The size of the electrolyser is often limited by the fact that the hybrid plant can not be a net importer of electricity on an annual basis. This is because the equivalent hydrogen price is higher than the electricity price most of the time, meaning it is more profitable to create hydrogen. The optimal operation of the hybrid plant is discussed in more detail in section 8.3.

One very interesting trend can be found in the time axis; the optimal size for an Alkaline electrolyser decreases over time while the optimal size of a PEM electrolyser increases. Similar to what was concluded from the NPV, this indicates that there will be a shift in the dominant electrolyser technology in the coming decade.

8.2.2. Solar PV system sizing

The optimal size of the solar PV system for the 9 scenarios is shown in fig. 8.3. It is clear that a PV system should always be added to the hybrid plant. The optimal size of the PV system is dependent on a number of factors. The electrolyser sizing and PV sizing seem highly correlated. Whenever there is a large electrolyser, the PV system will optimise to the maximum value. This is as expected because when the combination of PV and electrolyser is profitable, you want to build as much of it as possible. This is because the electrolyser can minimise the curtailment of solar energy, which minimises the "lost profit" due to curtailment.

The optimal size for the PV system is most often the maximum of 400 MWp. This indicates that adding more PV capacity would make the system more profitable. However, in scenario 4 and 5, the optimal PV capacity is smaller than 400 MWp, indicating that there is an optimum PV capacity. In this optimum, the marginal costs of adding more PV outweigh the additional value they are able to create. in an attempt to find the optimum for other scenarios as well, a sensitivity analysis is performed with respect to the maximum PV capacity in section 9.4.

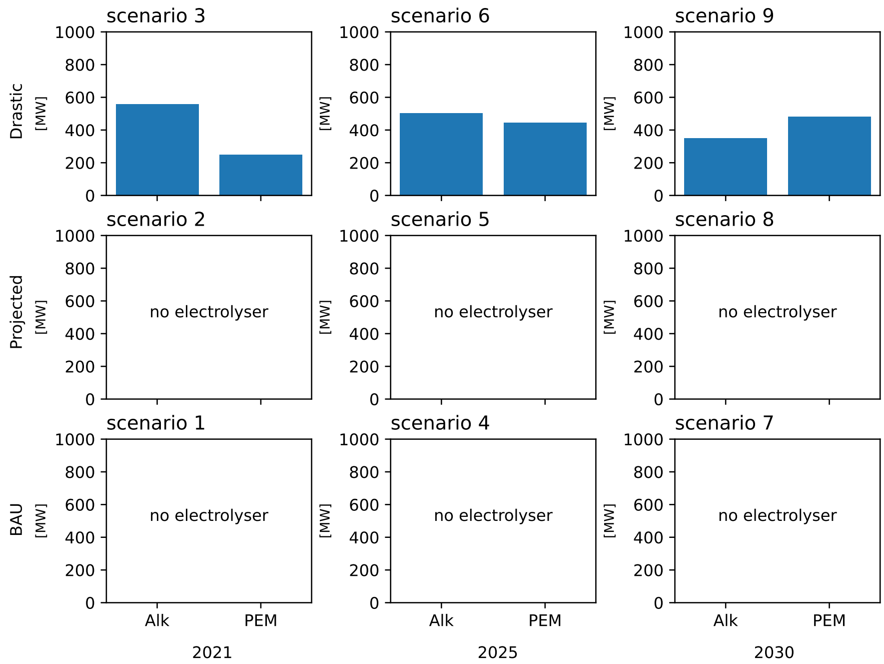


Figure 8.2: Optimal electrolyser sizing for different scenarios

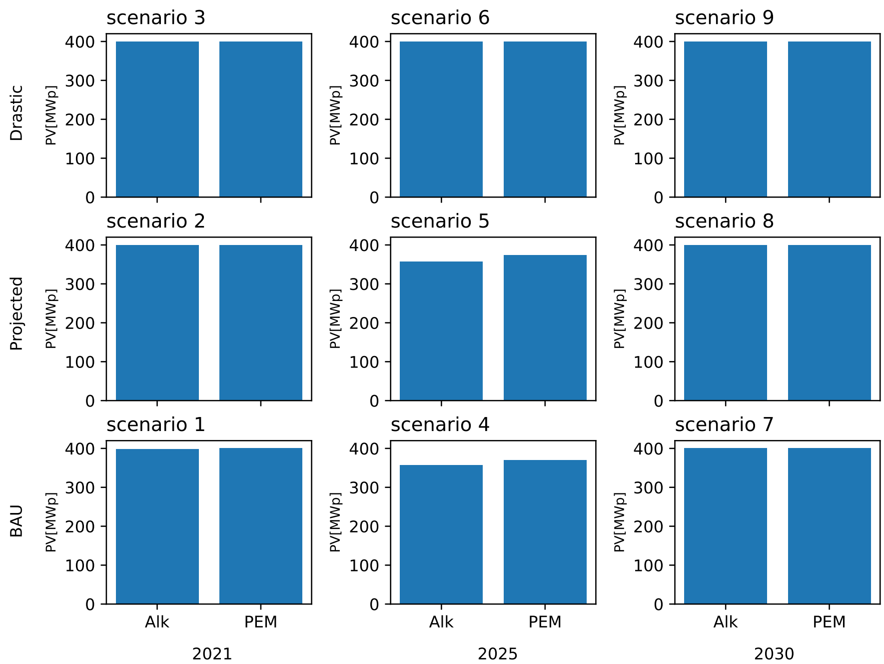


Figure 8.3: Optimal Solar PV system sizing for different scenarios

In conclusion, the size of the electrolyser is heavily dependent on the amount of climate action taken and the electrolyser technology used. Furthermore, the sizing of the PV system and electrolyser are highly correlated. A larger electrolyser means a large PV system and the other way around. From these results, it is unclear whether an electrolyser would also be competitive without the addition of a PV system. To find out whether this is the case, a sensitivity analysis is performed where the maximum allowed PV is set to 0 MWp. A second sensitivity analysis will be performed, increasing the maximum PV capacity to 1000MWp to evaluate whether this is enough to make the electrolyser competitive and what the optimum PV capacity is if it's not limited to 400MWp. The results of this sensitivity analysis can be found in section 9.4.

8.3. Optimal operation of hybrid plant

The average annual energy use per category is given in fig. 8.4. The electricity exchange with the grid is divided into the total import and export. The net annual export is the difference between the two. From the import and export of electricity and hydrogen production, it can be concluded that for most of the scenarios where an electrolyser is built, close to all net electricity production is used to create hydrogen. The system is then bound by the fact that it shall not be a net importer of electricity. However, some combinations of scenario and electrolyser technology do produce a combination of electricity and hydrogen.

In scenario 3, with a PEM electrolyser, the energy used to produce hydrogen is twice the net electricity export. In scenario 9 with Alkaline electrolyser, the combination of hydrogen production and electricity sales also appears. In this scenarios, the energy used to create hydrogen is nearly 80% of the total energy. This indicates that the extra cost of increasing the size of the electrolyser is too high compared to the benefit of being able to produce more hydrogen. This hypothesis is backed by the fact that the electrolyser runs at a very high capacity factor, 0.6, in scenario 3. This high capacity factor is needed to recover the high investment cost of the electrolyser.

In scenario 9 Alk, the reason for the mix of electricity sales and hydrogen production is likely caused by a combination of the lower efficiency of the Alkaline electrolyser as well as the minimum load at which it has to operate. The lower efficiency means that a lower electricity price is required to match the equivalent hydrogen price. This means there are fewer moments where it is beneficial to produce hydrogen. Furthermore, the alkaline electrolyser is relatively small because it still needs to operate at minimum load during moments of high prices. The smaller electrolyser can thus take less advantage of the moments when the electricity price is good for hydrogen production.

Curtailment of energy happens in all projected and business as usual scenarios. In these scenarios, it is beneficial to over-dimension the generation capacity with respect to the grid connection. The amount of curtailed energy scales with the added PV as expected, the more PV, the more curtailment. What's interesting, however, is the fact that these both start off high, then decrease in 2025 and increase again in 2030. This is caused by the combination of PV cost reductions and PV subsidy, which is still present in 2021 but no longer in 2025. In 2021 the subsidy gives an incentive to invest in a larger PV system by supplying more revenue. In 2025 this subsidy is no longer available, reducing the incentive to invest in PV, decreasing the optimal PV size. Then finally, by 2030, the PV cost has been reduced to a point where it is again beneficial to place a larger PV system, and the curtailment does not matter as much.

However what's even more interesting is that for all scenarios with an electrolyser, the curtailment reduces to negligible levels. The only scenario with curtailment here is scenario 3 with PEM electrolyser. However, the curtailment is only 356 MWh per year which is orders of magnitude less than the energy generation. The addition of an electrolyser, therefore, seems like a good method to reduce curtailment.

8.3.1. Optimal hydrogen production capacity factor

The capacity factor of the electrolyser gives an indication of how much of its capacity is utilised throughout its lifetime. The capacity factor, Cf, of the electrolyser is calculated using eq. (8.1). The lifetime of the electrolyser is indicated with T, the energy sent to the electrolyser by $E_{H2}(t)$ and de electrolyser capacity with Cap_{H2}. Hydrogen is only produced in the scenarios where an electrolyser is built. Therefore the capacity factor is only calculated for scenarios 3, 6 and 9 as shown in fig. 8.5. As the SDE++

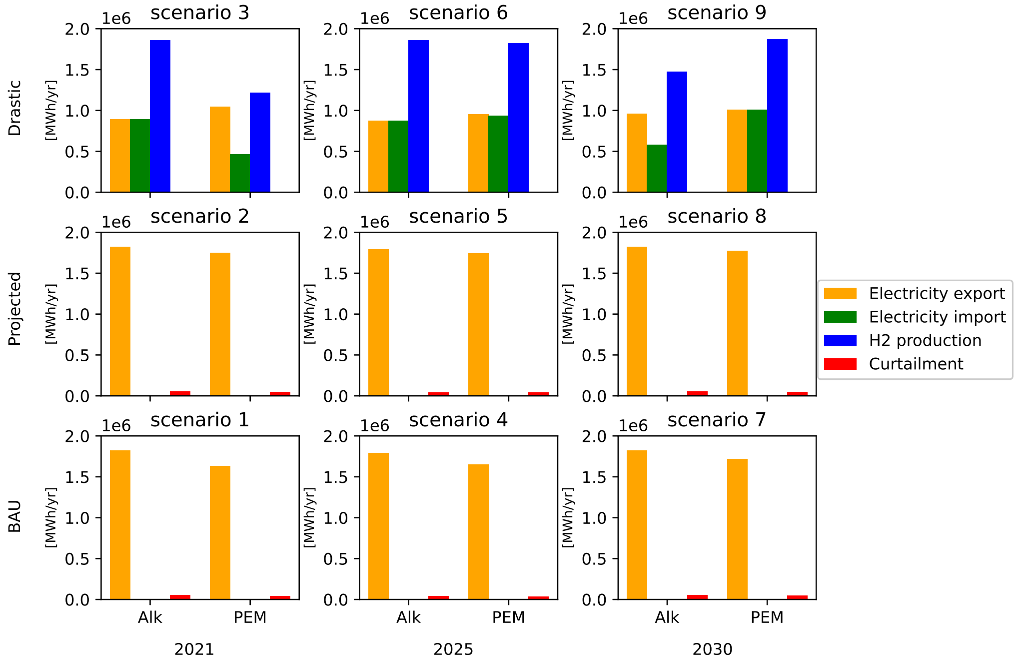


Figure 8.4: Average annual energy use per category

subsidy is only available for a total of 2000 full load hours, a capacity factor of 23% would be expected. However, for all scenarios, it is found that the optimal capacity factor is significantly higher at 39% to 58%. This means that for half of the hydrogen produced, no subsidy is received. In section 9.3 the sensitivity to the number of full load hours is investigated.

$$Cf = \frac{\sum_{t=0}^{T} E_{H2}(t)}{T * Cap_{H2}} \tag{8.1}$$

8.3.2. Insights from scenario comparisons

Many lessons can be learned from comparing the scenarios; this section will highlight the main ones.

The first thing which becomes clear is that adding a solar PV and electrolyser to an existing wind farm will only add value when more climate action is taken than currently projected. This climate action

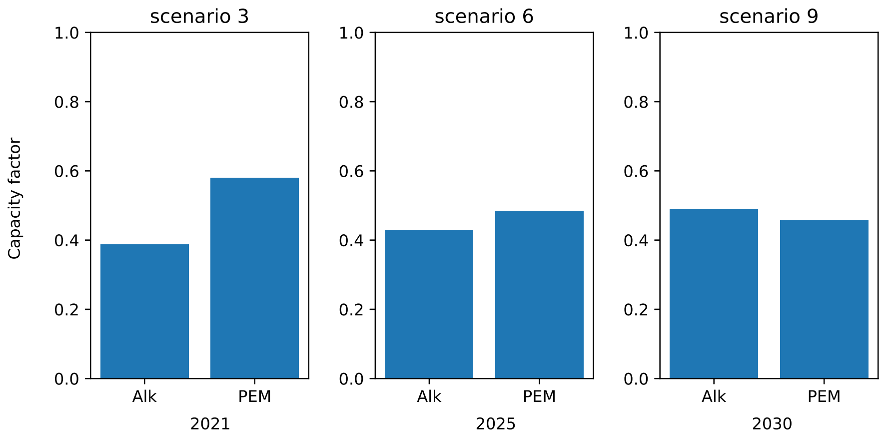


Figure 8.5: Optimal electrolyser capacity factor for different scenarios

is in the form of higher subsidies, natural gas prices and higher CO_2 emissions prices.

From the results of the drastic climate action scenarios (3, 6 and 9), a few interesting trends can be seen. There seems to be a shift from Alkaline electrolyser technology to PEM electrolyser technology. Scenario 3 results in a larger Alkaline electrolyser size and NPV, while in scenario 9, both the size and NPV of the PEM electrolyser are higher. This can be explained in several by several effects. At first, the cost of an Alkaline electrolyser is significantly lower than the cost of a PEM electrolyser, and this causes it to be more competitive than the PEM electrolyser. However, over time the R&D and thus the prices of the PEM electrolysers catch up to the Alkaline electrolysers, and thus the marginal cost of hydrogen production becomes more important. Since PEM electrolysers are more flexible in their operation than Alkaline electrolysers, they become more competitive.

Another interesting trend is the fact that the electrolyser is only added to the system when a PV system is also added. The link between the electrolyser and PV sizing makes does make sense mostly for the reason of curtailment. Because the grid connection can not be increased, adding a large amount of PV would cause a lot of energy to be curtailed. This can also be seen in the sensitivity analysis in section 9.2. In these versions of the Hybrid plant, the total generation of Wind and Solar combined exceeds the grid connection causing large amounts of electricity to be curtailed. An electrolyser can use this "free" energy to create hydrogen. However, the capital costs of the electrolyser should not outweigh the benefits of the lower marginal costs.

Next to the dependence of the electrolyser size on the PV system size, the opposite is also true. An increased electrolyser size allows for more PV to be added to the system. This is again caused by curtailment and the income from the solar PV subsidy. When solar energy is curtailed due to the limited grid connection, it decreases not only the income from electricity sales but also the income from the solar SDE++ subsidy. Increasing the size of the electrolyser will allow the solar energy to still be generated, thus increasing the subsidy income and profitability of the system.

This chapter has presented the results of the optimisation under different scenarios. These give many insights with respect to the hybrid plant's competitiveness. The sensitivity analysis in the next chapter will analyse the sensitivity of the results to several factors providing even more insights and a better understanding of the functioning of the hybrid plant.

9

Sensitivity analysis

The results presented in chapter 8 are dependent on the inputs to the system. This chapter aims to answer the question: *How sensitive is the optimal system to changes in the markets and system parameters and other assumptions?* To see how changes in the inputs affect the optimal system, a thorough sensitivity analysis was performed with respect to the electricity price (9.1), subsidy height (9.2), subsidy coverage (9.3) and weather variability (9.7). The sensitivity analyses were performed by re-evaluating the hybrid plant competitiveness if these parameters were to change.

9.1. Sensitivity to electricity prices

This section will discuss the sensitivity of the optimal hybrid plant to changes in the electricity price. This was done by optimising all 9 scenarios with a low and High electricity price path based on the ”klimaat en energieverkenning” bandwidth[44]. The resulting NPV of these runs, both for the entire system as well as exclusively for the PV and electrolyser system, are given in fig. 9.1 and fig. 9.2 respectively. It becomes very evident that the value of the electrolyser and PV system is very sensitive to the electricity prices. However, the NPV of the system as a whole is relatively constant for scenarios 3, 6 and 9. This highlights the strength of the hybrid plant to add robustness to the system by creating an alternative source of income for moments with low electricity prices.

An interesting trend in the NPV of the electrolyser and PV system, in fig. 9.2, is the contrast between the Drastic and the BAU and Projected scenarios. There is a negative relation between NPV and electricity prices in the drastic scenarios, while in the other scenarios, there is a positive relation. This can be explained by the PV and electrolyser sizing and the way they generate revenue. The electrolyser uses electricity, at a varying price, to produce hydrogen and sells this at a relatively fixed price. The electrolyser will thus benefit from lower electricity prices. The PV system generates electricity, which can be sold at the market price. The PV system thus benefits from high electricity prices. The large electrolyser in the drastic scenarios causes the negative relation between NPV and electricity prices, while the Pv system is responsible for the positive relationships in the other scenarios.

The magnitude of the NPV change indicates the sensitivity to the electricity price. From this, it can be concluded that the electrolyser is more sensitive to the electricity price than the PV system. A threshold effect can explain this sensitivity. The PV system will always generate revenue from electricity sales unless the price is negative. Changes in electricity price will affect the revenue, but they will not affect the operation of the PV system. In the electrolyser, this is different; the electrolyser will only operate in moments when the electricity price is lower than the equivalent hydrogen price. This relation creates a threshold for hydrogen production; a small price change can make the relation cross this threshold. This threshold is the most important factor in shifting from a positive to a negative NPV for the electrolyser.

The sensitivity of the optimal size of the electrolyser and PV systems are given in fig. 9.3 and fig. 9.4. A few things can be learnt from these figures. Again the threshold effect can be seen in the electrolyser size, most drastic scenarios, the electrolyser size drops to zero for high electricity prices. This is because it is no longer profitable to produce hydrogen as the electricity price is higher than the equivalent hydrogen price for the majority of the time. In scenario 2, with Alkaline electrolyser with low electricity prices, the threshold is crossed in the other direction. Here it becomes profitable to add

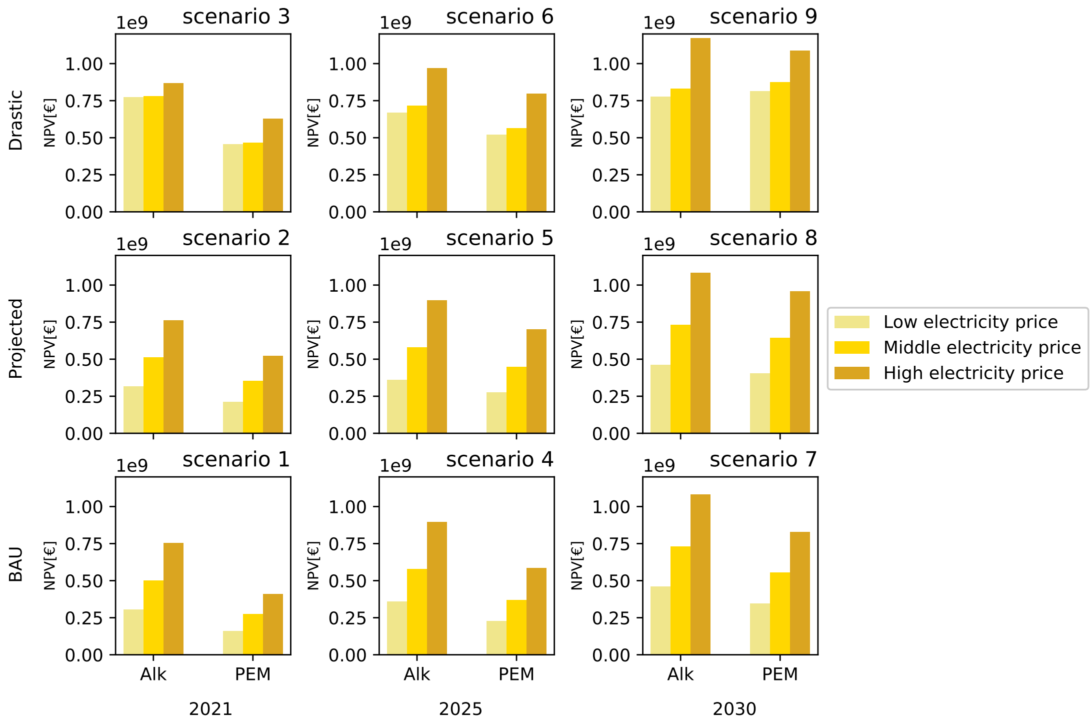


Figure 9.1: Sensitivity of System NPV to electricity price changes

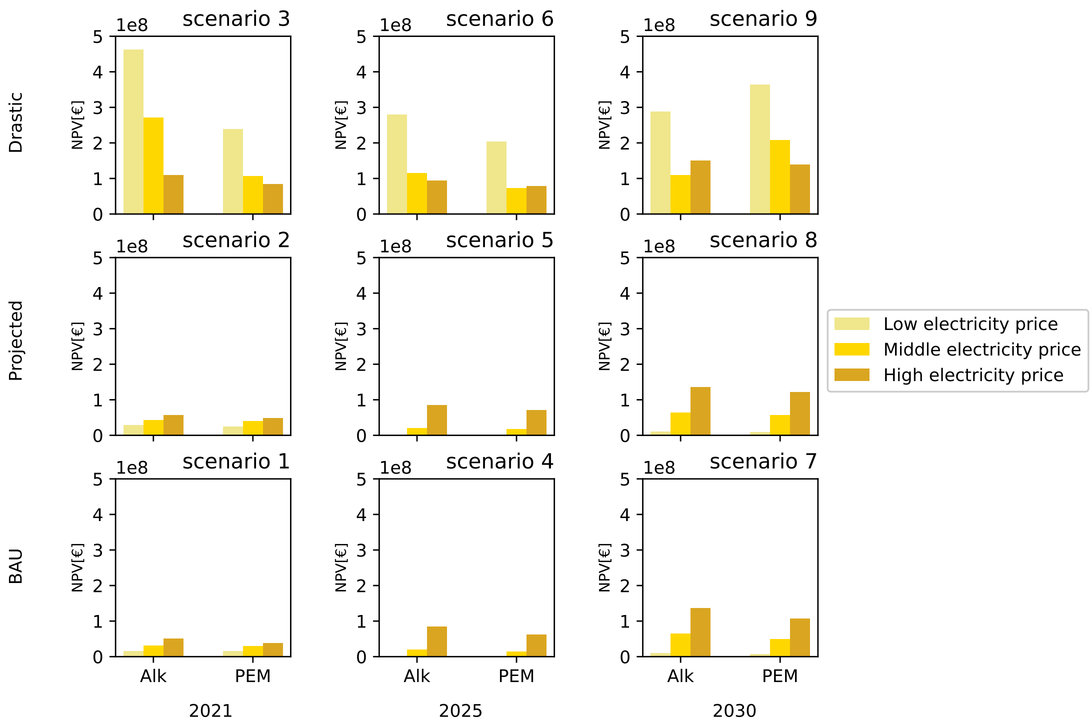


Figure 9.2: Sensitivity of electrolyser and PV system NPV to electricity price changes

a small electrolyser of 60 MW to the hybrid plant. This electrolyser operates at a capacity factor of 0.83, indicating that the electricity price is lower than the equivalent hydrogen price for the majority of the time. Furthermore, this indicates that the capital cost of the electrolyser is very high as many operating hours are necessary to recoup the cost.

One peculiar fact can be noticed in scenario 6 and scenario 9 with the PEM electrolyser. In these scenarios, the size of the electrolyser is larger in the middle electricity price scenario than in the low electricity price scenario. The explanation for this phenomenon gives interesting insights into the working of the hybrid plant system. In all of these scenarios, hydrogen production is bound by the assumptions that the hybrid plant can not be a net importer of electricity annually. In other words, the total annual energy generation is equal to the amount of energy used to produce hydrogen. Since this is only related to the generation, the total hydrogen production depends on the electricity price. The only thing that changes is at what moment the hydrogen is produced. The optimisation model will only choose to produce hydrogen at moments of low electricity price, but it also considers the capital cost of the electrolyser. A larger electrolyser will offer more flexibility of when to produce hydrogen and thus the electricity price at which hydrogen is produced. A smaller electrolyser will incur less cost to the system. The optimisation thus has to trade-off between capital cost and marginal cost. It turns out that when electricity prices are low, it is favourable to have a smaller electrolyser operating at a higher capacity factor because this lowers capital cost. Flexibility is less important in this case because the equivalent hydrogen price is almost always higher than the electricity price. However, in the middle electricity price scenarios, flexibility is favoured over capital cost because the electricity price is often higher than the equivalent hydrogen price. These results underline the fact that not only the average prices but also the price volatility is very important for the competitiveness of the electrolyser.

The importance of price volatility and electrolyser flexibility is also clear in scenario 9. When the electricity prices are high in this scenario, only the PEM electrolyser is competitive; this is caused by the fact that, on average, the electricity price is higher than the equivalent hydrogen price. However, the PEM electrolyser can take advantage of the price volatility to produce hydrogen only at moments of low electricity prices; this way, it can be competitive where the less flexible alkaline electrolyser is not competitive.

The PV system appears in nearly all scenarios and is often optimised to the maximum of 400 MWp. However, in scenarios 4 and 5 with low electricity prices, it is no longer profitable to add a PV system to the hybrid plant, and thus it is optimised to 0 MWp. In scenario 6, however, the electricity prices are the same, but the PV system is optimised to 400 MWp. This is because the energy generated by the PV system can be used in the electrolyser to generate a profit. At these electricity prices, a PV system by itself is not competitive but combined with an electrolyser, it is. This further confirms the hypothesis that a combined wind, solar and electrolyser plant is more competitive than the individual systems.

In many scenarios, the PV system appears even without the addition of an electrolyser. In these scenarios, a significant amount of the produced energy is curtailed as the grid connection does not allow all energy to be exported. This supports the problem stated in chapter 2 that renewable energy is often curtailed without sufficient implementation of energy storage. Even without adding an electrolyser, there is an optimum amount of PV that can be added. However, this is often more than the maximum 400 MWp; therefore, this number is increased to 1000 Mwp for one run of all scenarios. The results of these runs can be found in section 9.4

9.2. Sensitivity to hydrogen subsidy height

To investigate the effect subsidy height has on the Hybrid plant, all scenarios were run with the maximum height of hydrogen subsidy possible according to the SDE subsidy in 2020.

A large change in NPV can only be seen in scenarios 6 and 9. This is because a large amount of hydrogen is only produced in drastic scenarios. In scenarios 3, there is no change in NPV because the normal run already includes the maximum subsidy. In scenario 8, with an alkaline electrolyser, the NPV increases, but only by a small amount, from €64.2 million to €66.0 million. This increase is caused by the small electrolyser, which is optimal in this scenario.

The optimal size of the PV system is not affected by the hydrogen subsidy. This is likely caused by the fact that the PV system is already at its maximum allowed size in most scenarios.

Figure 9.6 shows the effect of the subsidy increase on the optimal sizing of the electrolyser. The effect is small for the drastic climate action scenarios, but a small increase in electrolyser sizing can be

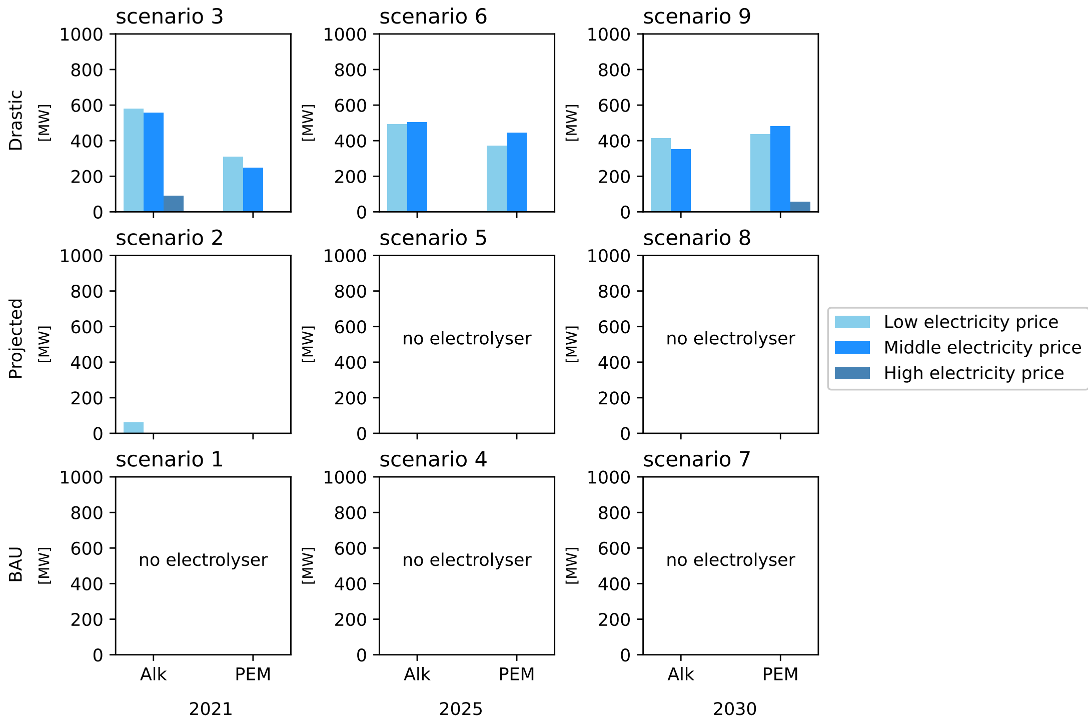


Figure 9.3: Sensitivity of optimal electrolyser size to electricity price changes

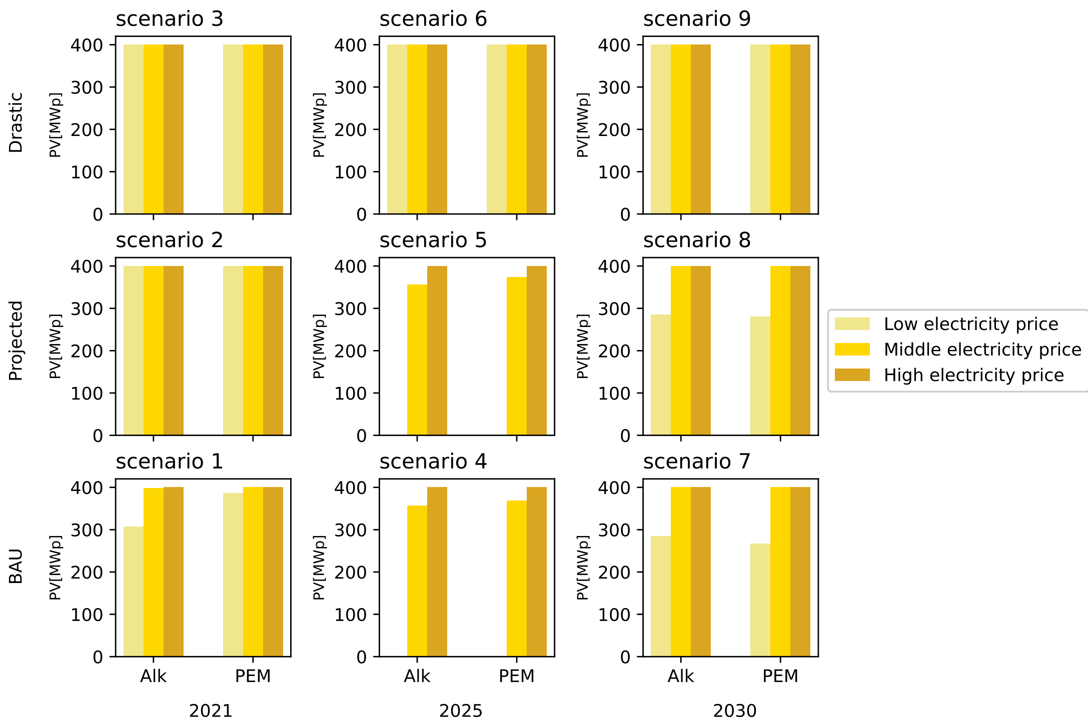


Figure 9.4: Sensitivity of optimal PV size to electricity price changes

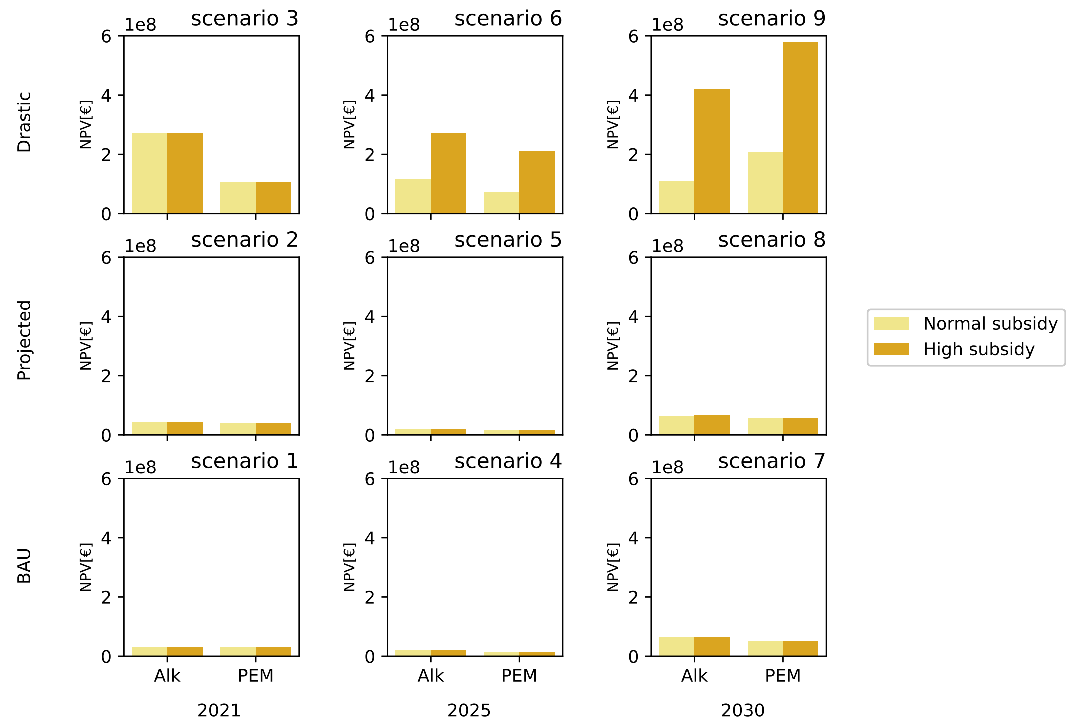


Figure 9.5: Sensitivity of optimal NPV of the solar system and electrolyser to subsidy height change

seen for scenarios 6 and 9. In these scenarios, the capacity factor decreases, resulting in similar total hydrogen production, where on a net annual basis, all energy is used to create hydrogen. The increase in electrolyser size is caused by the limited full load hours for which the electrolyser can receive the subsidy. With a larger electrolyser, more hydrogen production is subsidised and therefore, with high subsidies, it is more beneficial to have a larger electrolyser operate at a lower capacity factor.

The projected and business as usual scenarios show that only in scenario 8 an alkaline electrolyser of 51 MW appears. In this case, the hybrid plant will mainly export electricity directly, as shown in fig. 9.7. The electrolyser is mostly used to produce hydrogen directly from the wind and solar generation as the imported power is minimal. The electrolyser can reduce curtailment to roughly half what it would be without the electrolyser (as seen in scenario 7).

The results of this sensitivity analysis indicate that the effect of the subsidy increase is not enough to make electrolysers competitive with steam methane reformers until approximately 2030 for the projected and business as usual scenarios. Only by 2030 is it enough to support a small alkaline electrolyser. The small effect the subsidy height has on the competitiveness is likely caused by the limited full load hours at which it is available. section 9.3 will investigate what the effect of an increased amount of full load hours would be on the competitiveness of the electrolyser and hybrid plant as a whole.

9.3. Sensitivity to subsidy coverage

The sensitivity of the hybrid plant competitiveness to the number of full load hours awarded by the SDE subsidy for the electrolyser is analysed in this section. This analysis was performed by doubling the full load hour of the electrolyser to 4000 hours and optimizing every scenario. 4000 hours corresponds to a capacity factor of 46%, which is much closer to the range in which the electrolyser is expected to operate according to the results in chapter 8. The resulting electrolyser sizing and NPV are given in fig. 9.8 and fig. 9.9.

The increase in Full load hours has a very large impact on the NPV of scenario's where it is optimum to have an electrolyser. In these scenarios, the NPV of the solar and electrolyser system is often doubled

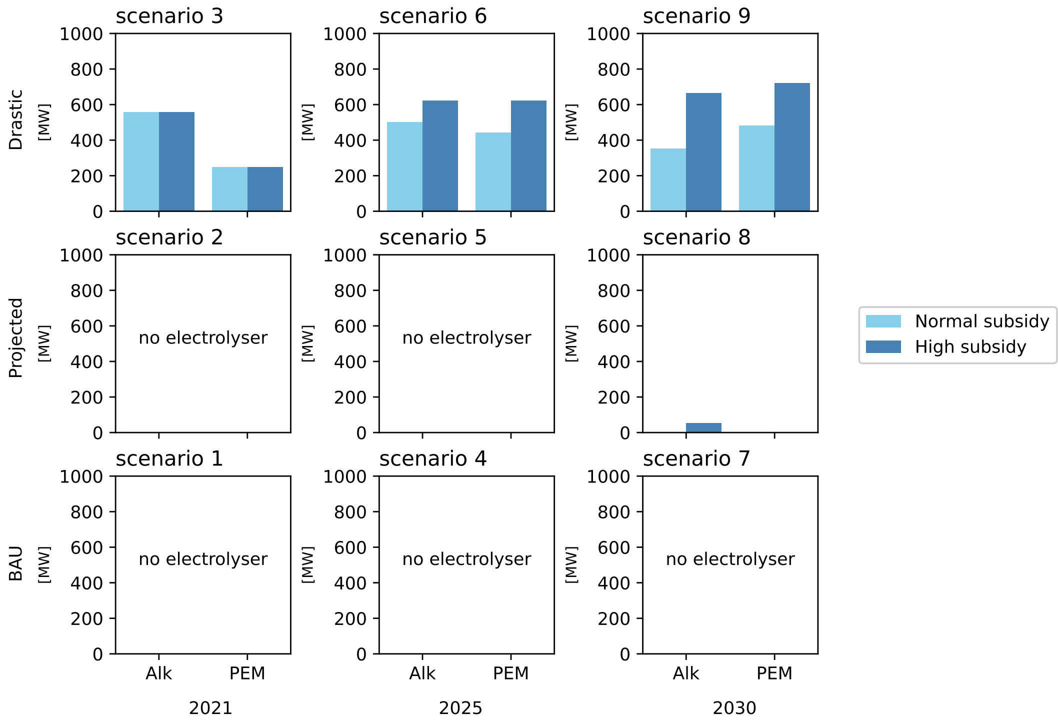


Figure 9.6: Sensitivity of optimal electrolyser size to subsidy height change

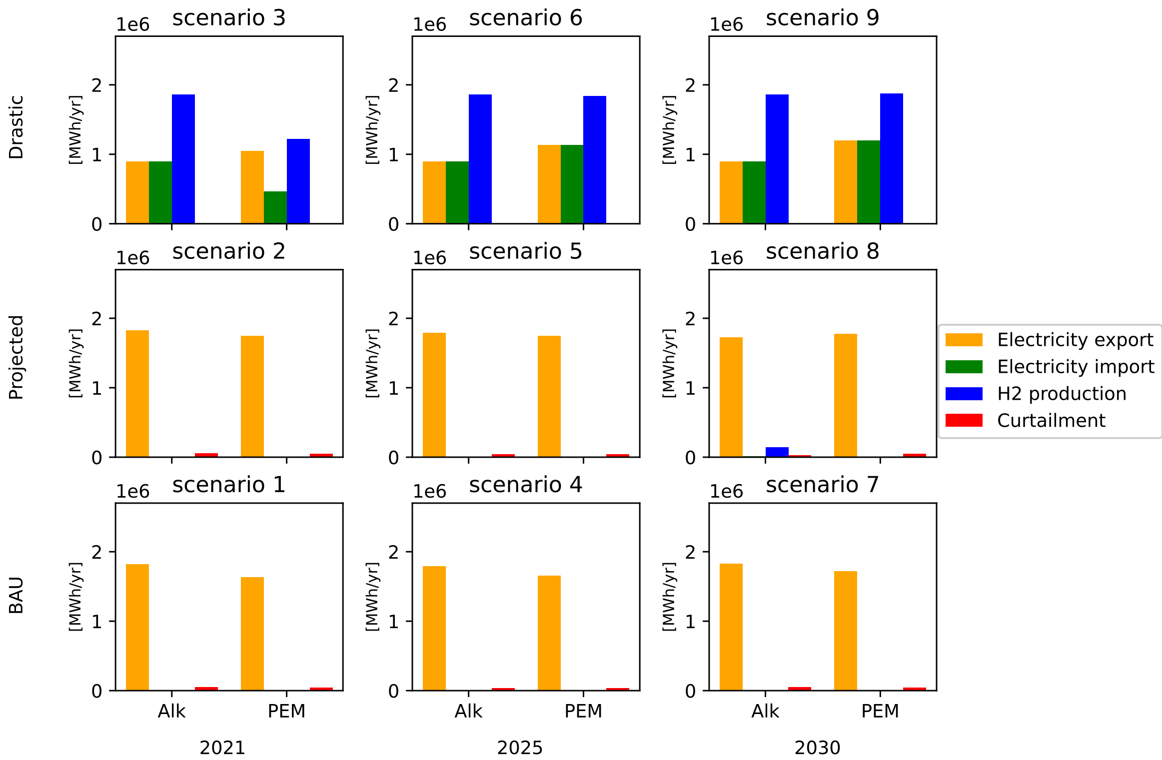


Figure 9.7: Average annual energy use per category with high subsidy

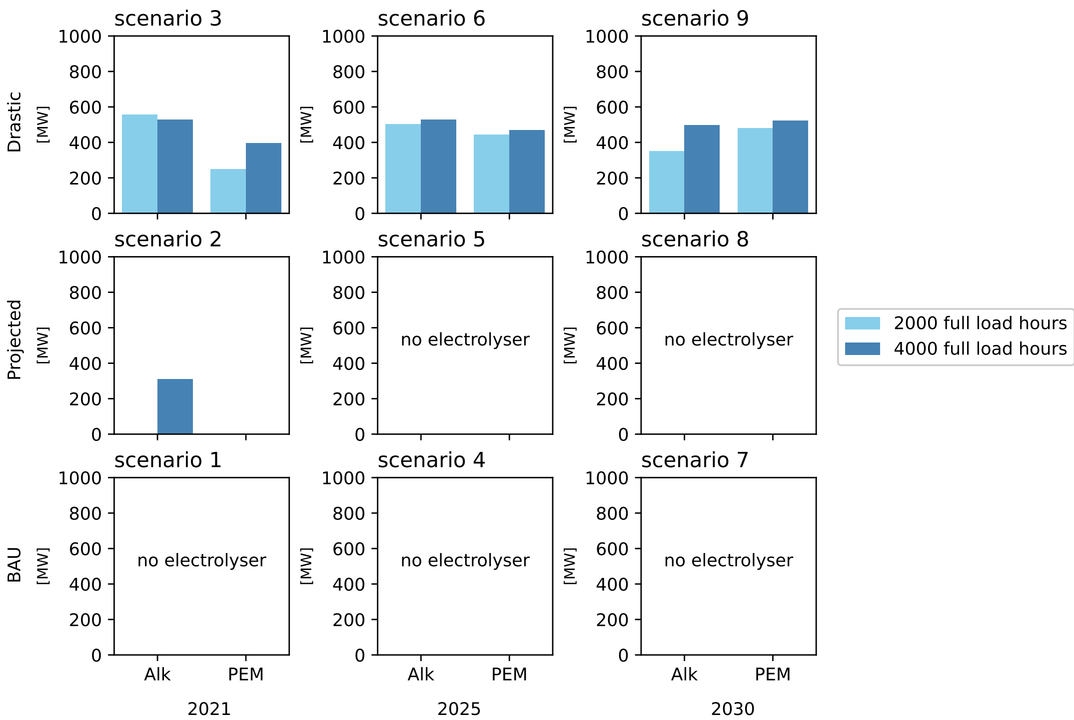


Figure 9.8: Sensitivity of electrolyser sizing to subsidy full load hours increase

and nearly quadrupled in scenario 6. Most importantly, it flips the NPV of the Alkaline electrolyser in scenario 2 from negative to positive. This allows an electrolyser to be feasible in this scenario.

The effect of the increase in full load hours on the electrolyser sizing is small for most scenarios apart from scenario 2. In this case, the change in subsidy does have a significant effect on the sizing. Here a 311 MW alkaline electrolyser appears, indicating that the increase in full load hours makes the alkaline electrolyser competitive in this scenario. The electrolyser operates at a capacity factor of 0.47, corresponding to 4122 annual full load hours. In this case, the subsidy matches the actual operation of the hybrid plant much better. In all Drastic scenarios, the additional subsidy increases the size of the electrolyser as expected. A larger electrolyser leads to more subsidised hydrogen production, which leads to higher revenues and NPV.

In scenario 3 with Alkaline electrolyser, however, the optimal size of the electrolyser decreases when the full load hours increase. This is caused by the fact that in the original results, the electrolyser already runs at a relatively low capacity factor of 0.39. Therefore it makes sense to decrease the size of the electrolyser to increase the capacity factor to use the electrolyser more. This way, the capital cost can be reduced while the income is still the same as the subsidy is no longer bound by the full load hours.

Another interesting fact to note about the capacity factors of the electrolysers and their operation is that in scenarios 6 and 9, the capacity factor is lower than 0.47. This indicates that it is beneficial to have a relatively large electrolyser to allow for more flexibility. The optimal capacity factor is always between 0.40 and 0.47.

From this analysis, it can be concluded that the competitiveness of the electrolyser is highly sensitive to the subsidy coverage. An increase to 4000 hours makes electrolyser feasible in scenario 2. However, it is not enough for the other BAU and projected scenarios.

9.4. Sensitivity to maximum PV farm size

To analyse the sensitivity of the optimal hybrid plant to the PV size, two analysis were performed, one with a maximum allowed PV size increased to 1000MWp and one decreased to 0 MWp. The analysis with 0 MWp PV was only performed on the drastic scenarios as these are the only ones where an

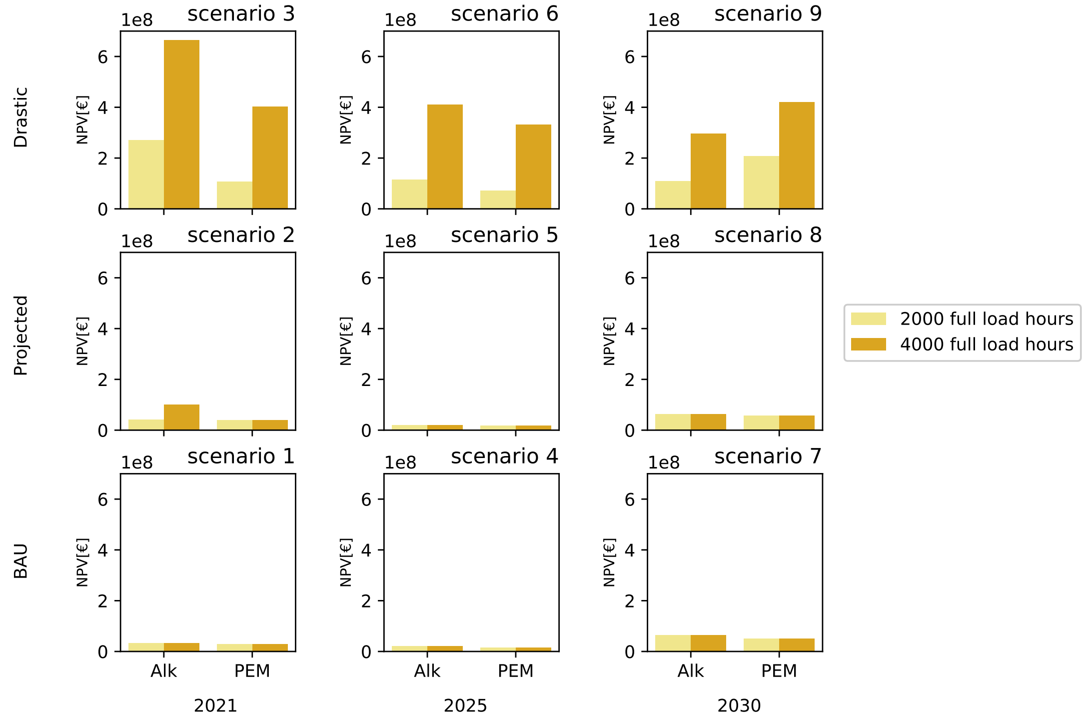


Figure 9.9: Sensitivity of solar PV and electrolyser NPV to full load hours increase

electrolyser is feasible.

PV optimal PV size is given in fig. 9.11. In this figure, an interesting trend can be found between the PV size and the presence of an electrolyser in the system. In all scenarios with an electrolyser, the PV size is optimal at its maximum allowed value. However, in the other scenarios, a different optimum is found. In these scenarios, the generation of electricity is limited by the grid connection. The optimum is found at a point where adding more PV does not increase the NPV. This is caused by the fact that if more PV is added to the system, a larger fraction of the energy it can produce will be curtailed. This point is determined by the relation between the PV capital cost and the energy prices. Surprisingly the optimal PV size is often larger than the grid connection. This means that not all electricity can be exported at moments of peak production, and a large fraction will be curtailed.

The optimal size of the electrolyser for all scenarios is displayed in fig. 9.10. In the projected and business as usual scenarios, an electrolyser is still not competitive. Instead, it is better to place a smaller PV farm in these cases. In the drastic scenarios, even without PV, the electrolyser is competitive and therefore added to the wind farm. In these scenarios, the electrolyser sizing behaves as expected. When the size of the PV system is increased, the size of the electrolyser follows and vice versa. This supports the hypothesis that the PV system and electrolyser support each other. This can also be seen in the NPV of the PV and electrolyser system in fig. 9.12

In conclusion, an electrolyser is only competitive in the drastic climate action scenarios, even when the maximum allowed PV capacity is increased to 1000 MWp. However, in the drastic scenarios, the electrolyser is also competitive without a PV system.

9.5. Sensitivity to electricity import

In section 8.3 it is found that the hybrid plant will often import electricity from the grid when an electrolyser is placed. However, regulations or transmission system operators might not allow electricity to be imported in some cases. To evaluate the effect of such regulations, scenarios 3, 6 and 9 are evaluated assuming no electricity can be imported from the grid.

The optimal electrolyser with and without the import of electricity can be found in fig. 9.13. The first thing that stands out is that an Alkaline electrolyser is no longer feasible when electricity can not

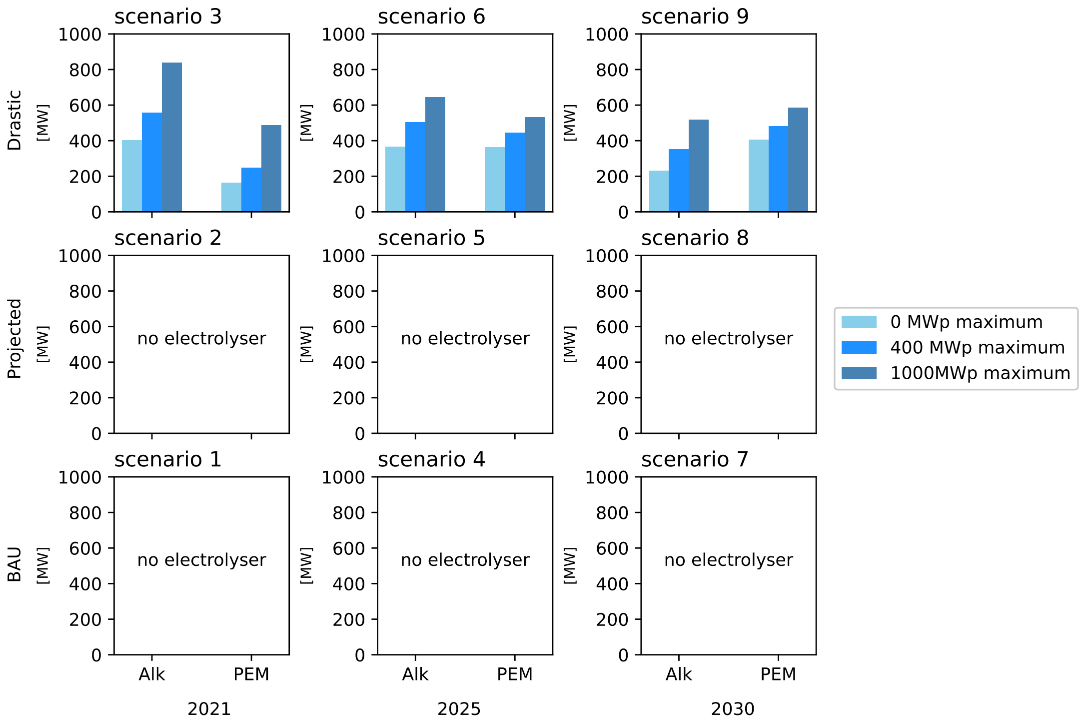


Figure 9.10: Optimal electrolyser sizing at different maximum PV levels

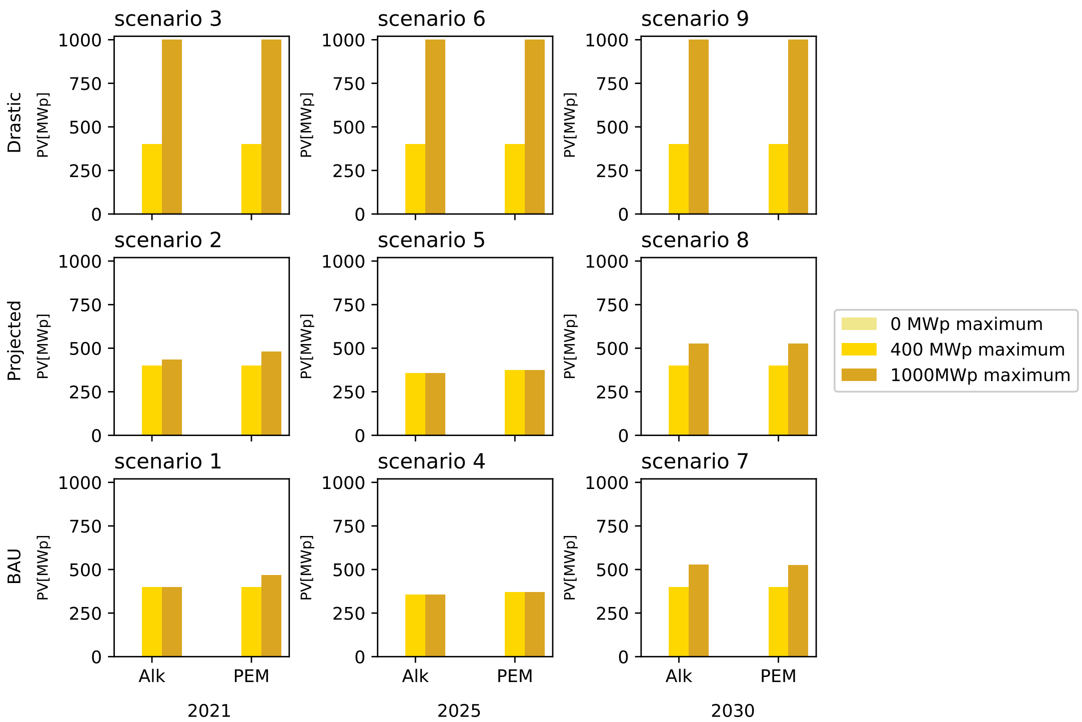


Figure 9.11: Optimal PV sizing at different maximum PV levels

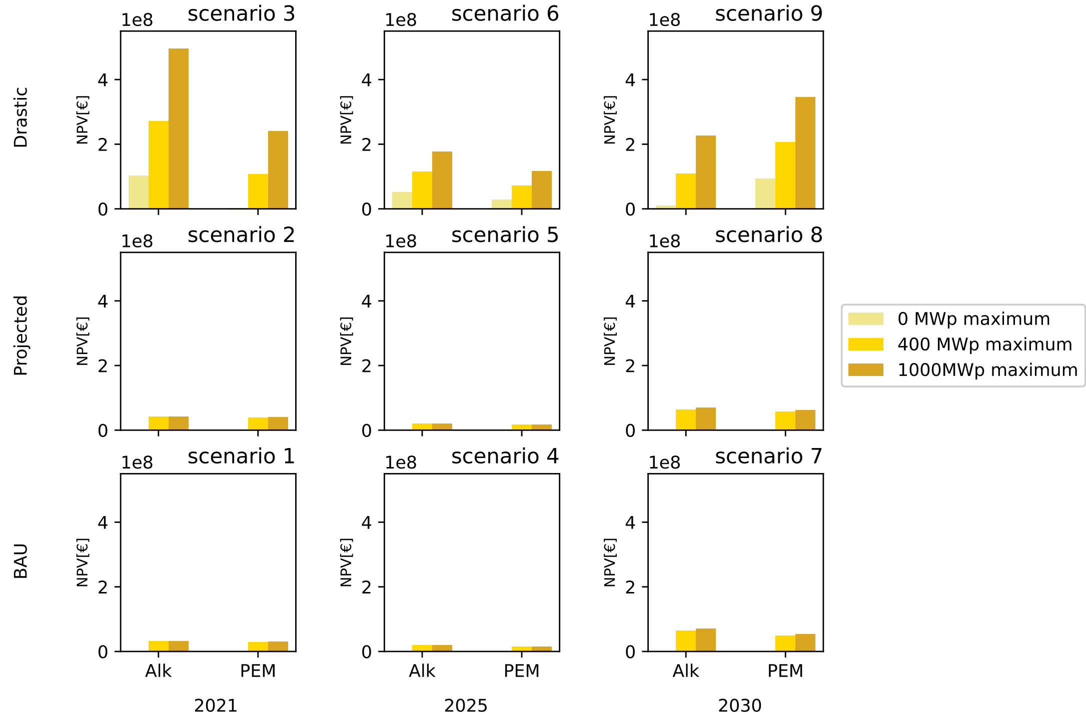


Figure 9.12: Optimal electrolyser sizing at different maximum PV levels

be imported. This is caused by the fact that the Alkaline electrolyser always needs to operate above its minimum load. Since there are always moments when no electricity can be generated by the solar and wind farm, electricity needs to be imported to operate the electrolyser. Because import is not possible, an Alkaline electrolyser is not possible.

PEM electrolysers can ramp down to 0% load. This allows them to be feasible even without import. However, a significantly smaller electrolyser is optimal in this case compared to the case with import. In these cases, the majority of electricity is exported to the grid as shown in fig. 9.16. Without import, a smaller electrolyser is optimal because the electrolyser is able to produce hydrogen only when the wind farm and/or solar farm are generating electricity and the electricity price is lower than the equivalent hydrogen price. However, wind and solar generation happen mostly during the day, while the lowest electricity prices occur at night. For this reason, the electrolyser will be able to operate less. Because the electrolyser operates less when no import is possible, it is better to have a smaller electrolyser to reduce capital cost.

The optimal PV size is displayed in fig. 9.14. In most cases, nothing changes when the import of electricity is eliminated as it is optimal to keep the maximum 400 MWp. However, in scenario 6 with Alkaline electrolyser, the optimal PV capacity is reduced to 363 MWp. This is caused by the fact that an electrolyser is no longer feasible in this scenario. This causes more energy to be curtailed as the grid connection limits the export. Because a part of the electricity has to be curtailed, adding as much PV as possible is no longer feasible. This is another confirmation that the combined wind, solar and electrolyser plant is more competitive than the sum of its parts.

The NPV of the PV system and electrolyser are given in fig. 9.15. In all cases, the NPV of the system is lower when the import of electricity is not possible. This is as expected as in all alkaline electrolyser cases, the electrolyser is no longer possible, but even in the PEM electrolyser scenarios, the NPV drops significantly. The reduction of NPV for the PEM electrolyser for scenario 3, 6, and 9 are 14%, 55% and 46%, respectively.

From the observations above, it becomes clear that the import of electricity greatly influences the electrolyser sizing and NPV of the hybrid plant. The aim of developers should therefore always be to have the ability to import electricity for use in the electrolyser.

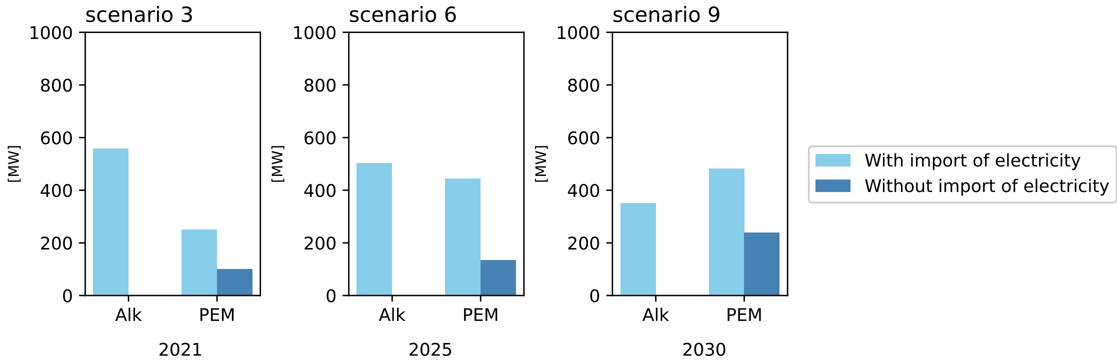


Figure 9.13: Sensitivity of electrolyser sizing to electricity import

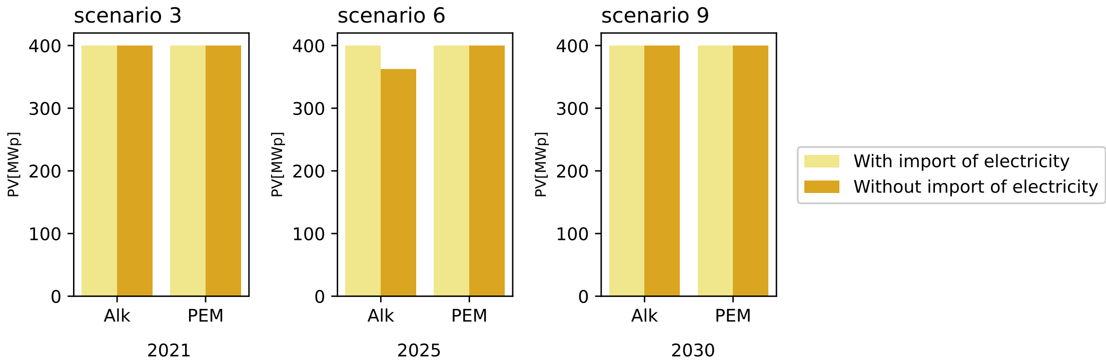


Figure 9.14: Sensitivity of PV sizing to electricity import

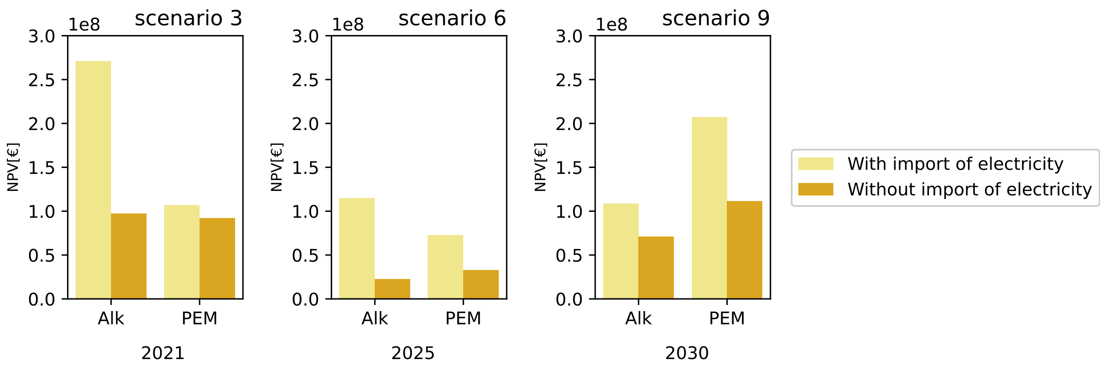


Figure 9.15: Sensitivity of Hybrid plant NPV to electricity import

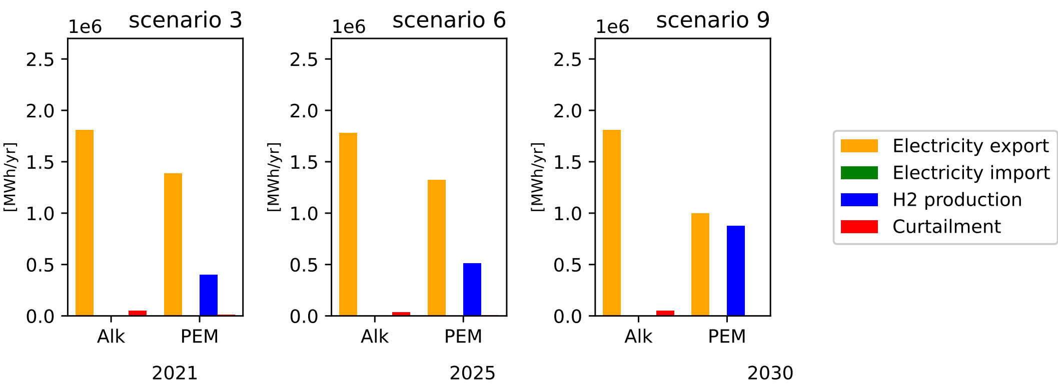


Figure 9.16: Average annual energy use per category without electricity import

9.6. Sensitivity to system lifetime

One major assumption taken in the analysis of the hybrid plant is that the lifetime of the electrolyser is based solely on the calendar life of the electrolyser. Furthermore, little is known about PEM electrolysers' practical lifetime as it is a relatively new and immature technology. To test the sensitivity to the system lifetime, all scenarios were run with an electrolyser lifetime of 15 years.

The increase in lifetime is expected to increase the competitiveness of the hybrid plant significantly. An increased lifetime allows the capital cost to be paid back over a longer period of time, effectively decreasing the annual depreciation of the system.

The optimal electrolyser size for the different scenarios is given in fig. 9.17. The first thing that stands out is that for the business as usual and projected scenarios, not building an electrolyser is optimal. This indicates that increasing the lifetime of the electrolyser is not enough to cross the threshold between negative and positive NPV for the electrolyser. To cross this threshold, higher hydrogen price or lower electricity prices are necessary.

In the drastic climate action scenarios, the increased electrolyser lifetime results in a larger electrolyser operating at a lower capacity factor. The larger electrolyser can be explained by the fact that the electrolyser essentially becomes "cheaper" when the lifetime is longer. This makes it more beneficial to have a larger electrolyser operate at a low capacity factor because this allows for more flexibility and more subsidised hydrogen production. In all cases, the net electricity export approaches zero as shown in fig. 9.20. This shows that hydrogen production is limited by wind and solar farm generation; for this reason, the flexibility and subsidy are extra important, leading to the larger electrolyser.

The optimal PV system size, given in fig. 9.18, also changes slightly with the increased lifetime. This is an artifact of the way the PV cost and incomes are modelled. The cost is calculated by multiplying the annual depreciation with the lifetime. However, the revenue is discounted to the NPV; this means that income further into the future is not worth much. This causes a slightly smaller PV system to be optimal in some cases. The effect of this on the NPV of the solar system is very almost negligible.

The most interesting results of the lifetime analysis can be found in fig. 9.19. This figure displays the NPV of the PV system and electrolyser. It is found that especially for the PEM electrolyser in scenario 3, the increased lifetime has a massive impact on the NPV. In fact, the increased lifetime causes the PEM electrolyser to be more competitive than the Alkaline electrolyser in 2021. Without the increased lifetime, this change only happened in 2030. This happens while the Capex of the PEM electrolyser is still significantly higher than Alkaline electrolysers. It can thus be concluded that PEM electrolyser research should be focused on increasing the lifetime of the electrolyser rather than decreasing the capital cost.

9.7. Sensitivity to weather variability

To analyse the sensitivity of the hybrid plant competitiveness to the weather variability, the generation data-set was split into two parts. The years with low generation and the years with high generation. All scenarios were then once more optimised for the high wind data-set to evaluate its effect on the optimal hybrid plant layout. The results for the electrolyser sizing PV sizing and their combined NPV are given in fig. 9.21, fig. 9.22 and fig. 9.23. For the scenarios where an electrolyser was already competitive, the size of the electrolyser and the NPV increase. However, the increased wind availability is not enough to make an electrolyser competitive in the projected and BAU scenarios. This is as expected because the availability of wind energy does not change the relationship between the hydrogen price and electricity price.

9.8. Insights from sensitivity analysis

In conclusion, the optimal design and operation of the hybrid plant are highly sensitive to the competitive environment in which it operates. Especially the sizing of the electrolyser is highly sensitive to changes. The PV system is less sensitive, as it often optimises to the maximum size possible.

The most important finding from the sensitivity analysis is the fact that the electrolyser has a threshold in the relation between hydrogen and electricity prices. This is the factor that influences whether having an electrolyser is or is not optimal. In other words, this threshold determines whether the electrolyser has a positive or negative NPV regardless of the size. This threshold can be crossed in a number of ways. The first is by increasing the hydrogen price, as is shown by the drastic climate

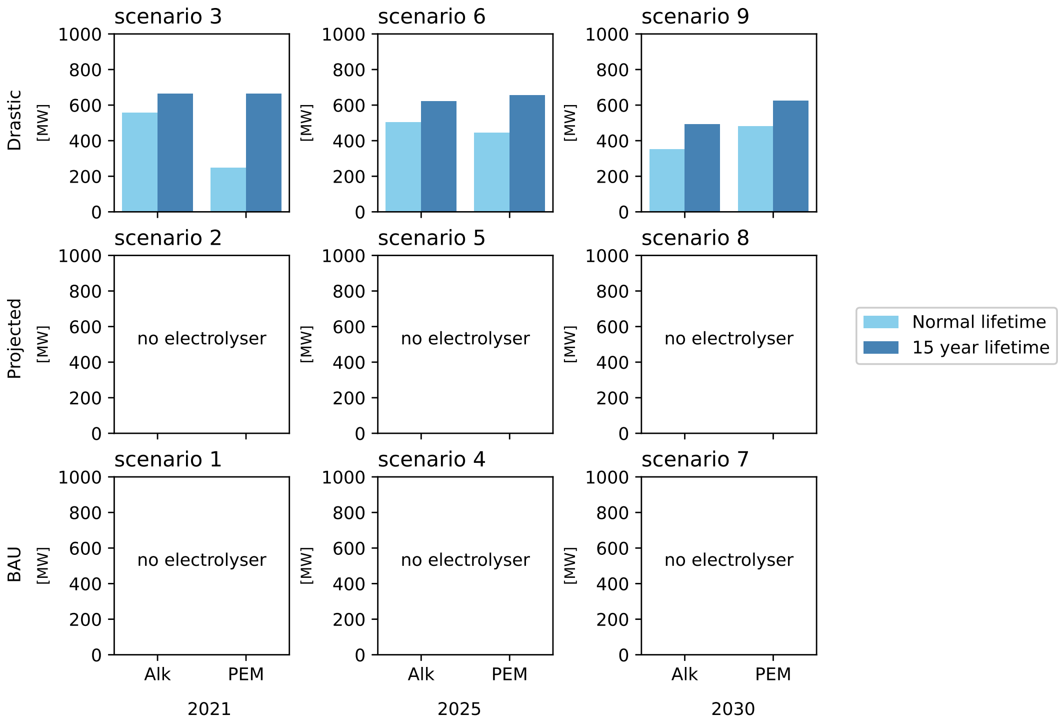


Figure 9.17: Sensitivity of electrolyser sizing to electrolyser lifetime

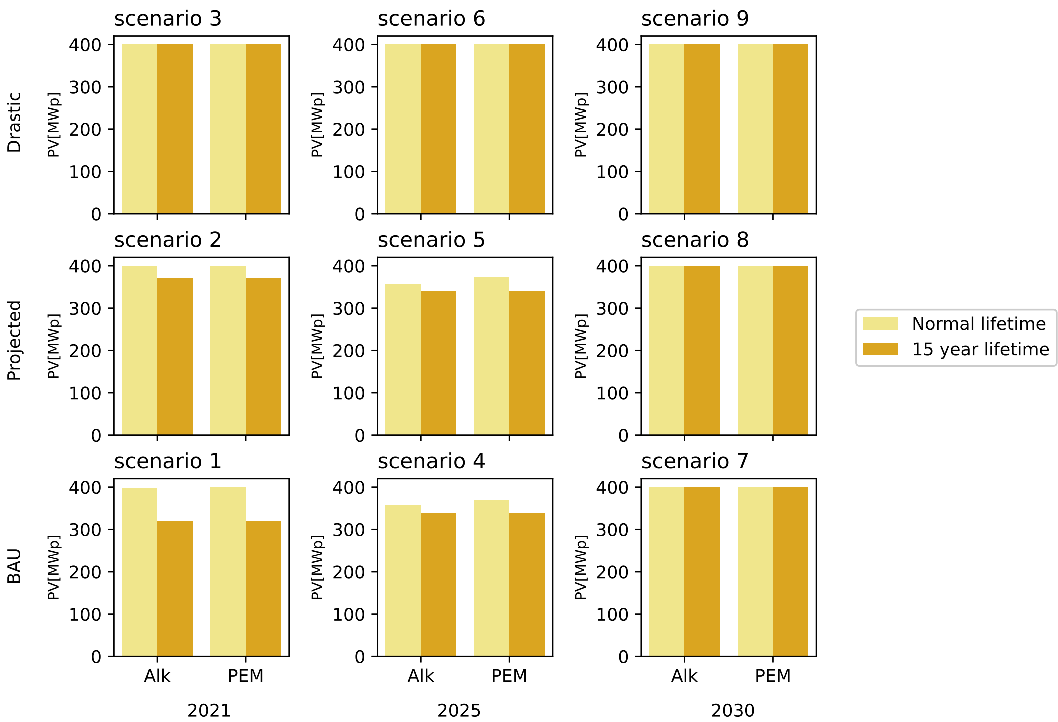


Figure 9.18: Sensitivity of PV sizing to electrolyser lifetime

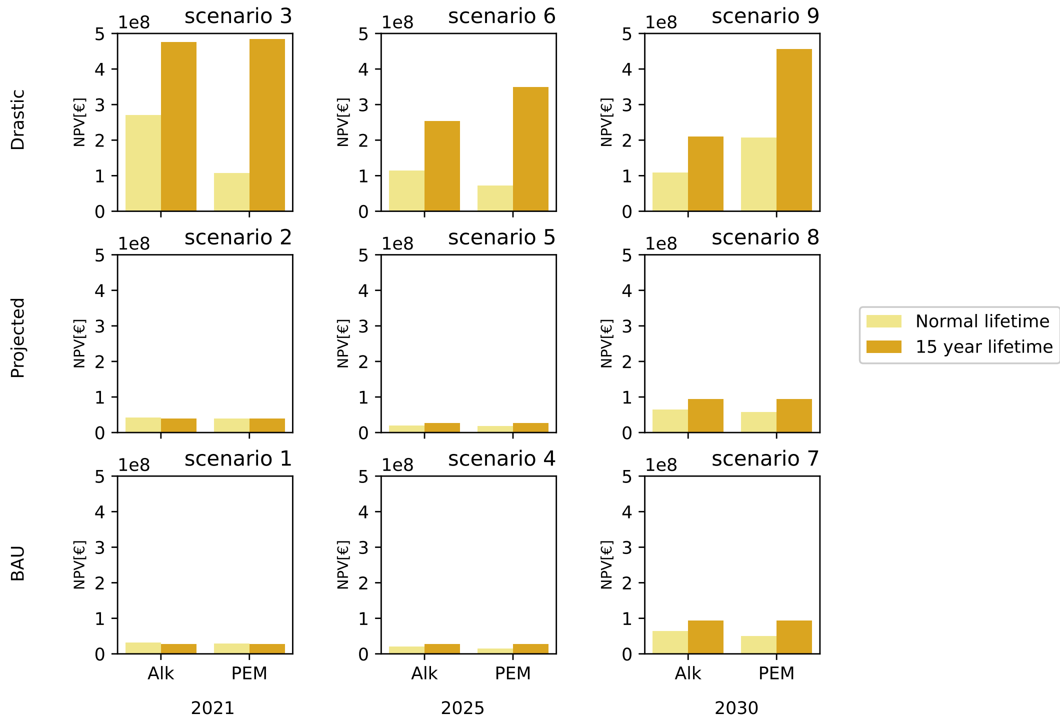


Figure 9.19: Sensitivity of Hybrid plant NPV to electrolyser lifetime

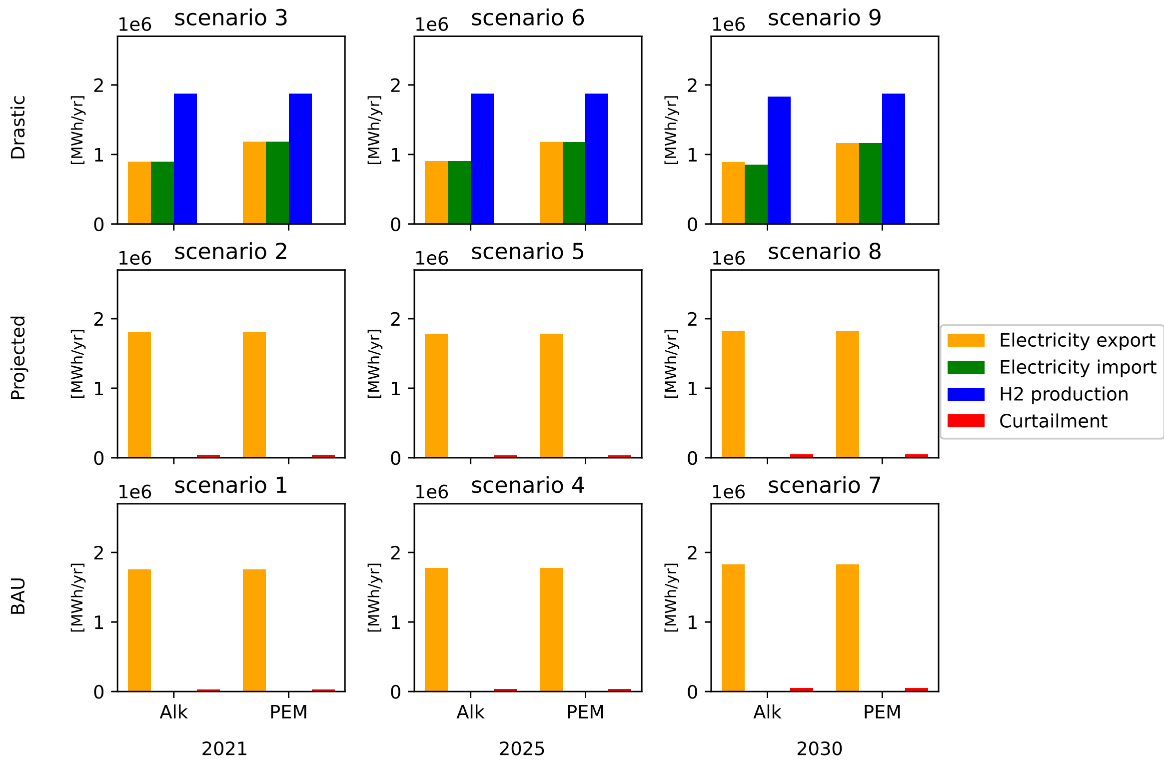


Figure 9.20: Average annual energy use per category without electricity import

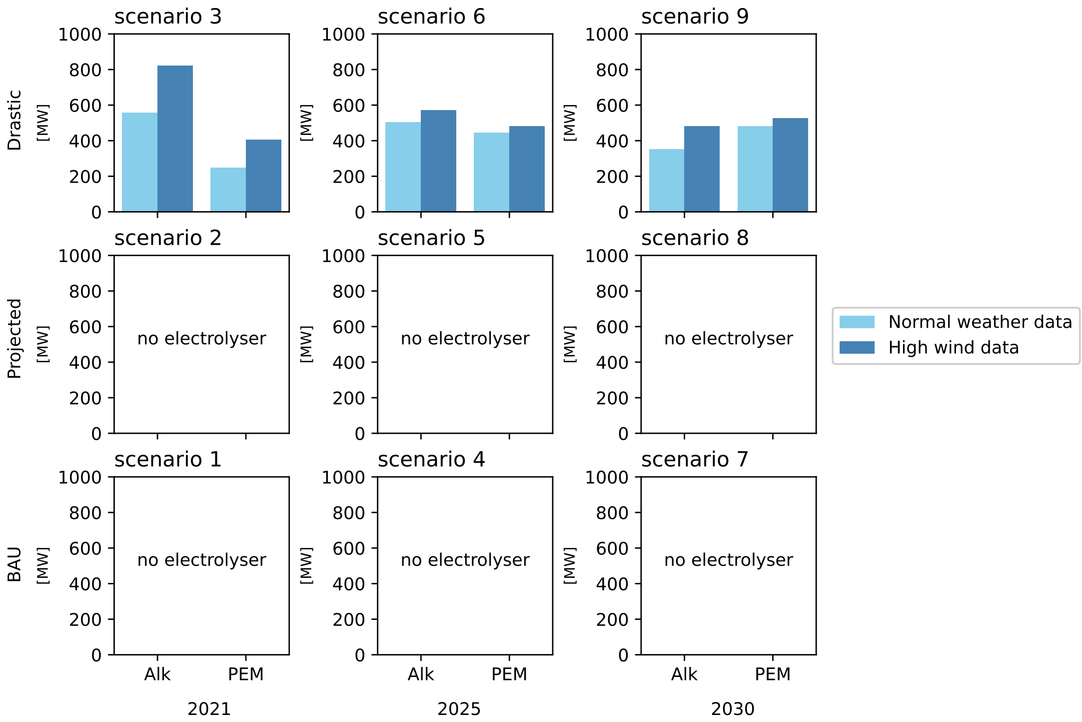


Figure 9.21: Sensitivity of electrolyser sizing to weather variability

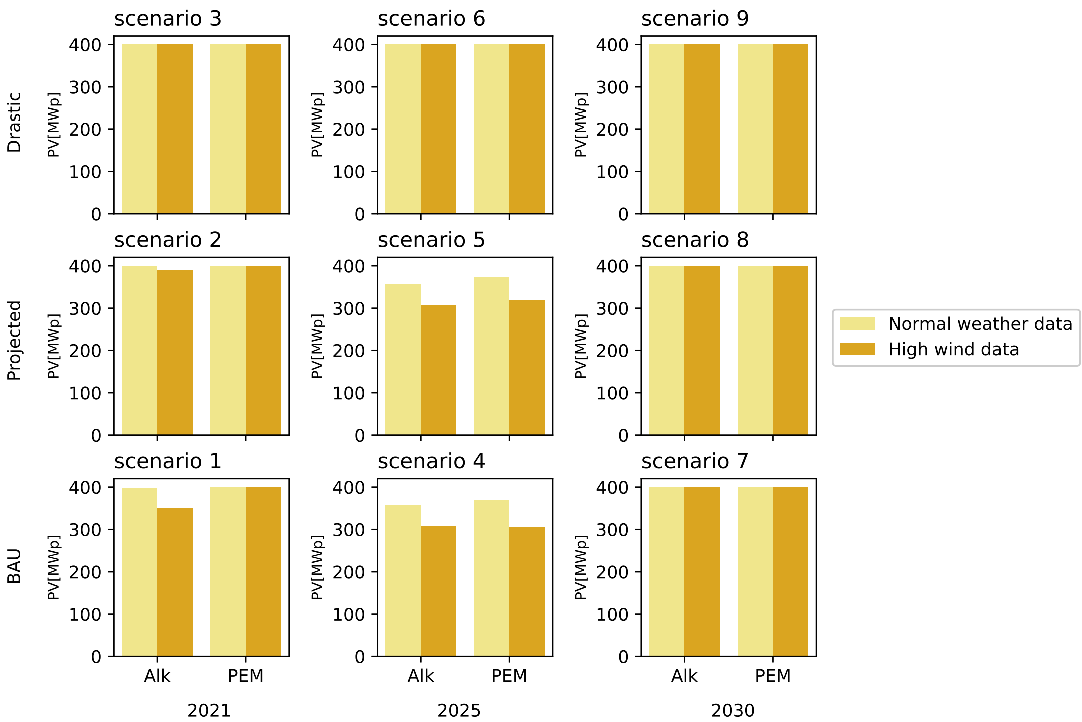


Figure 9.22: Sensitivity of electrolyser sizing to weather variability

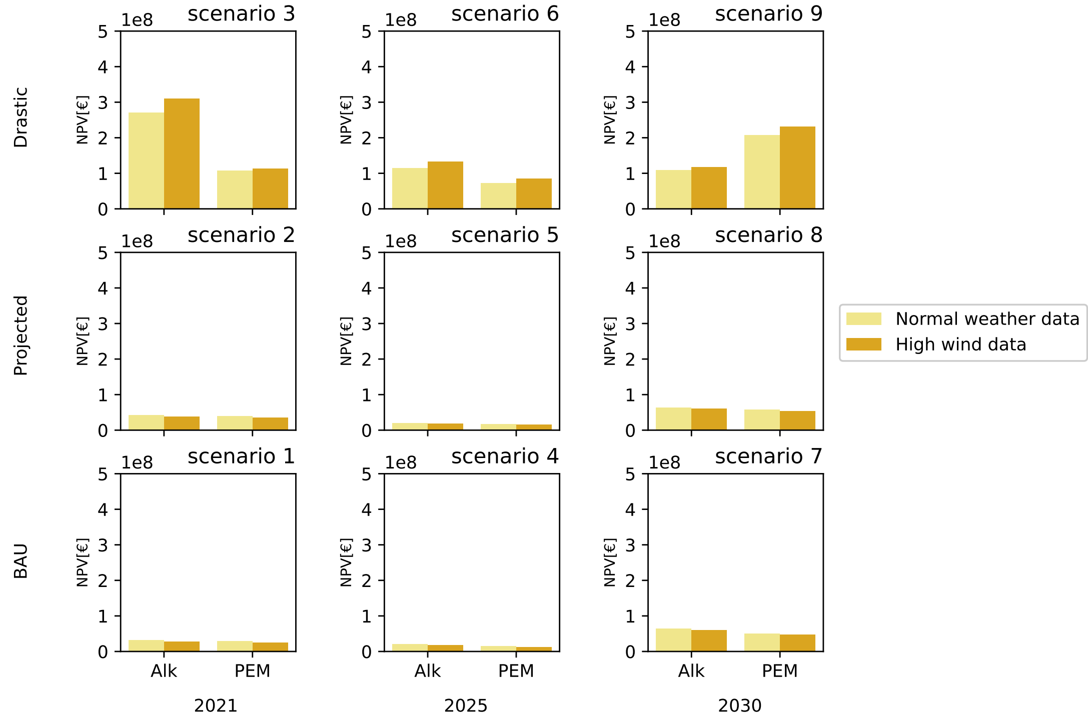


Figure 9.23: Sensitivity of solar PV and electrolyser NPV to weather variability

action scenarios where the gas and CO_2 price and thus the hydrogen price are high. The second option is lowering electricity prices, this method is less effective, but it is possible, as shown in scenario 2 with low electricity prices (fig. 9.3). Thirdly, the subsidy can be used to increase the hydrogen price to cross the threshold effectively. Note that this subsidy should be sufficiently high and available for a sufficient number of full load hours. This is shown by the fact that even the maximum subsidy available in 2020 will only allow the electrolyser to be competitive by 2030. In contrast, an increase in full load hours makes the electrolyser competitive in scenario 2 in 2021.

Once the threshold for the electrolyser is passed, the optimal size is influenced by many factors. Especially the amount of added PV has a large impact on the optimal electrolyser size. The Electrolyser and PV system supplement each other to create more value than either of the systems can add separately. This is clearly shown in section 9.4, the sensitivity to maximum added PV shows that an electrolyser allows more PV to be added and that more PV allows a larger electrolyser to be added. this combined creates a positive feedback loop and thus a significantly higher net present value.

The lifetime of the electrolyser is also an important factor in its competitiveness, especially PEM electrolysers need to have a longer lifetime in order to outcompete Alkaline electrolysers. However, a longer lifetime of the electrolyser helps little to cross the NPV of the electrolyser from negative to positive.

10
Conclusions & Recommendations

In this research, some important steps have been taken towards the optimal design of a grid-connected hybrid plant consisting of a wind farm, solar PV farm, and a water-splitting electrolyser.

A method was developed to optimise the competitiveness of this hybrid plant, given certain energy market developments. From the literature study, it was concluded that the combination of electrolyser and fuel-cell, which is able to turn the hydrogen back into electricity, is not profitable; therefore, hydrogen is sold as a product. The dominant technology for hydrogen production is steam methane reforming, and this is thus assumed to be the price-setting technology. The hydrogen produced by the hybrid plant is sold at the equivalent cost of hydrogen produced by steam methane reforming (SMR). And in this way related to the natural gas and CO_2 emissions prices. The electricity produced by the hybrid plant is sold to the EPEX spot market.

The model uses these external variables and optimises the configuration and sizing of the hybrid plant accordingly. It is shown that the model delivers a different optimisation result for each scenario. The results are consistent between the scenarios, and the model is found to optimise the hybrid plant in a correct way. Another important simulation result is that the results presented are consistent with what can be seen in the market. The model can therefore be viewed as a valuable tool for both policymakers as well as investors.

Policymakers can use the model to quantify the effect of new policies on the competitiveness on the competitiveness of a hybrid plant system. The results clearly show that more climate action is needed in order to make the hybrid plant competitive. Policymakers could use this model to quantify what subsidy levels are required to make the hybrid plant competitive. A key finding for policymakers is the fact that the current SDE++ subsidy is not sufficient to make electrolysers competitive with the projected market developments.

Developers interested in exploring the concept of building a hybrid plant can use the model to optimise the design of their plant. Due to the complexity and sensitivity of the hybrid plant system, investors should aim to reduce uncertainty as much as possible to reduce investment risk. Uncertainty can be reduced in a number of ways. The uncertainty regarding the PV and electrolyser Capex and lifetime can be removed with offers and lifetime guarantees from manufacturers. Furthermore, to reduce market risk, bilateral contracts are favourable for the sales of hydrogen as they will ensure hydrogen can be sold at a certain price.

10.1. Conclusions

The main question of this study is: *What is the most economically competitive configuration of a PV system and/or an electrolyser added to an existing wind farm, trading on the Dutch electricity and hydrogen market under different scenarios?* The answer derived from this research is that the hybrid plant's competitiveness depends on many factors, and so does the most competitive configuration. The developer of the hybrid plant can control some of these factors, while the external factors depend on the competitive environment in which the hybrid plant operates and are thus uncontrollable. The controllable variables, consisting of the hybrid plant sizing and operation, can be optimised using the optimisation model developed in this study. The external and thus uncontrollable variables consist of the development of the electricity and hydrogen market prices and the policies implemented by governments. These external variables were predicted using market forecasts and compiled into scenarios. These cover a range of climate action intensities, from business as usual to drastic climate action and commercial operating dates from 2021 until 2030.

When viewing the model results, 'Drastic climate action' scenarios, the hybrid plant is found to be very competitive, as it has a very high net present value. However, it also found that in the 'business as usual' and the 'projected' scenarios, the hybrid plant is unable to compete with hydrogen production through SMR. Adding solar PV in these scenarios does increase the NPV of the hybrid plant. Overall, it is concluded that adding both solar PV and Electrolyser to an existing wind farm will only add value when more climate action is taken than currently projected. This climate action is in the form of high subsidies, higher CO_2 emissions prices and higher natural gas prices.

A crucial factor in determining the competitiveness of the electrolyser is the ratio between electricity and hydrogen prices. If the hydrogen price is too low in relation to the electricity price, no profit can be made from the production of hydrogen. In this case, it is better to sell electricity directly; hence an electrolyser is not competitive. Providing subsidy can help this relation. However, the current SDE++ subsidy with a maximum of 2000 full load hours per year is not enough to make the electrolyser competitive in the projected and business as usual scenarios. Increasing the number of full load hours for which the hydrogen subsidy is available will also help the hybrid plant competitiveness. Instead, a significant increase in full load hours is needed to give the electrolyser a positive NPV.

If the electrolyser is competitive, such as in the 'drastic climate action' scenarios, there are still many factors that influence the optimal size of the electrolyser. Of these, the amount of PV added to the system and legislation that applies for importing electricity from the grid have the largest impact. Additionally, the lifetime of the electrolyser has a large effect on the optimal size. This is especially important for the PEM electrolyser. Adding more PV will increase the electrolyser size. However, removing the ability to import electricity reduces the optimal size of the electrolyser. An Alkaline electrolyser is, in fact, not technically feasible without import due to the minimum load at which it should operate.

The relative competitiveness of Alkaline to PEM electrolysers is mostly dependent on Capex, lifetime and minimum operational load. The Capex and lifetime together constitute the depreciation of the electrolyser. The less the electrolyser depreciates, the less it needs to earn to turn a profit. In their current state of development, alkaline electrolysers have a lower CAPEX and longer lifetime and are therefore preferred. However, a significant decrease in price and an increase in their expected lifetime are projected for PEM electrolysers. These developments will shift the competitive balance in their favour. The minimal load determines the flexibility of the hybrid plant to choose when it operates, especially in highly volatile electricity markets. Given the higher operational flexibility of PEM (0% minimum load vs 15% for Alkaline), PEM electrolysers can be foreseen to become more competitive around 2030. However, if the lifetime of PEM electrolysers can be increased to 15 years, this has a significant impact. When applying this increased lifetime as input for the hybrid plant model, it is found to be of significant impact, effectively making the PEM electrolyser already competitive with Alkaline.

It can be concluded that adding PV to the wind farm almost always increases the NPV of the system. This is with the only exception of scenarios with low electricity prices and no subsidy. The optimal size depends on a number of factors, under which the most important one is the size of the electrolyser. The size of the PV system is highly correlated with the size of the electrolyser. This is because the electrolyser is able to use the excess PV generation, which can not be exported to the grid, to produce hydrogen. This creates project income from otherwise curtailed energy, confirming the strength of combining a wind and PV farm with an electrolyser.

10.2. Recommendations

This research provides valuable insights into the competitiveness of the hybrid plant. However, there are also several limitations to the method used. These limitations are divided into two categories; the data used to run the model and assumptions in the model.

The electricity market data used to run the optimisation was generated using historical price patterns and price forecasts. This method negates some effects on the electricity price, which could significantly affect the hybrid plant competitiveness. The effects include the effect of the weather on the electricity price through intermittent renewable energy supply, the effect of an increased market share of intermittent renewable and the effect of demand pattern changes by energy consumers. It is therefore recommended to use an economic dispatch market model to take these effects into account in future research.

The hydrogen market data assumes that the price of hydrogen is set by the production price of steam methane reforming. This is a reasonable assumption for the current fossil fuel dominated hydrogen market. However, in the future, the hydrogen market might operate differently with different suppliers and users. The demand is expected to grow due to industries shifting towards using hydrogen as a fuel or feedstock. The increased demand should be filled by new suppliers, potentially increasing the hydrogen price. This will have a profound positive effect on the competitiveness of the hydrogen plant. However, competition from foreign sources of hydrogen generated from cheaper electricity in countries with more favourable weather patterns could also decrease the hydrogen price, reducing the competitiveness of the hybrid plant. A better understanding of how the hydrogen market will develop and its effect on hydrogen prices is therefore needed.

One of the proposed use-cases of hydrogen energy storage is seasonal energy storage. However, from the results, it can be concluded that in the 'business as usual' and 'projected' scenarios, the hydrogen market is still dominated by SMR. In an SMR dominated hydrogen market, using hydrogen for seasonal energy storage does not make sense as the hydrogen will be generated from natural gas. In those cases, it is far more economical to store natural gas. In the 'drastic climate action' scenarios, seasonal hydrogen storage might make sense depending on the height of seasonal electricity and hydrogen price fluctuations. By adding a fuel-cell or turbine to the hybrid plant optimisation model, the feasibility of seasonal energy storage using hydrogen could be evaluated.

It was assumed that the electrolyser would not perform any balancing or ancillary services. However, balancing and ancillary services could potentially be an additional source of income for the hybrid plant. This additional source of income will increase the competitiveness of the hybrid plant. The use of an electrolyser to perform balancing or ancillary services is, therefore, an interesting subject for future research.

Besides hydrogen and electricity, the hybrid plant also produces oxygen and residual heat. It was assumed that these create no additional value to the hybrid plant. If a customer can be found, these could be sold for additional revenue. However, additional infrastructure is needed for this synergy to materialise. Generally, the cost of such infrastructure is considerable, and the business case will be strongly dependent on the actual location of the hybrid plant and the proximity to existing infrastructure and to the new customers. The additional value of selling oxygen and heat will improve the hybrid plant competitiveness. The value of selling the oxygen and heat by finding potential customers is therefore worth researching.

The electrolyser was assumed to have a constant efficiency regardless of the operational load. In reality, there are small changes in efficiency between operational loads. Running the electrolyser at lower operational loads at a higher efficiency might create a slightly more competitive hybrid plant. Although it is generally expected to have only a modest impact on the model results, this should be verified. Quantifying the effect of operational load on electrolyser efficiency and its effect on the hybrid plant operation could be an interesting subject for future research.

In literature, it was found that little is known about the lifetimes of electrolysers. This is due to a lack of data caused by the fact that PEM electrolysers are a relatively new technology, and not many Alkaline electrolysers are in operation as of now. However, the electrolyser lifetime is an extremely important factor in determining the hybrid plant competitiveness. Therefore more research is required studying the lifetime of electrolysers, especially the effect of the intermittent operation on electrolyser lifetime.

This research shows that it is not possible to provide a definitive, generally applicable answer to whether a hybrid plant is competitive or not. However, it improves the understanding of what such a system needs to be competitive. Furthermore, it provides valuable tools to optimise hybrid plant system for any given market.

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A

Model verification

This Appendix displays the verification process of the optimisation model using unit tests. The first column, of table A.1, shows the version number, the second column the functionality which was added in this version and finally the third column shows the way this new functionality was tested.

A.1. Versions and unit tests

Table A.1: Versions and unit tests

Version	Added functionallity	Unit tests
1.0	8760 hours (1 year) of operation	Electricity exports vs hydrogen exports as a function of:
	No electrolyser cost	Hydrogen price
	Maximum electrolyser size	Electrolyser capacity
	Constant generation	
	Infinite grid export capacity	
	No grid import	
	EPEX spot electricity price	
	Constant hydrogen price	
1.1	Random generation function	Total generation = grid export + electrolyser + curtailment
	Energy curtailment	
	Finite grid export capacity	Effect of grid connection on electrolyser size
	Electrolyser cost	Effect of electrolyser cost on electrolyser size
1.2	Pandas Dataframe compatibility	Results not altered by Dataframe
1.3	Finite grid import capacity	Effect of grid import on hydrogen prodcution & electrolyser capacity
	electrolyser minimum load	Electrolyser load doesn't drop below minimum load
1.4	Random sample solar generation	total generation = wind + solar * solar capacity - curtaiment
	Solar PV capacity	
	Solar PV cost	Effect of solar PV cost on optimal PV capacity
1.5	Variable hydrogen price data	Check wether marginal cost of hydrogen production <price leads to hydrogen production
	SMR hydrogen price based on historical gas and CO2 prices	Comparison with hydrogen known hydrogen price ranges

1.6	Electrolyser ramping rates	Check if electrolyser does indeed not ramp quicker than the ramp rate
	(Functionallity is later removed)	
1.7	Hydrogen subsidy	Effect of subsidy on hydrogen production and electrolyser capacity
	Subsidised hydrogen production	Check if full load hours are not exceeded
1.8	Realistic wind data	Verify capacity factor
	Realistic solar data	Verify capacity factor
2.0 -2.2	On site hydrogen storage	Not used in final model
	On site hydrogen demand	Not used in final model
3.0	Electrolyser scenario capability	Test whether scenarios are properly imported by the model overall model test
3.1	Turn on/off subsidy	
3.1 NPV	single year NPV	Discounted income from later months
	discount income per month	
3.2	Solar SDE subsidy	Test subsidy height & effect of subisdy on PV sizing (high & low subsidy)
4.0	Multi year optimisation for total profit	
	Compatibility with electrolysers scenarios	
	Annual hydrogen subsidy	
	PV deprecitaion cost	
4.1	Multi year optimisation for NPV	
	Discount rate factors	
4.2	Compatibility with reseach scenarios	Test if inputs are correct
	Scenario builder	
4.3	Solar PV subsidy	Test subsidy height & effect of subisdy on PV sizing (high & low subsidy) Verify decreasing annual subsidy income with price increase
4.4	No net importer of electricity	
	improved scenario builder	
4.5	Compatibility with sensitivity analysis	
	Sensitivity to electricity price	
	Sensitivity to subsidy height	
	Sensitivity to subsidy coverage	
	Sensitivity to wind generation	

B

Summary of scenario assumptions

This Appendix shows the assumptions in the 9 research scenarios. Tables B.1 and B.2 show the assumptions for the Alkaline and PEM electrolysers respectively. Table B.3 gives the assumptions on market developments and PV cost.

Table B.1: Alkaline electrolyser scenarios

	Scenario								
	1	2	3	4	5	6	7	8	9
Efficiency	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
Min. load	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Capex [$€_{2016}$/kW]	988	926	712	869	838	606	750	750	500
Lifetime [h]	85000	85000	94444	85000	85000	94444	85000	85000	94444
OM [capex/yr]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table B.2: PEM electrolyser scenarios

	Scenario								
	1	2	3	4	5	6	7	8	9
Efficiency	0.65	0.67	0.68	0.65	0.68	0.7	0.65	0.7	0.75
Min. load	0	0	0	0	0	0	0	0	0
Capex [€/kW]	1225	1149	867	1131.5	1049.5	735.5	1038	950	604
Lifetime [h]	50500	60251	67481	58312.5	67911	76249.5	66125	75571	85018
OM [capex/yr]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Table B.3: Scenario assumptions

Scenario	start	H2 subsidy	CO2 price path	Gas price path	E price path	H2 color	PV subsidy	PV Base	PV cost	PV lifetime
1	2021	2	Low	Low	Mid	Grey	59.5	29	894	25
2	2021	3	Mid	Mid	Mid	Blue	63.2	29	894	25
3	2021	4	High	High	Mid	Green	80	29	894	25
4	2025	1.8	Low	Low	Mid	Grey	59.5	29	766	25
5	2025	2	Mid	Mid	Mid	Blue	63.2	29	766	25
6	2025	3	High	High	Mid	Green	80	29	766	25
7	2030	0	Low	Low	Mid	Blue	59.5	29	663	25
8	2030	1.8	Mid	Mid	Mid	Green	63.2	29	663	25
9	2030	2	High	High	Mid	Green	80	29	663	25