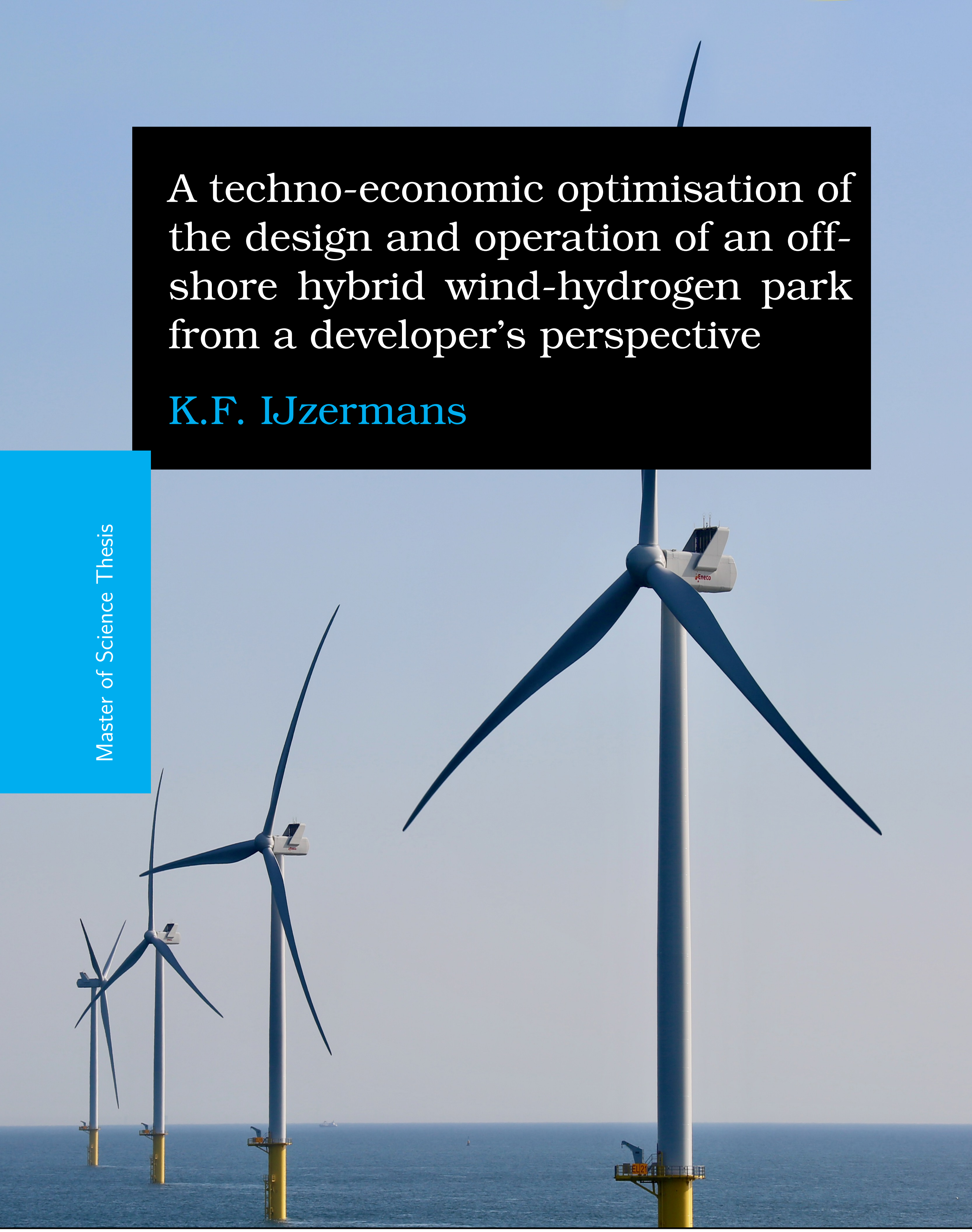
A techno-economic optimisation of the design and operation of an offshore hybrid wind-hydrogen park from a developer's perspective

K.F. IJzermans

Master of Science Thesis



Delft University of Technology

Sustainable Energy Technology

A techno-economic optimisation of the design and operation of an offshore hybrid wind-hydrogen park from a developer's perspective

Master of Science Thesis

For the degree of Master of Science in Sustainable Energy Technology
at Delft University of Technology

K.F. IJzermans

May 25, 2021

Student number:	4362888	
Thesis duration:	September 1, 2020 - May 25, 2021	
Thesis committee:	Dr.ir. M.B. Zaayer,	TU Delft (AE)
	Prof.dr. D.A. von Terzi,	TU Delft (AE)
	Prof.dr. A.J.M. van Wijk,	TU Delft (3mE)
	Dr.ir. R. Bos,	Eneco

Faculty of Faculty of Electrical Engineering, Mathematics and Computer Science (EEMC)
Delft University of Technology

The research presented in this report was commissioned by Eneco, one of the leading energy companies in the Netherlands. Their cooperation is hereby gratefully acknowledged. It has been experienced as motivating to see how academic research proves to be of pivotal importance in the advancement of sustainable energy technologies and their application.
Cover photo courtesy of Eneco.

" **Roles and responsibilities** have to be defined early and clearly, for example who is operating the grid infrastructure, who is responsible **for balancing the power**, etc."
- *North Sea Wind Power Hub - Industry report, 2020 [1]*

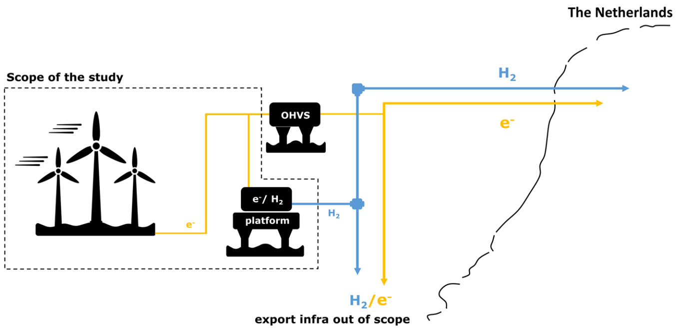
" In the North Sea Energy Outlook, no statements are made about **the optimal ratio of hydrogen and electricity production** or about the optimal technical integration solution for energy production in the North Sea. **Insufficient knowledge is yet available** on this topic."
- *North Sea Energy Outlook, 2020 [2]*

" Future discussions within the overall debate on the energy transition should **aim for a detailed power-to-gas implementation strategy**, with special consideration of the implications it will have on the electricity and gas grids. The strategy should include work on the **technical and economic feasibility of power-to-gas** facilities."
- *Infrastructure outlook 2050, 2019 [3]*

" Parties that invest in wind farms must have a timely **overview of feasible business cases**. In addition, the social costs must be clearly defined in advance and the question of **who has to pay for what** should be discussed transparently. There are currently no such action plans nor a cross-sectoral roadmap to 2050."
- *Het akkoord voor de Noordzee, 2020 [4].*

The findings presented in this research can help inform researchers, policymakers, and the energy industry in the transition towards hybrid wind-hydrogen parks.

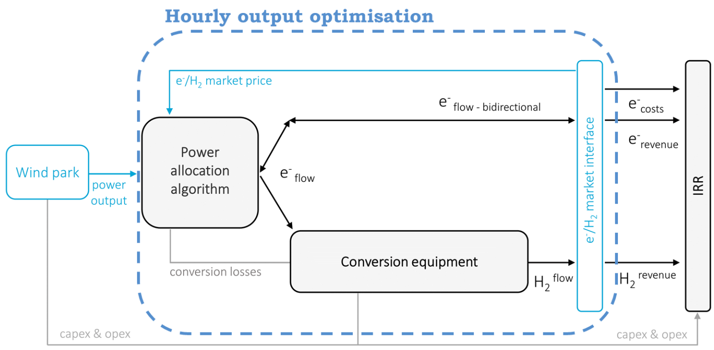
A techno-economic optimisation of the design and operation of an offshore hybrid wind-hydrogen park from a developer's perspective



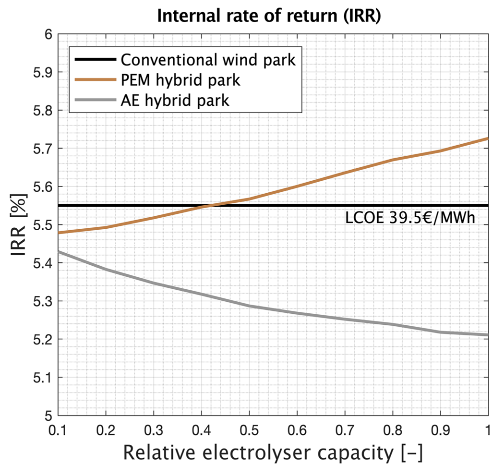
- A lack of knowledge on the economic feasibility and optimal design and operation of offshore hybrid wind-hydrogen parks is identified by utility companies and grid operators.
- This study reviews the techno-economic optimisation of an offshore wind-hydrogen park from a developer's perspective and specifically considers the electrolyser technology and wind-hydrogen ratio.
- A socialised hybrid export infrastructure is assumed, similar to the existing Dutch offshore electricity grid.

Methodology

- A MATLAB model has been developed that optimises between electricity and hydrogen production based on the wholesale energy prices and conversion losses. Electricity uptake and curtailment are included too.
- The model comprises an electrolyser, desalinator, compressor, transformer, additional cabling, and platform. All components scale automatically with the selected electrolyser technology and capacity.
- The performance of the hybrid park is condensed into the internal rate of return (IRR), facilitating comparison of different park designs by economic measure.
- A case study of a hybrid wind-hydrogen park, 'North Sea 2030', was performed to determine the optimal electrolyser technology and capacity.



Results



- The figure presents the conventional wind park's IRR and the hybrid parks' IRR upon the addition of a PEM or AE electrolyser over a range of capacities.
- Dominant case study assumptions include an average e^-/H_2 price of 60 €/MWh and 2 €/kg, wind park capex of 2M€/MW, and electrolyser capex of 0.5 and 0.35 M€/MW for PEM and AE, respectively.

Conclusions

- Adding an electrolyser to an offshore wind park significantly improves the capture value and can improve the park's IRR, depending on the electrolyser technology and capacity.
- PEM is the preferred electrolyser technology. The low capex of the AE electrolyser cannot compensate for its minimum load of 10%, which significantly reduces its flexibility.
- From an IRR perspective, adding a large relative electrolyser capacity is desired. However, this also increases the exposure to the hydrogen price development and significantly reduces the electric grid utilisation.

Recommendations

- Perform a cost-benefit analysis on a socialised hybrid export infrastructure.
- Continue research into AE minimum load and alternative AE operational strategies.
- Continue research into the individual financial and technical parameters of all components to increase the certainty of the techno-economic analysis.

Abstract

Utility companies, grid operators and policy makers in the Netherlands have identified a lack of knowledge on the topic of offshore wind-hydrogen. To move ahead on offshore wind-hydrogen, more information needs to become available on the optimal design and operation of an offshore wind-hydrogen park, the park's economic feasibility, and the effect that the park has on the national grids.

The objective of this study is to provide insight into the techno-economically optimal design and operation of an offshore hybrid wind-hydrogen park from a developer's perspective, by examining how various design and operational choices – i.e. the electrolyser technology, capacity and operational strategy - resound in the economic feasibility of the park.
To this end, a model of an offshore wind-hydrogen park has been developed in MATLAB, comprising an electrolyser, desalinator, compressor, transformer, platform and additional cabling. The model optimises between electricity and hydrogen production based on the conversion losses and wholesale market prices, and assumes an existing export infrastructure. The model considers the technical and financial parameters of the components involved, and condenses the performance of any hybrid park design into the park's Internal Rate of Return. Examining the IRR and the flows of energy for various park set-ups allows to reflect on the parks' economics and effect on the national grids.

First of all, the results point out that adding an electrolyser to a wind park is clearly beneficial from a flexibility perspective and significantly increases the park's electricity capture value. Secondly, the PEM electrolyser appears to be the technology of choice. The results show that the AE's slightly higher efficiency and significantly lower CAPEX cannot compensate for its reduced production flexibility as a result of its minimum load. Moreover, the lower AE electrolyser output pressure proved to be of limited importance, as it does not affect the park's production flexibility. Thirdly, the optimum relative electrolyser capacity highly depends on the perspective from which the optimum is determined, and on many input conditions such as the electrolyser CAPEX and energy prices. However, when the conditions are favourable to the addition of any electrolyser capacity, the results show that from an IRR perspective the addition of the full electrolyser capacity is optimal due to economies of scale in the electrolyser CAPEX and the increasing flexibility of the park to respond to market prices upon larger installed capacities. From an investment risk perspective, installing a moderate electrolyser capacity could be favourable to balance the exposure to the uncertainty in the electricity and hydrogen markets. Fourthly, the results show that it is beneficial for the electricity grid operator to reduce the electric export capacity for hybrid parks, as the electric export capacity factor significantly reduces upon favourably conditions for hydrogen conversion. Besides, the results show that reducing the electric grid connection only limitedly affects the park's economic feasibility.

Acknowledgements

First of all, I want to express my utmost gratitude to Michiel Zaaijer and René Bos for guiding me through the overall thesis process and the day-to-day course of events. Michiel's constructive and meticulous feedback motivated me, acted as a great source of guidance, and undoubtedly helped me take my thesis's output to a higher level. René's interest in the topic and far-reaching academic and industry experience made him an excellent sparring partner on all topics ranging from problem-solving approaches to reflection on my findings. Most importantly, both Michiel's and René's helpful and approachable characters have made my thesis a pleasant experience to look back on.
Moreover, I want to thank Ad and Dominic for their interest in my research, supporting expertise and the time and effort put in to hold my work against the academic standard as committee members.

Finally, I want to express my contentment with the choice I made to pursue a Master's in Sustainable Energy Technology. Transitioning towards a sustainable energy system is an immense challenge of global importance, and the Master's Sustainable Energy Technology does a great job educating about the complexity of the challenge and addressing how integral and versatile the solution must be; the more you learn about the energy transition, the more appreciative you become of how advanced we already are in our technology, but the more aware you also become of how far we are from achieving our goals.

Delft, University of Technology K.F. IJzermans
May 25, 2021

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

The introductory chapter provides context to and defines the objective and scope of the research presented in this report. Section 1-1 provides insight into the hopeful rise of renewable electricity generation and its associated challenges. Moreover, the section introduces power-to-hydrogen as a potential contribution to solving these challenges and discusses various offshore conversion configuration alternatives. Subsequently, section 1-2 presents the state-of-the-knowledge in literature, and provides argument for complementary research on the topic presented. Next, section 1-3 clearly presents the research question central to this study and demarcates the scope of the research. The final two sections of this chapter present the methodology used to address the research question and the outline of the report.

1-1 Hybrid systems in the energy transition

1-1-1 The rise of wind and solar energy

To mitigate global warming, the transition towards sustainable energy systems emerges as a central challenge to countries and companies worldwide. Over the past decades, a strong backbone for decarbonisation of the global energy supply has been developed by the emergence of renewable electricity generation technologies. In particular, wind and solar technologies have advanced rapidly, with an increase in annual deployment of over 30% year-over-year since 2010 [8]. The adoption of wind and solar in the global energy mix remains relatively limited, but with rapidly declining costs and a strong urgency to change our energy systems, the deployment of wind and solar energy is projected to increase exponentially towards 2050 [8].

The Netherlands is one of the global front runners in offshore wind, and is among the top five countries worldwide in terms of installed offshore wind capacity and share of electricity from offshore wind. In 2018, 3% of the country's electricity demand was met with offshore wind energy, compared to a global average of 0.3% [8, 25]. In the future, offshore wind is expected to play an expanding role in the electricity supply of the Netherlands, because of the North Sea's vast and readily available resources, onshore space limitations, and high public resistance in densely populated areas [5]. Figure 1-1 highlights the rise of offshore wind in the Netherlands.

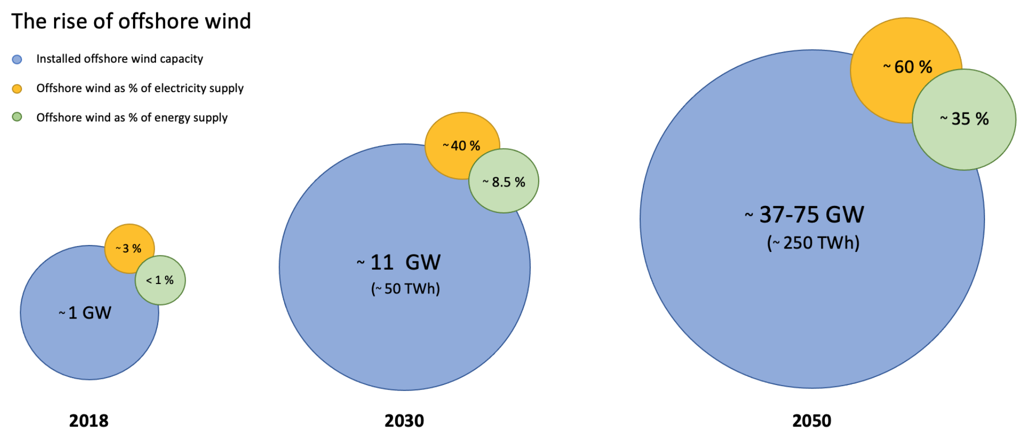


Figure 1-1: Installed offshore wind capacity and share of offshore wind in the national electricity and energy mix of the Netherlands in 2018, 2030 and 2050. Based on data from [5, 6, 7, 8, 9].

1-1-2 The associated challenges of wind and solar energy

The swift increase in renewable electricity generation is promising, but the transition towards wind and solar power brings two critical challenges. The first challenge is the intermittent nature of wind and solar resources on a geographical scale and a multitude of timescales. In times of low wind and solar resources, this intermittency endangers the reliability of the energy supply. Meanwhile, in abundant resources, the large quantity of renewable electricity leads to grid congestion issues and requires curtailment due to grid constraints [26, 27]. Moreover, the supply-demand challenge resulting from the intermittent nature of wind and solar power increases volatility in electricity market prices, complicating the developer's business case and lowering the investors' confidence [27, 28]. This challenge becomes all the more significant with increasing installed renewable electricity capacity, if not complemented by storage, demand side response, and conversion technologies [3, 29].
The second challenge is the decarbonisation of the non-electrical demand. In various industries, full electrification of demand is unfeasible, inefficient or cost-ineffective, even though the significant consumption of fossil fuels and feedstock in these sectors too must be mitigated as a matter of urgency. Exemplary for such industries are the steel, chemical and fertiliser industries or heavy-duty rail, road and maritime transportation sector [8, 10, 30].
To respond to both these challenges, future energy systems must become more flexible to fulfil the demand across industries, geographical locations and timescales.

1-1-3 Power-to-hydrogen as part of the solution

Part of the solution to the aforementioned challenges is converting renewable electricity into green hydrogen through water electrolysis. Power-to-hydrogen can relieve stresses on the grid in times of oversupply and provide the molecular energy carriers required to carbonise the non-electric energy demand [17, 31, 32]. When power-to-hydrogen is integrated into a renewable generation asset, for example an offshore wind park, the renewable electricity can either partly or entirely be converted into hydrogen. In the former case, the renewable generation asset can output electricity as well as hydrogen; only in this hybrid configuration the conversion of electricity into hydrogen results in the required increased flexibility in the energy system [7]. Moreover, only a hybrid conversion configuration provides the developer with the flexibility to respond to market price dynamics and potentially improve the asset's business case [7].

1-1-4 The potential of offshore conversion

In the particular case of offshore wind energy, the conversion of electricity into hydrogen can either occur onshore or offshore. Advantages of onshore conversion include less costly installation and easy accessibility for maintenance purposes [33]. Moreover, electricity is onshore converted closer to residential areas and hydrogen-demanding industrial clusters, which reduces the need for a hydrogen transport infrastructure. This allows for the reuse of the two main byproducts from electrolysis, heat and oxygen, for purposes such as residential- and agricultural heating, wastewater treatment and medical use [10, 34, 35]. Various onshore electrolysis projects with capacities ranging up to 1 GW are currently being undertaken in the United States, France, Paraguay, Germany, and the Netherlands [36]. For example, in the Netherlands, a coalition of companies have recently performed a feasibility study into a multi-GW scale electrolysis plant powered by nearby offshore wind capacity in the North of the country [37]. Because onshore electrolyser projects are gaining traction globally, more and more knowledge and experience become available on the onshore application of electrolysers.

Many other arguments, however, favour the conversion of electricity into hydrogen offshore.
Firstly, exporting offshore wind energy in the form of electricity requires expensive grid reinforcements [3]. Converting electricity into molecules offshore mitigates these grid reinforcements, and allows for notably more efficient and cheaper transport of energy [32, 33]. This benefit increases in significance for larger energy volumes and longer transport distances, and offshore wind parks will presumably be located further offshore and be of greater installed capacities towards the future [8, 9].
Secondly, to solve the intermittency challenge of renewable sources on a seasonal time scale by using power-to-hydrogen, the hydrogen must be stored. Storing hydrogen offshore instead of onshore is advantageous from a safety and social acceptance perspective and allows the re-purposing of empty, offshore salt caverns that have proven to be suitable and cost-effective for large scale hydrogen storage [12, 17, 38]. In the Netherlands in particular, plentiful offshore salt cavern storage capacity is available [38].
Finally, approximately 3500 km of gas pipelines and 150 platforms in the Dutch North Sea are to be decommissioned in the next decade, which is estimated to cost up to € 7 billion [39]. In the case of offshore hydrogen conversion, the obsolete infrastructure can be re-purposed. Delayed decommissioning of the old oil and gas infrastructure is favourable from a sustainability perspective and yields a financial bonus. Various studies have confirmed the technical feasibility of reusing the existing oil and gas infrastructure for offshore electrolysis purposes [40, 41].
North Sea Energy [20] provides an insightful, interactive map of the North Sea that shows the spatial planning of the North Sea for the decades to come, the assets currently available, and the potential synergies between activities. Because of the aforementioned advantages, it is highly interesting to explore the topic of offshore power-to-hydrogen at the North Sea in greater detail.

1-1-5 On-platform conversion

Three alternatives exist for offshore conversion: on an artificially created island, on-platform or in-turbine.
Conversion on artificially created islands is a much-discussed topic in the Netherlands. Compared to on-platform conversion, the main benefit of energy islands is that the economy of scale effect for energy islands is significant. In contrast, platform costs scale linearly with increasing capacity [7, 42]. According to [7], energy islands become economically favourable compared to platforms from an installed electrolyser capacity of 6 GW onward. However, this study aims to research the topic of offshore hybrid wind-hydrogen conversion from a developer's perspective, and offshore undertakings of the aforementioned capacities are beyond a single developer's scope (1-2 GW).
The alternative of in-turbine conversion is a more technically challenging concept, but one received with hopeful expectations, amongst others, by the large turbine manufacturer Siemens [43]. The main benefit of integrating the electrolyser in the turbine or on the gallery around it is that high weight, cost, and energy savings can be realised when electrical conversion equipment in the turbine becomes no longer necessary [7, 44]. However, in a hybrid wind-hydrogen park, the electrical conversion equipment is still required, and the concept loses much of its potential. Meanwhile, offshore wind parks that produce hydrogen only are not expected to receive a permit, since these parks cannot contribute to the grid flexibility [7]. Finally, fitting the electrolyser and its auxiliary equipment inside the turbine will be technically challenging and leave limited space for electrolyser stack replacement [7, 45]. Although this challenge could be overcome, in-turbine conversion is not assumed to be available for competitive prices in the short term.
For on-platform conversion, the technology is readily available and the scope suits well to an individual developer. Therefore, it could be the first offshore alternative to take off commercially. Figure 1-2 is a visual representation of an offshore hybrid wind-hydrogen park where conversion occurs on-platform. Interestingly, the Netherlands currently accommodates the world's first 1 MW offshore electrolysis pilot, where desalinated seawater is used in combination with an electricity input profile that typifies an offshore wind generation profile [34]. However, knowledge and experience on the feasibility of offshore electrolysis are generally scarcely available. The following section evaluates what topics of interest are regarding offshore on-platform conversion, which information is available and what gaps in the knowledge base are identified.

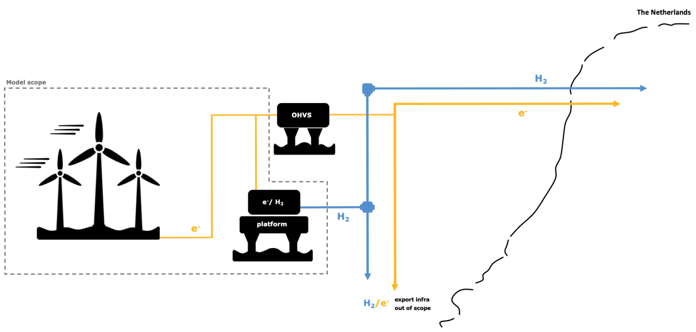


Figure 1-2: Graphical representation of an offshore hybrid wind-hydrogen park with on-platform conversion, the scope of this research. An existing hybrid export infrastructure is assumed.

1-2 A developer's perspective on offshore wind-hydrogen

In literature, hydrogen production from offshore wind parks is a much-discussed topic. Various studies address specific technical details, such as electrolyser specifications and applicability [14, 32, 46, 47, 48, 49], infrastructure requirements for hydrogen transport [3, 50, 51], availability and refurbishment costs of old offshore platforms [42, 52, 53], hydrogen compression [16, 54, 55, 56], and electrolysis from (desalinated) seawater and seawater desalination [15, 44, 57, 58, 59].
Other studies look into the techno-economic feasibility of integrated wind-hydrogen parks by using the available knowledge from literature about the specific components [7, 12, 33, 42, 52, 60, 61]. According to the author's knowledge, the selected studies for review are among the most elaborate techno-economic evaluations on this topic to date.
Generally, the studies agree on the conclusion that the business case for offshore hybrid conversion improves upon increasing distance to shore, increasing capacities, and the progression of time [7, 33, 42]. However, whether or not a hybrid park outperforms an all-electric park and from what exact distance and year this is the case, depends highly on the assumptions used in each study. Besides, each of the studies uses a different set of assumptions underlying the feasibility.

For a developer to move ahead on offshore wind-hydrogen, it is of utmost importance to gain quantified insight into how various assumptions influence the economic feasibility of an offshore hybrid wind-hydrogen park. Up to date, this essential information on offshore wind-hydrogen is not available in a compellingly gathered manner; Developers need clarity and insight into the design and operation of a hybrid wind-hydrogen park and the responsibility for energy transport to shore [1, 2, 4]. These topics are also the main recurring underlying assumptions in the aforementioned techno-economic studies, and are therefore valuable to take a closer look at.

The main assumptions encountered regarding the design of a hybrid wind-hydrogen park are about the electrolyser technology and the installed electrolyser capacity relative to the wind park capacity.
First of all, no consensus on the optimal electrolyser technology exists in literature. One electrolyser technology, called PEM, is often selected on a qualitative basis for its alleged technical superiority [33, 52, 61, 62, 63]. However, another electrolyser technology, called AE, is mentioned to have significantly lower CAPEX and adequate technical capabilities for the application in wind-hydrogen parks [13, 14, 47, 64, 65].
Secondly, it remains unclear what the optimal relative electrolyser capacity is and how this parameter resounds in the parks' feasibility. Earlier studies either simply assume the relative electrolyser capacity a fixed number, or determine the optimal relative electrolyser capacity from a national grid-flexibility perspective [7, 33]. A quantified, in-depth understanding of the effect of the electrolyser selection and capacity on the feasibility of the hybrid wind-hydrogen park would be valuable from a developer's perspective.

Another recurring topic of assumptions is the operation of a hybrid wind-hydrogen park. Most of the aforementioned techno-economic studies assume either a base load conversion of electricity into hydrogen, determine the share of electricity that is converted from a grid-flexibility perspective, or use a fixed electricity price for the park to switch to hydrogen production [7, 33]. However, it could be economically beneficial for a hybrid park to optimise between hydrogen and electricity, based on market value [60, 66].
Secondly, the uptake of electricity from the grid is generally not included in earlier studies [42, 60]. However, this could potentially improve the developer's business case and is also important for the grid connection requirements for the TSO. The topics of output optimisation by using electricity and hydrogen market prices, and the addition of electricity uptake to improve the developer's business case are therefore interesting to study in more detail.

A final large uncertainty for developers is the responsibility of hydrogen transport to shore [1, 4, 7, 42]. However, assumptions on this topic prove to be decisive in the feasibility of offshore wind-hydrogen in earlier studies.
For the specific situation in the Netherlands, it is valuable to examine the business case for an individual developer when an existing, socialised infrastructure is assumed, and energy transport to shore is excluded from its scope. The Netherlands already has a socialised offshore electricity transmission infrastructure, which has significantly accelerated the deployment of offshore wind energy by reducing the investment risk for developers. A socialised, offshore hybrid export infrastructure is therefore considered by the Dutch TSO's [3].
Removing the responsibility of hydrogen transmission from the business case of the individual developer in this study allows to reflect on the requirements for a hybrid export infrastructure from a developer's perspective in a later stage. Moreover, it can provide insight on the interaction of offshore wind-hydrogen parks with the gas and electricity grids, as requested by the Dutch TSO's Tennet and Gasunie [3].

This study aims to build on the existing knowledge base, and address, in particular, the topics of interest to a developer to move ahead on offshore wind-hydrogen. To this end, the study aims to provide quantified insight into how a hybrid wind-hydrogen park can be optimally designed and operated from a developer's perspective, including the topics of electrolyser selection, relative electrolyser capacity, electricity allocation based on market prices and the uptake of electricity from the grid.

1-3 Research objective and scope

The objective of this study is to provide insight into how the design and operation of an offshore hybrid wind-hydrogen park can be optimised for output value by using electricity and hydrogen market prices. As described before, conversion occurs on-platform, and an existing, socialised hybrid export infrastructure is assumed that the park can connect into. The objective of the study is translated into a research question below, and a set of sub questions is defined to approach the research question methodically.

How can the design and operation of an offshore hybrid wind-hydrogen park be optimised for output value, by using electricity and hydrogen market prices, and assuming an existing hybrid export infrastructure?

- **i.** What system components are required, and most suitable, for the design of an offshore hybrid wind-hydrogen park?
- **ii.** What parameters of the system components are of prime importance to the design and operation of an offshore hybrid wind-hydrogen park?
- **iii.** What values can be assumed for these key parameters of the system components, and how do those scale with wind park and conversion equipment capacity?
- **iv.** How can electricity and hydrogen market prices be used to optimise the electricity allocation- and electrolyser operation strategy?
- **v.** How do the operation and economic feasibility of a hybrid wind-hydrogen park compare to an all-electric reference case?
- **vi.** How sensitive is the economic feasibility of a hybrid wind-hydrogen park to the different design and operational choices, parameter value assumptions and alterations in electricity and hydrogen market price profiles?

1-4 Methodology

To answer the aforementioned research questions systematically, an extensive literature review was first performed to determine a suitable configuration for an offshore hybrid wind-hydrogen park, and to obtain an in-depth understanding of the various components it comprises. Additional communication with experts from the TU Delft, TNO and the Technical University of Madrid were helpful to discuss and verify the information obtained.

Subsequently, a MATLAB model was purpose-built to represent the hybrid wind-hydrogen park. All hardware components between the wind park and the grid interfaces are represented in the model, and include the electrolyser, desalination unit, compressor, transformer, platform and additional cabling. The technical and financial specifications of the hardware components are implemented as input parameters to the model. As a result, the model is adaptable to changing design choices of the hybrid wind-hydrogen park, and the model can be easily updated when new information becomes available on any of the components. The parameters were then assigned indicative values based on literature research and manufacturer data. Since the industry develops at a high pace, sources from 2018 onward were used to obtain realistic indications for parameter values.
The Internal Rate of Return (IRR) is used in the model to quantify, and condense in a single metric, the out-turn of the hybrid wind-hydrogen park. Thereby, the different park designs can easily be inter-compared. The IRR calculation predominantly serves the goal of providing insight into how the design and operation of an offshore hybrid wind-hydrogen park influence the park's economics instead of indicating the absolute economic return of the park. Next, a representative case study was defined to apply the generic model to a particular location and set of input data. The results obtained from the case study were then compared to an all-electricity reference configuration and reflected upon. Subsequently, an extensive sensitivity analysis was performed to observe how the results of the case study alter upon variations in the presumed parameter values as well as design decisions. As a result, the sensitivity within the model itself is reflected upon, as well as the sensitivity of the application of the model.

1-5 Report outline

The study is structured as follows. First, chapter 2 describes the model that has been developed for the purpose of this research; it includes an overview of the real configuration of the hybrid wind-hydrogen park, an overview of the model equivalent of the configuration, an elaboration on the individual model components, and the validation of the model's intended functioning. Subsequently, chapter 3 presents the results of the all-electric reference case, the case study, and the sensitivity analysis. Thereafter, chapter 4 reflects on what the afore presented results essentially mean for the design and operation of a hybrid wind-hydrogen park, how these findings fit into the existing knowledge base, and what topics of interest are for future research. Finally, the study is concisely concluded on in chapter 5.

Chapter 2

Model set-up and modelling

This chapter describes the model developed in pursuit of the research objective articulated in chapter 1. First, section 2-1 provides an overview of the configuration of a real offshore hybrid wind-hydrogen park. Subsequently, section 2-2 provides an overview of the model equivalent of the hybrid wind-hydrogen park. In the section that follows, each of the model's components is elaborated upon. In the final section of this chapter, the model's intended functioning is validated such that it can be applied to obtain the results presented in chapter 3.

2-1 Configuration of a real offshore hybrid wind-hydrogen park

In addition to the conventional wind park and Offshore High Voltage Station (OHVS), the system design of an offshore hybrid wind-hydrogen park consists of three main system components: the conversion equipment, a transmission system and a platform to host the conversion- and transmission equipment. Figure 2-1 is a visual representation of the hybrid system's components and their interconnecting flows of physical substance.
To be more specific, the conversion equipment includes an electrolyser unit and a desalination unit. The transmission infrastructure comprises the power cables leading up to the electrolyser, the power electronic units and the hydrogen compressor for grid injection after conversion.

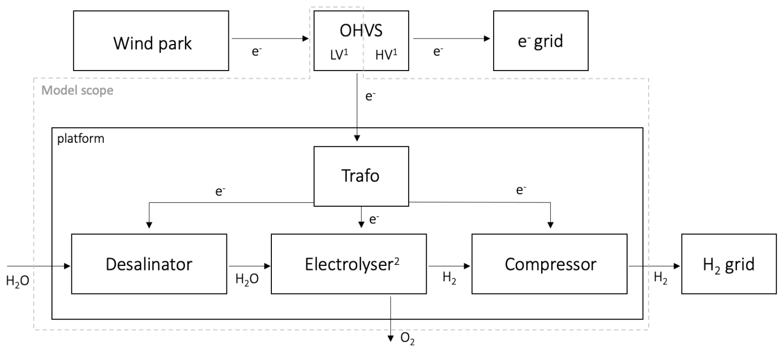


Figure 2-1: Configuration of the offshore hybrid wind-hydrogen park under review in this research. [1] the decision algorithm and physical switch that send power to the conversion platform are located on the low voltage side of the OHVS. [2] A rectifier is included in the electrolyser unit.

Not all hardware components from the hybrid system's representation in figure 2-1 are included in the model that has been developed for this study. For the scope of this study, only the hardware components that have to be added to a conventional wind park to make it into a hybrid wind-hydrogen park are included in the model. Each of the hardware components included in the model is addressed in more detail in section 2-3. First, an overview of the model equivalent of the hybrid wind-hydrogen park is presented in the following section.

2-2 Overview of the park's model equivalent

This section provides an overview of how the park's configuration is translated into a purpose-built model, representing the offshore wind-hydrogen park. First, the economic calculation is introduced that condenses the performance of the wind-hydrogen park's design and operation into a single metric. Subsequently, an overview of the complete model logic is presented, accompanied by a visual representation of the model's logic in figure 2-2. At the end of this section, the model's interfaces with the wind park and hybrid export grid are elaborated on.

2-2-1 Model logic and IRR calculation

IRR calculation - To assess the design and operation of the wind-hydrogen park from an economic perspective, the model condenses the park's out-turn in a single economic metric, being the Internal Rate of Return (IRR). The main argument for using the IRR as economic metric instead of the Net Present Value (NPV) is that the IRR metric gives priority to the percentage return of the investment, whereas the NPV merely presents today's absolute value of future cash flows and provides no insight into the return per invested capital [67, 68]. Besides being suitable to compare projects of different capital requirements, the IRR is also intuitively interpretable and can be used to assess a project according to its risk profile, as conventionally done by developers.
In the IRR calculation, the generated output value from electricity and hydrogen sale as well as the costs over the full life of the park are included. The economic calculation is represented rightmost in figure 2-2 and in equation 2-1 [68].

$$\sum_{t=1}^{n} \left[\frac{NOV_t - OPEX_t}{(1+IRR)^t}\right] - CAPEX_0 = 0 \tag{2-1}$$

$$\begin{aligned} \text{where} \quad CAPEX &: \quad \text{CAPEX in year t} = 0 \\ NOV_t &: \quad \text{Net Output Value in year t} \\ OPEX_t &: \quad \text{OPEX in year t} \\ n &: \quad \text{Economic lifetime in years} \end{aligned} \tag{2-2}$$

For the economic calculation, the CAPEX and OPEX costs of the hardware components of the hybrid wind-hydrogen park are of importance, as well as the net output value of the park; the revenue and costs associated with the sale and uptake of electricity and hydrogen. The following paragraph introduces broadly how the net output value of the wind-hydrogen park is determined.

Model logic - To obtain the net output value of the wind-hydrogen park, the model takes into account the revenue from electricity and hydrogen sale. as well as the costs of electricity uptake. In figure 2-2, these three values are illustrated by black arrows pointing towards the IRR calculation.
The revenues and uptake costs result from an optimisation that uses the efficiency of conversion and the electricity and hydrogen market prices. The optimisation is performed for each distinct hour over the lifespan of the wind-hydrogen park. The hourly optimisation performed is indicated with a light grey, overarching plane and is explained in depth in section 2-3-6.
The only three design parameters of the model are the wind park capacity, electrolyser capacity, and electrolyser technology. The model automatically scales the required cable, transformer, desalinator, compressor and platform capacities, as indicated in the top of figure 2-2.

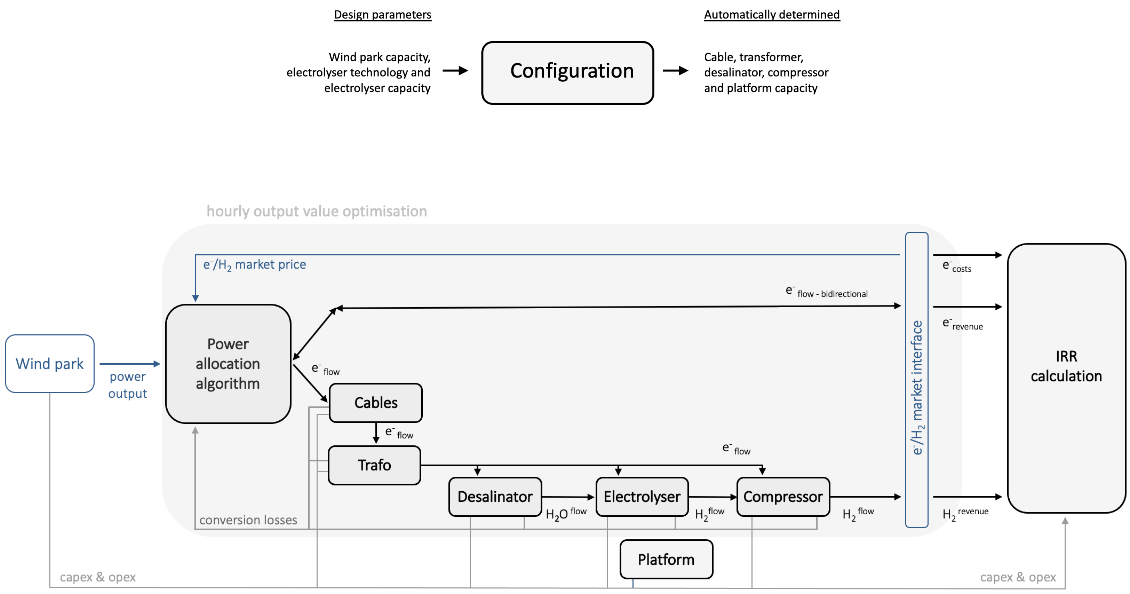


Figure 2-2: Overview of the hybrid wind-hydrogen park's model equivalent. The components included in the model are indicated in black. The interfaces of the model with the wind park and energy market are indicated in blue. The hourly output optimisation is indicated with a light-grey, overarching plane.

2-2-2 Model interfaces

Wind park & OHVS - The connection of the conversion platform with the wind park via the OHVS is one of the interfaces at the model boundary. Since there is no response from the wind park to feedback from the conversion, the wind park itself is left out of the modelling scope, and the data required from the wind park is merely imported into the model. This data comprises CAPEX and annual OPEX figures, and an hourly power output series for the economic lifetime of the wind park; The CAPEX and OPEX figures are used in the aforementioned IRR calculation, and the hourly power output series is used in the hourly

output value optimisation in section 2-3-6. By leaving the wind park out of the modelling scope, the model is applicable to any wind park if the three required input values are available, regardless of wind park specifications such as capacity and layout.
The power cables connecting the low-voltage side of the OHVS to the electrolyser conversion platform are included in the model since the cables' losses are a function of the electrical throughput, which is included in the model's optimisation. More information on the cabling and the model implementation thereof can be found in 2-3-4.

Grid interfaces - As mentioned in the introductory chapter, the hybrid export infrastructure is assumed available to connect into, and not accounted for in the model. The connection to the export infrastructure results in two model interfaces; one for the power grid and one for the hydrogen grid.
The interface with the power grid remains unchanged when compared to a conventional wind park. Power is delivered at the low voltage side of the OHVS and participates in the power market at the responsibility of the Transmission System Operator (TSO) from that point onward. The power grid interface is represented by an hourly time series of electrical power exported to - and imported from - the national grid. Moreover, a cap limits the power that can be delivered to - or taken from - the grid.
The interface with the existing hydrogen grid brings the operating grid pressure as a novel technical constraint to the hybrid park. The required grid pressure is included in the model as an input variable. The interface with the hydrogen grid is represented in the model by an hourly time series of power sold to the market, with a cap on the maximum export quantity. Hydrogen purity requirements at the grid inlet are not considered a constraint since electrolysers produce hydrogen of purity higher than the current standard of industrial-grade hydrogen. When a higher purity is required by the end-user, onshore purification can be tailored to the specific application of the hydrogen [50].

2-3 Individual model components and the implementation thereof

This section elaborates on the individual hardware components that are represented in the model, and on the model logic that governs the hourly output value optimisation. First, the hardware components represented in the model are discussed; the electrolyser, desalination unit, hydrogen compressor, additional cabling and power electronics, and platform that hosts the equipment. For every component, relevant theory is presented first, after which the model implementation is presented. At the end of this section, the hourly output value optimisation is extensively explained that considers the technical parameters from the individual components, and determines the optimal electricity allocation within each hour.

2-3-1 Electrolyser

The electrolyser is the core component of the conversion equipment and has the most significant contribution to the conversion equipment costs, losses, weight, and surface requirements. In the next paragraphs the electrolysis process is briefly explained, after which the two most common electrolyser types are introduced and evaluated on a qualitative basis on their suitability for conversion in an offshore hybrid wind-hydrogen park.

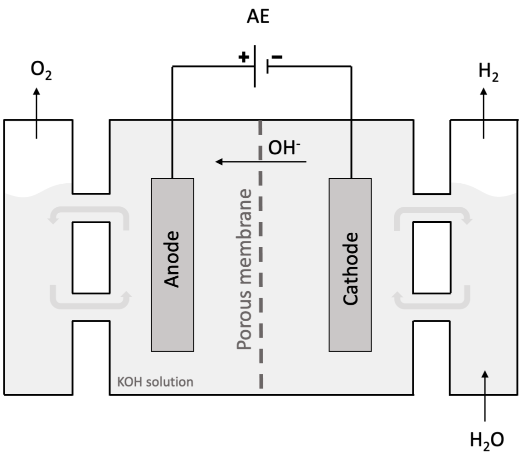
2-3-1-1 Electrolyser theory

Introduction - The electrolysis reaction of water into hydrogen and oxygen is the sum of two electrochemical half-cell reactions that occur at two separate electrodes under the application of an electrical current. Oxygen is formed at the anode side, and hydrogen at the cathode side. An electrolyte and a membrane separate the anode and cathode. The electrolyte facilitates the transport of ions but not electrons and closes the electrical circuit between the two half-cells. The membrane keeps the produced gasses separated at the respective electrodes.
Three main technologies are available for water electrolysis: Alkaline Electrolysis (AE), Polymer Electrolyte Membrane electrolysis (PEM) and Solid Oxide Electrolyser Cell electrolysis (SOEC) [49]. SOEC is the least advanced technology, and is not yet available at commercial scale [69]. One of the promising advantages of SOEC is that it operates at higher efficiencies than AE and PEM as a result of improved kinetics and thermodynamics at high operating temperatures of up to 900 °C [49]. Even though SOEC is a promising technology, the early stage of development and high operating temperature make the technology unsuitable for offshore conversion in the near future, and SOEC is therefore not considered in the electrolyser selection of this study.
Regarding AE and PEM electrolysis, various elaborate reviews are readily available in literature [8, 49, 64, 65]. Therefore, this study only concisely introduces the basics of AE and PEM technology in the following paragraphs, and then addresses the suitability of the two technologies for application in a hybrid offshore wind-hydrogen park in 2030.

Two remarks apply to both electrolyser types and are therefore addressed centrally.
First, both electrolyser types require a Direct Current (DC) power supply to the electrolyser stacks whilst the power received from the wind park is AC. However, the rectifier is generally included in the scope of the electrolyser manufacturer for power security reasons, and, therefore, Alternating Current (AC)-power can be fed to the electrolyser unit [13, 14, 47].

Secondly, the water purity level that goes into the electrolyser stack for both AE and PEM is <1 mg/L Total Dissolved Solids (TDS). Such purity levels are obtained with techniques as continuous electro-deionisation, ion exchange polishing, or mechanical vapour compression [44, 52]. However, electrolyser manufacturers often take responsibility for the advanced purification steps to safeguard the electrolyser stacks and oversee the water feed. For most electrolysers commercially available, a feed-in of tap water-quality suffices, which corresponds to approximately 300-500 mg/L TDS.
For the scope of this research, the final water purification step and the power conversion from AD to DC are included in the scope of the electrolyser and not separately addressed; the losses and costs associated with these activities are assumed included in the electrolyser values, as in accordance with [13, 14, 47].

AE - Alkaline electrolysis is a mature technology that has already been used on a MW-scale in industrial applications since the 1920s [49, 70]. Figure 2-3 provides a visual representation of an alkaline electrolyser cell and the equations that govern the reactions in the cell. The process operates at a relatively low temperature and is characterised by the use of a liquid, alkaline electrolyte solution that allows the transport of the hydroxide (OH^-) charge carriers. A separator permeable to OH^- ions keeps the product gasses from electrolysis separated.

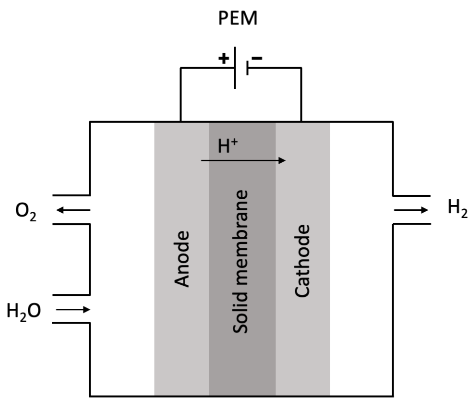


$$\begin{aligned} \text{Cathode:} &\quad 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \\ \text{Anode:} &\quad 2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \\ \hline \text{Overall:} &\quad 2H_2O \rightarrow O_2 + 2H_2 \end{aligned}$$

Figure 2-3: Left: schematic representation of an AE electrolyser cell. Right: the electrochemical half-cell and overall equations of an AE electrolyser cell [10].

Due to the use of common materials and the advanced maturity level, AE electrolysers have relatively low capital costs compared to PEM electrolysers [48, 70]. However, the use of a liquid electrolyte and a porous membrane brings various challenges and disadvantages. For example, at low partial loads, the accidental diffusion of product gasses across the separator becomes significant, with potentially flammable gas mixtures as a result. AE electrolysers must therefore always maintain a minimum operational load [71**?**]. Besides that, alkaline electrolysers show inferior dynamic behaviour with respect to cold start-up-, warm start-up- and ramp-up times due to the inertia of the liquid electrolyte [49, 63, 65, 71, 72, 73]. Also, ohmic losses across the electrolyte and separator limit the current density of alkaline electrolysers, which negatively impacts the physical dimensions of the system [71]. Finally, AE electrolysers operate at lower operating pressures than PEM electrolysers because of their more feeble membrane, resulting in the need for external compression for transport and storage purposes [70]. Development of the AE technology is particularly focused on solving the challenges that the electrolyte and membrane bring, and as the technology is even more widely applied in the future, increased economies of scale are expected to lead to significant cost reductions [70].

PEM - PEM technology was introduced in the 1960s as an alternative to alkaline technology and is to a lesser extent applied on a large scale due to its low maturity [49, 70]. Figure 2-4 provides a visual representation of a PEM electrolyser cell and the equations that govern the reactions in the cell. A fundamentally different property of PEM technology compared to alkaline is the solid polymer electrolyte membrane that separates the electrodes and serves simultaneously as electrolyte and membrane. The solid nature and membrane properties provide superior structural strength and lower gas permeability. The increased structural strength allows for pressurised operation up to 350 *bar*, and the lower permeability of the membrane implies lower gas crossover between the electrodes and allows for a larger operational range and higher purity hydrogen output [49].



$$\text{Cathode:} \quad 2\text{H}^+ + 2e^- \rightarrow H_2$$

$$\text{Anode:} \quad H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$$

$$\text{Overall:} \quad 2\text{H}_2\text{O} \rightarrow \text{O}_2 + 2\text{H}_2$$

Figure 2-4: Left: schematic representation of a PEM electrolyser cell. Right: the electrochemical half-cell and overall equations of a PEM electrolyser cell [10].

On the downside, PEM technology comes at higher capital costs [48, 70]. Not only is the membrane more expensive, but it also requires higher purity input water, and the corrosive acidic composition of the PEM cell requires the use of expensive noble metals for the electrodes [49, 70]. Therefore, the development of the technology is focused on the use of alternative materials for the electrodes and membrane, which is expected to result in significant cost reductions [70].

Electrolyser efficiency - As mentioned in the introductory chapter, electrolysers are increasingly often connected to renewable, fluctuating supplies instead of continuous supplies. This increases the importance of electrolyser characteristics such as the part-load efficiency.
The electrolyser efficiency can be either expressed in terms of Lower Heating Value (LHV) or Higher Heating Value (HHV). The LHV is the energy quantity released at the combustion of a mol of hydrogen when the product water is in the vaporised state. The HHV refers to

the energy content of the produced hydrogen, including the heat of evaporation of water, assuming that the output product water is recovered to the liquid state. The HHV efficiency is used as standard in this research.
For both the AE and PEM electrolyser, the DC-efficiency of the electrochemical reaction that takes place in the electrolyser stack increases at part-load operation [11, 49]. Meanwhile, the efficiency of the auxiliary equipment of the electrolyser unit, amongst others the rectifier and cooling equipment, decreases at part-load operation. Figure 2-5 shows how these two opposite efficiency courses lead to a point of optimal system efficiency [11]. The figure is not to scale and serves an illustrative purpose only. A commercial electrolyser of which this part-load efficiency has been studied in detail is the 6 MW PEM electrolyser from Siemens in the Energiepark in Mainz, Germany [74]. For this particular electrolyser, the maximum system efficiency is obtained at operation at 27% of nominal load [74]. Section 2-3-1-2 elaborates on the implementation of the part-load efficiency in the model.

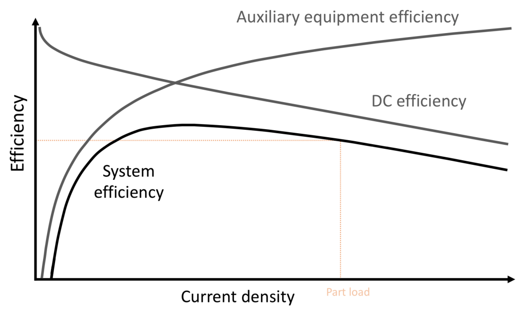


Figure 2-5: Rough sketch explaining the concept of electrolyser part-load efficiency. The efficient curves implemented in the model are presented in appendix A-2 [11].

Technology comparison - In this paragraph, the two electrolyser technologies are assessed on various essential criteria that apply for operation in a commercial offshore hybrid wind-hydrogen park.
CAPEX, OPEX, and electrolyser efficiency are the most straightforward parameters of importance. Various authoritative and recent sources, such as the International Energy Agency (IEA), Bloomberg New Energy Finance (BNEF), Fuel cell and Hydrogen Joint Undertaking (FCH JU) and International Renewable Energy Agency (IRENA) favour the AE electrolyser significantly with regards to the CAPEX and moderately with regards to the OPEX and efficiency [13, 14, 46, 47].
Other important electrolyser selection criteria are the electrolyser weight and surface requirements, translating into platform CAPEX later on. Indicative values for surface and weight point out that the AE electrolyser requires more surface than the PEM, but weighs less [34, 52, 75, 76]. Assuming that weight contributes more significantly to platform costs than the surface requirement allows to cross off these criteria against each other in the comparison.
Dynamic behaviour finally remains as important category of selection criteria, and comprises the operational range, cold start-up, warm start-up and ramp-up times. As mentioned earlier in this section, PEM shows indisputable superiority with regards to dynamic behaviour on all aspects [49, 63, 65, 71, 72, 73, 77]. However, for the particular application in a hybrid wind-hydrogen park, outstanding dynamic behaviour is not a requirement by itself. In a hy-

brid wind-hydrogen park, fluctuations in electricity generation can be fed into the grid when the dynamic behaviour of the electrolyser does not suffice at times, as opposed to an electrolyser facility that is not connected to the grid. Moreover, variations in wind park output occur mainly on timescales longer than a second- or minute basis, amongst others due to the spread of the turbine placement and rotor inertia [78, 79]. For the aforementioned arguments, AE electrolysers are also assumed to have sufficient dynamic behaviour to operate in an offshore hybrid wind-hydrogen park. However, the superior dynamic behaviour of the PEM electrolyser does allow the electrolyser to respond more astutely to market dynamics, resulting in increased revenues. Whether or not this superiority in dynamic operation makes up for the significantly higher CAPEX cannot be determined on a qualitative basis, and must be indicated by the model.

2-3-1-2 Model implementation

Since the electrolyser technology selection cannot be confidently made on a qualitative basis only, the model is made compatible with both electrolyser types to observe their performances in the hybrid park quantitatively as well. The two types of electrolyser can be implemented in the same parametric model by differing the parameter values.
The electrolyser capacity and technology are the only two electrolyser design parameters in the model, and are manually assigned a value. From a predefined specification sheet for AE as well as PEM, the electrolyser nominal efficiency, water consumption rate, output pressure and minimum load are then automatically loaded into the model, corresponding to the selected technology. When less than the rated capacity is sent into the electrolyser, the model determines the electrolyser part-load, $P_{part-load}$, by equation 2-3, where P_{in} represents the power sent into the electrolyser.

$$\mathrm{P_{part\text{-}load}} = \left(\frac{\mathrm{P_{in}}}{\mathrm{Electrolyser_{capacity}}} \right) \tag{2-3}$$

The efficiency that corresponds to the part-load is then obtained from a look-up table in the model, which is derived from the part-load efficiency curve of the Siemens electrolyser in [74]. A visual representation of the part-load efficiency look-up table can be found in appendix A-2. P_{in} is also used in the model to determine the electrolyser's water consumption. The water consumption of the electrolyser, Electrolyser_{wc}, scales linearly with the power sent into the electrolyser, and is implemented in the model as presented in equation 2-4. The specific water consumption of the electrolyser, $\text{Electrolyser}_{swc}$, is further described in section 2-3-2.

$$\mathrm{Electrolyser_{wc}} = \mathrm{P_{in}} * \mathrm{Electrolyser_{swc}} \tag{2-4}$$

Electrolyser CAPEX - The electrolyser contributes most significantly to the overall CAPEX of the equipment required for conversion, and a realistic representation of the CAPEX in the model is therefore of utmost importance. Scaling effects lower the investment cost per MW when the installed capacity increases, and a formula capturing the shape if this effect is presented in [12]. This formula is implemented in the model and presented in equation 2-5.

$$\text{Electrolyser}_{\text{capex}} = \text{Reference}_{\text{capex}} * \left(\frac{\text{Reference}_{\text{capacity}}}{\text{Electrolyser}_{\text{capacity}}}\right)^{0.1} * \text{Electrolyser}_{\text{capacity}} \tag{2-5}$$

Figure 2-6 shows the curve obtained from source [12] when fitted to the 2030 electrolyser CAPEX projections of FCH JU and IRENA [13, 14]. From the various authoritative sources used in this study, these particular two have been used to construct the CAPEX curves because these provide a singular CAPEX estimate associated with a disclosed capacity, instead of a CAPEX range. For reference, the singular values from the sources are presented in the figure as well. The specific CAPEX of the AE electrolyser is approximately 30% lower than that of the PEM electrolyser, as in correspondence with the average difference in CAPEX from FCH JU, IRENA, BNEF and IEA [8, 13, 14, 46]. The electrolyser OPEX are proportional to the electrolyser CAPEX and described by equation 2-6.

$$\text{Electrolyser}_{\text{opex}} = \text{Electrolyser}_{\text{specific opex}} * \text{Electrolyser}_{\text{capex}} \tag{2-6}$$

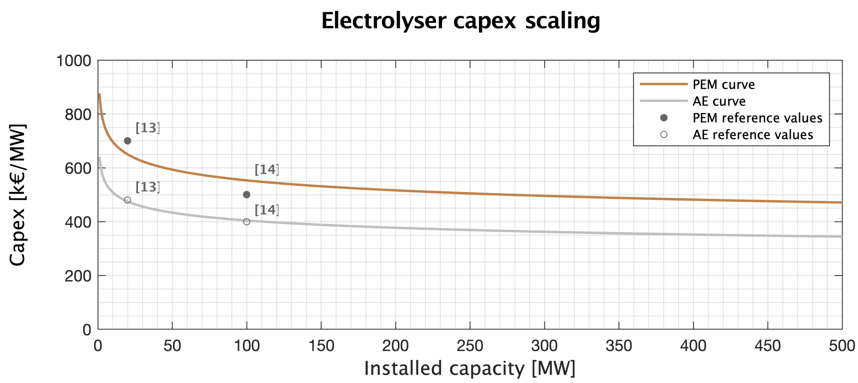


Figure 2-6: Electrolyser CAPEX scaling: The formula that governs the shape of the curve is obtained from [12] and the curve is calibrated with CAPEX estimations from [13, 14]. The rectifier, gas conditioning equipment, and electrolyser balance op plant components are included in the scope of the electrolyser CAPEX.

Electrolyser operational strategy - The electrolysers are chosen to operate on or above their minimum load at all times. For the PEM electrolyser with no minimum load this makes little difference, but for the AE electrolyser this requires a significant amount of electricity to be allocated to the electrolyser at all times. In reality, the AE electrolyser operation can potentially be optimised by day-ahead wind and price forecasts. The AE electrolyser could be selectively switched on if hydrogen production is desired for long periods, albeit with a lag in hydrogen production due to the start-up time. The potential of increased performance by astute on/off switching is examined in the sensitivity analyses in chapter 3-3, but the model conservatively uses the minimum load operational strategy by default.

2-3-2 Desalinator

2-3-2-1 Desalinator theory

Although direct electrolysis from seawater is a topic being researched, it comes with many technical challenges and will presumably not be available on a commercial scale in the near future [57]. Therefore, a unit is required to provide the electrolyser with desalinated water. Two topics are discussed more elaborately in this section, being the desalination technology selection and its energy consumption.

Technology selection - As mentioned in the electrolyser introduction, feed-in water of tap water quality suffices for the electrolyser unit and has a TDS level of approximately 300-500 mg/L. For comparison, North Sea water has a TDS level of approximately 35.000 mg/L [15].

The most suitable desalination process that is commercially available, scalable, and can attain the required purity level is Reverse Osmosis (RO) [15, 59]. The first step in reverse osmosis is to pre-treat the seawater to remove any large particles that could damage the equipment. Seawater is then pressed through a semi-permeable membrane that allows the water to proceed but holds back the solid particles. High pressure must be applied to the seawater in this process to overcome the osmotic pressure. Before the concentrate is discharged, the pressure that remains in the concentrate is recovered to improve the energy efficiency of the process [15]. A purity level of 300-500 mg/L can be obtained with a single pass through the membrane, and the water purity can be further increased up to 15-130 mg/L when the permeate is passed through a second stage of reverse osmosis [15].

Energy consumption - In [15], over 70 large scale Sea Water Reverse Osmosis (SWRO) plants have been studied, and the study concludes that the specific energy consumption of SWRO plants increases with increasing salinity of the feed water due to the higher pressure required to overcome the sea water's osmotic pressure. On the other hand, the specific energy consumption of the studied SWRO plants shows no correlation with seawater temperature. Figure 2-7 is obtained from [15] en visualises both correlations well.

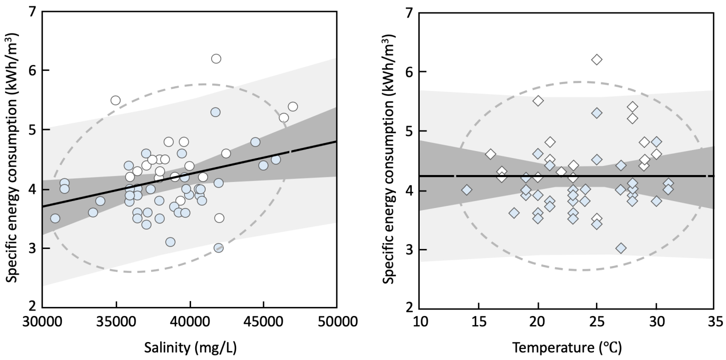


Figure 2-7: Specific energy consumption of large-scale reverse osmosis plants plotted against the feed-in conditions *salinity* and *temperature*. [15]

The specific energy consumption for desalination by means of reverse osmosis is low compared to the electrolyser losses; an electrolyser typically consumes water at a rate of 300 $L/(MW_{el} * hour)$ [52], and at a specific energy consumption of the desalination unit of 4 kWh/m^3, this corresponds to an energy loss of approximately 0.12% of electrical input of the electrolyser at full load [15]. For comparison, electrolyser losses are approximately two orders of magnitude larger. However, the desalination losses are considered non-negligible and included in the model as described in the following section.

2-3-2-2 Model implementation

Sufficient desalination capacity is included in the model to supply the installed electrolyser capacity at full load. This is a conservative modelling approach and in practise, an optimisation can be performed for the installed desalination and reservoir capacity.
The energy consumption of the desalinator is determined by equation 2-7 in the model, which uses the electrolyser water consumption from the previous section, Electrolyser$_{wc}$, and the specific energy consumption of the desalinator, Desalinator$_{sec}$, as input. As introduced in the previous paragraph, the Desalinator$_{sec}$ is taken to be 4 kWh/m^3 in the model.

$$dP_{\text{Desalinator}} = \text{Electrolyser}_{\text{wc}} * \text{Desalinator}_{\text{sec}} \tag{2-7}$$

Moreover, the desalinator CAPEX scale linearly with the installed electrolyser capacity, and the desalinator OPEX, in turn, scale linearly with the desalinator CAPEX, as described by equation 2-7 and 2-9, respectively. The specific CAPEX and OPEX are assigned a value in the case study in chapter 3.

$$\text{Desalinator}_{\text{capex}} = \text{Desalinator}_{\text{specific capex}} * \text{Electrolyser}_{\text{capacity}} \tag{2-8}$$

$$\text{Desalinator}_{\text{opex}} = \text{Desalinator}_{\text{specific opex}} * \text{Desalinator}_{\text{capex}} \tag{2-9}$$

2-3-3 Compressor

2-3-3-1 Compressor theory

Depending on the electrolyser output pressure and the required hydrogen grid pressure, a compressor is required to alter the hydrogen pressure level before grid injection [34]. The parameters of importance to the model are the energy consumption, CAPEX, and OPEX of the compressor. The CAPEX and OPEX functions are relatively straightforward, but the compressor's energy consumption deserves an elaboration in the following paragraph.

Energy consumption - The energy consumption of a hydrogen compressor stems from the required work for compression and the electromechanical efficiency of the compressor unit to deliver that work. Figure 2-8 shows the minimum theoretical work required for compression of hydrogen, plotted as a function of output pressure for isothermal compression as well as adiabatic- and practical compression of hydrogen. The work required for isothermal compression is the theoretical absolute minimum work required. However, in practice, heat losses occur and the work required for practical hydrogen compression falls approximately at the average of isothermal and adiabatic compression [16].

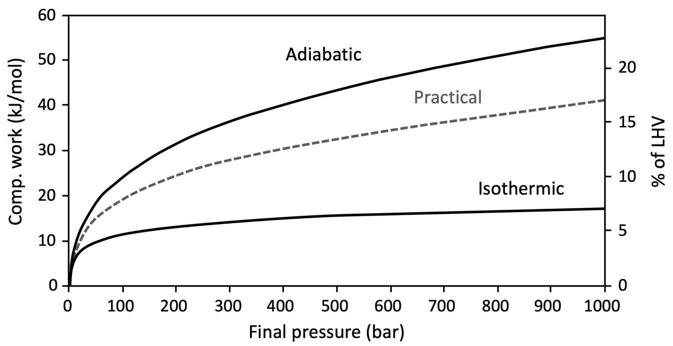


Figure 2-8: Hydrogen compression work as a function of output pressure. Three cases: isothermal, adiabatic and practical compression [16].

It can be observed from the figure that the compression work scales favourably at higher pressures; the work required for compression from 1 to 10 *bar* is approximately equal to the amount required for compression from 100 to 1000 *bar* [16]. On top of the theoretical compression work requirement, the compressor also has an electromechanical efficiency of approximately 65% [80]. As a result, compression of hydrogen from 30 to 100 *bar* takes approximately 0.72 kWh/kg, which corresponds to 1.8% of the hydrogen HHV and 1.5% of electrical electrolyser input. However, for compression from 50 to 100 *bar* only 0.38 kWh/kg is required, which corresponds to 1.00% of the hydrogen HHV and 0.8% of electrical electrolyser input.
This becomes important when comparing the PEM and AE electrolyser; PEM electrolysers can compress the hydrogen electrochemically to a higher output pressure than AE electrolysers. This reduces, or eliminates, the need for an additional mechanical compressor, which brings the advantages of less moving parts and a more efficient compression [81]. In the case of AE electrolysers, achieving a higher output pressure is one of the leading research topics since this could significantly reduce the energy required for mechanical compression.

2-3-3-2 Model implementation

As mentioned at the beginning of this section, the compressor is only required to alter the hydrogen pressure when the grid operates at a higher pressure than the electrolyser output pressure. Since the future operating pressure of electrolysers and the grid remain uncertain, these parameters are modelled as input variables, and a presumption of their value is used to run the model.
The compression losses per kg of hydrogen are accounted for in the model as a function of the input-output pressure ratio, PR, and the electrical efficiency of the compressor, $\eta_{electrical}$, as described in equation 2-10. The total compression loss is subsequently determined by multiplication of the energy loss per kg of hydrogen with the throughput quantity in equation 2-11.

$$dP_{\text{kwh/kg}} = \left(\frac{SF}{SF-1}\right) * nRT * (PR)^{\left(\frac{SF-1}{SF}\right)-1} * \left(\frac{500}{3600}\right) * \left(\frac{1}{\eta_{electrical}}\right) \tag{2-10}$$

$$dP_{\text{Compressor}} = \left(\frac{P_{\text{in}}}{\text{HHV}}\right) * dP_{\text{kwh/kg}} \tag{2-11}$$

Similar to the case for the desalinator, the compressor CAPEX and OPEX scale with the electrolyser capacity and are described by equation 2-12 and 2-13, respectively. Again, the specific CAPEX and OPEX are assigned values in the case study in chapter 3.

$$\text{Compressor}_{\text{capex}} = \text{Compressor}_{\text{specific capex}} * \text{Electrolyser}_{\text{capacity}} \tag{2-12}$$

$$\text{Compressor}_{\text{opex}} = \text{Compressor}_{\text{specific opex}} * \text{Compressor}_{\text{capex}} \tag{2-13}$$

2-3-4 Electrical system

2-3-4-1 Transformer and model implementation

Electrolysers operate at DC, which requires conversion of the AC power supply through a rectifier. As mentioned in section 2-1, the rectifier is included in the scope of the electrolyser unit, and, therefore, AC-power is simply fed into the electrolyser. The voltage level that must be supplied to the electrolyser differs per manufacturer, but a conservative value of 400 kV is assumed in the model, as in accordance with manufacturer information [82, 83]. A transformer of the same electrical capacity as the electrolyser is implemented in the model, as described by equation 2-14, to step down the voltage from $66kV$ to $400V$.

$$\text{Trafo}_{\text{capacity}} = \text{Electrolyser}_{\text{capacity}} \tag{2-14}$$

The transformer losses comprise a no-load loss and a load loss, that scale with the transformer capacity. The no-load loss, dP_{noload} is taken to be 0.65 kW per MW installed transformer capacity. The the load loss, dP_{load}, is 10 kW per MW installed transformer capacity at nominal load, but scales with the load on the electrolyser. The no-load loss and a load loss values are based on internal data from Eneco. Equation 2-15 presents the model implementation of the transformer loss.

$$dP_{\text{trafo}} = \text{Trafo}_{\text{capacity}} * (dP_{\text{noload}} + \left(\frac{P_{\text{in}}}{P_{\text{nom}}}\right)^2 dP_{\text{load}}) \tag{2-15}$$

Similar to the desalinator and compressor, the transformer CAPEX scale linearly with the installed capacity, and the OPEX scale linearly with the transformer CAPEX, as described by equation 2-16 and 2-17, respectively. Power compensation equipment and switchgears are also required for the electrical system, but for the scope of this study these are included in the specific CAPEX and OPEX of the transformer and the losses are considered negligible [84]. Again, the specific CAPEX and OPEX are assigned values in the case study.

$$\text{Trafo}_{\text{capex}} = \text{Trafo}_{\text{specific capex}} * \text{Trafo}_{\text{capacity}} \tag{2-16}$$

$$\text{Trafo}_{\text{opex}} = \text{Trafo}_{\text{specific opex}} * \text{Trafo}_{\text{capex}} \tag{2-17}$$

2-3-4-2 Cabling and model implementation

The power is transmitted from the OHVS to the conversion platform via multiple 66 $kVAC$ power cables. The number of cables required to keep the energy loss in the cable within reasonable bounds is calculated by dividing the installed electrolyser capacity by the rated power of the cables, as presented in 2-18.

$$\text{Cable}_{\text{nr.}} = \lfloor \text{Trafo}_{\text{capacity}} / \text{Cable}_{\text{rated power}} \rfloor \tag{2-18}$$

To obtain the power transmitted through a single cable, the available power at any point in time is divided by the number of cables. The losses per cable are subsequently determined and multiplied again by the number of cables to obtain the aggregated energy loss, as presented in 2-19. The cable voltage (U) is taken to be 66 kV, the resistance (R) 0.05 Ω/km, the sheet loss factor of the cable (λ_1) 0.05 and the armour loss factor (λ_2) 0.33, as in accordance with Eneco's manufacturer data.

$$dP_{\text{cables}} = 3\, R \left(\frac{P_{\text{per cable cable}}}{U\sqrt{3}}\right)^2 (1 + \lambda_1 + \lambda_2) * \text{Cable}_{\text{nr.}} * \text{Cable}_{\text{length}} \tag{2-19}$$

Finally, the cables' CAPEX is proportional to the cable length and the number of cables, and the OPEX is, in turn, proportional to the cable CAPEX. Again, the specific CAPEX and OPEX are assigned values in the case study in chapter 3.

$$\text{Cable}_{\text{capex}} = \text{Cable}_{\text{specific capex}} * \text{Cable}_{\text{length}} * \text{Cable}_{\text{nr.}} \tag{2-20}$$

$$\text{Cable}_{\text{opex}} = \text{Cable}_{\text{specific opex}} * \text{Cable}_{\text{capex}} \tag{2-21}$$

2-3-5 Platform

2-3-5-1 Platform theory

The platform hosts the electrolyser, desalinator, compressor, transformer and necessary operational facilities such as a helideck. As mentioned in the introductory chapter, a newly built platform can be used, or an existing platform can be refurbished. Plentiful existing platforms are to become available in the North Sea in the upcoming decade, and reusing an old platform brings the benefit of delayed decommissioning and potential sustainability benefits [33]. However, reusing an old platform also makes the project dependent on the timing of the availability of a suitable platform and adds the constraint of a single electrolyser capacity that can be placed on the platform [7, 52]. According to [52], an average production platform in the North Sea can host approximately 250 MW of electrolyser capacity and a satellite platform around 60 MW. Even when multiple platforms are used in combination, the design will still be limited to a discrete set of options, which would complicate the design process. Above all, various studies indicate that the refurbishment and reuse of existing platforms could be more expensive than the use of newly built platforms [33, 42, 52]. For the scope of this study, newly built platforms are therefore selected for the design of the hybrid wind-hydrogen park.

CAPEX - The platform is a significant contributor to the overall CAPEX of the conversion components, and the main differentiator in costs between an onshore and offshore hybrid wind-hydrogen park [33, 42]. The platform costs are broadly determined by the topside weight that the platform must support and the topside surface area required, since these parameters determine the quantity of primary steel, gratings, cladding and coatings required [42]. An extensive study into the CAPEX of conversion platforms has been performed in [42]. The study compares newly built power-to-hydrogen platforms to existing OHVS stations, and it considers topside mass requirements as well as surface area requirements. The study concludes that the CAPEX of a newly built platform scale linearly in the range of 100 to 2000 MW electrolyser capacity, at a rate of approximately 165 $k€/MW_{el}$. The water depth selected in the study is 30 m, the electrolyser surface requirement is assumed to be approximately 20 m^2/MW_{el} and the weight of the electrolyser is assumed to be 26 $tonnes/MW_{el}$, including balance of plant components. Even though the surface requirement assumption deviates from the one in this study, the weight assumption corresponds well to the findings in section 2-3-1, and the platform CAPEX from [42] are used in this study.

2-3-5-2 Model implementation

The platform is represented in the model by two formula's that scale the CAPEX and OPEX of the platform with the installed electrolyser capacity, as presented by equation 2-22 and 2-23. The specific CAPEX and OPEX values are assigned values in the case study in chapter 3. As in accordance with [42], the CAPEX values used are applicable to platform sizes ranging from 100 to 2000 MW installed electrolyser capacity and a water depth of 30 m.

$$\text{Platform}_{\text{capex}} = \text{Platform}_{\text{specific capex}} * \text{Electrolyser}_{\text{capacity}} \tag{2-22}$$

$$\text{Platform}_{\text{opex}} = \text{Platform}_{\text{specific opex}} * \text{Platform}_{\text{capex}} \tag{2-23}$$

2-3-6 Output value optimisation

As mentioned briefly in section 2-2, an output value optimisation is performed for each hour over the lifespan of the wind-hydrogen park. To this end, available electricity must be allocated to the grid and the conversion platform on an hourly basis. This section explains the electricity allocation options that the model disposes of and the hourly output value optimisation in more detail. First, all possible operations that the model can execute are described: selling electricity, taking up electricity, converting electricity and selling the produced hydrogen and curtailing the wind park output. Thereafter, the model logic is explained that decides what operation, or combination of operations, the model ought to execute for optimal output value in each respective hour.

2-3-6-1 Electricity allocation options

The operations at the control's disposal are:

i. **Sale of electricity -** The most straightforward action that the model can carry out is to sell available power from the wind park as electricity at the corresponding hourly electricity price. Hereto, it is assumed that the quantity of the output of the hybrid park under review does not affect the electricity market price. The maximum power that can be exported through the grid connection is included in the model as an input variable. Additionally, the model is limited in the power it can sell as electricity by the available wind park output power in each respective hour.

ii. **Conversion of electricity and sale of hydrogen -** Another operation that the model disposes of is to convert the electricity and to sell the hydrogen at the corresponding hourly hydrogen price. Again, it is assumed that the quantity of the output of the hybrid park under review does not affect the hydrogen market price. As described in section 2-3-1, the electrolyser minimum load must be met at all times. Above that minimum load, whether electricity is converted into hydrogen depends on the market prices and conversion losses. Converting the electricity into hydrogen results in losses at each of the hardware components described in chapter 2. In sequential order, losses occur in the cables, the transformer, the electrolyser, and the compressor. In this series, the losses of the electrolyser dominate the aggregate conversion efficiency. As described in section 2-3-1, the conversion losses of the electrolyser depend on the electrical load sent through the electrolyser. The electrolyser efficiency increases at lower load factors but then rapidly decreases from a turning point onward at a load factor of approximately 25%. Figure A-3 presents the exemplary aggregate conversion losses for the range of electrolyser loads for a 500 MW AE electrolyser. The overall efficiency of the conversion steps as a function of electrolyser part-load is presented in the figure too. For the remainder of this work, the power that must be sent into the conversion track to allow the electrolyser to run at minimum load after subtraction of the cable, transformer and desalination losses is referred to as $conversion_{min}$. Similarly, the power that must be sent into the conversion track for the electrolyser to operate at its maximum load is $conversion_{max}$.

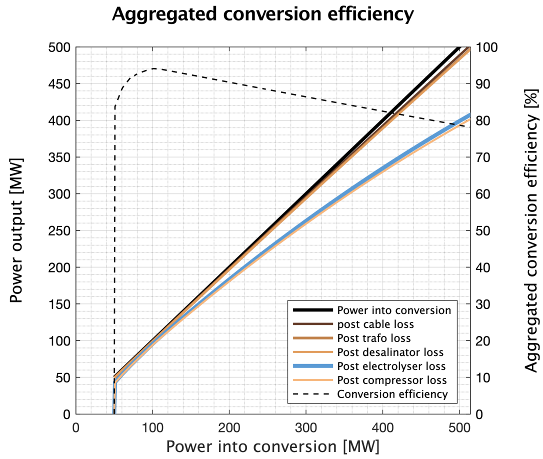


Figure 2-9: Individual and aggregate conversion losses of the hardware components over the load range of the AE electrolyser. The figure is exemplary for an installed electrolyser capacity of 500 MW and the x-axis is limited from $conversion_{min}$ to $conversion_{max}$.

iii. Uptake of electricity - The use of available power from the wind park is primarily desired, but additional power can be taken up from the grid for conversion purposes in two cases; either when too little power is available from the wind park to meet the electrolyser minimum load constraint or when the uptake of electricity in a particular hour generates additional value. An example of the latter case is a scenario in which it is economically beneficial to produce hydrogen, but too little wind power is available to run the electrolyser at rated capacity. Another example is when just enough wind power is available to run the electrolyser at minimum load, but it is desirable to run the electrolyser at a slightly higher part-load to obtain a higher part-load conversion efficiency. The model is limited in the power it can take up from the grid as electricity by the capacity of the electric connection to the grid, which is an input variable to the model.

iv. Curtailment of available wind power - The final operation that the model can choose to execute is the curtailment of wind power. In this case, a part of the available wind power is not sold as electricity nor converted into hydrogen. In this model, curtailment is desirable in two particular cases; when the electricity price is below the curtailment threshold, for example a negative electricity price, and more wind power is available than the electrolyser capacity, or when the wind park delivers more power than the combined capacity of the electric connection to the grid and the electrolyser. In reality, other criteria might apply that make curtailment (un)desirable in various situations, such as turbine wear. However, these criteria have been excluded from the scope of this research.

2-3-6-2 Hourly output optimisation

Now that the operations at the disposal of the model have been elaborated upon, this section explains the model logic that decides what operation, or combination of operations, the model ought to execute for optimal output value in each respective hour. Within each hour, the model calculates the net output value from the sale of electricity and hydrogen, uptake of electricity and curtailment of wind power for all possible electrolyser loads that satisfy the minimum and maximum electrolyser load constraint. For each respective electrolyser load, the wind power that remains after subtracting the electrolyser load, if any, is sold as electricity. The additional power that is required to supply the respective electrolyser loads, if any, is taken up from the grid. For each hour, the model selects the electrolyser load that results in the optimal hourly output value when summing the revenues from electricity and hydrogen sale, as well as the costs of electricity uptake. Equation 2-25 represents the model logic that determines the optimal hourly electricity allocation.

$$\max f_{(a,b,c,d)} \tag{2-24}$$

$$f_{(a,b,c,d)} = (a-b) * E_{price} + c * \eta_{\text{conversion}} * H_{2price} + d * 0 \tag{2-25}$$

$$\begin{aligned}
\text{s.t.} \qquad & a + b + d - c = windoutput \\
0 \leq{} & a \leq electriccapacity_{max} \\
0 \leq{} & b \leq electriccapacity_{max} \\
0 \leq{} & d \leq windoutput \\
conversion_{min} \leq{} & c \leq conversion_{max}
\end{aligned} \tag{2-26}$$

2-4 Model validation

In this section, the model's intended functioning is validated. Only when the model is properly validated, it can be employed for the objective of this research; to obtain insight into the design and operation of an offshore hybrid wind-hydrogen park. To validate the power allocation algorithm described in section 2-3-6, the operation of the model is illustrated and elaborated upon for various telling scenarios. First, a single 'hour' is discussed from which the model logic can be observed in detail. Next, a time series of multiple hours is presented in which various telling scenarios are illustrated in sequence.

One hour validation - In the scenario discussed here, the functioning of the model's power allocation is presented for a single hour. In this particular example, a 1000 MW wind park operates at nominal capacity, and is equipped with a 500 MW AE electrolyser. Consequently, the minimum and maximum power that can be sent into the conversion track are $conversion_{min}$ and $conversion_{max}$ as described in 2-3-6-1, and can be observed in the figure around 51 and 520 MW. The electric export capacity poses no limit, meaning that up to 1000 MW of electricity can be exported. Moreover, as presented on the right axis of figure 2-10, the hydrogen price is slightly higher than the electricity price, but when the conversion losses are taken into account, the output value from electricity sale and hydrogen sale are about evenly matched. Figure 2-10 illustrates the revenues induced from electricity sale and hydrogen sale, as a function of the different electrolyser loads that can be chosen by the model. The figure illustrates that the principle of equation 2-25 and 2-26 is implemented in the model as a stepwise increase in power sent into conversion, combined with a rigorous search for the electricity distribution that yields the optimum combined output value.

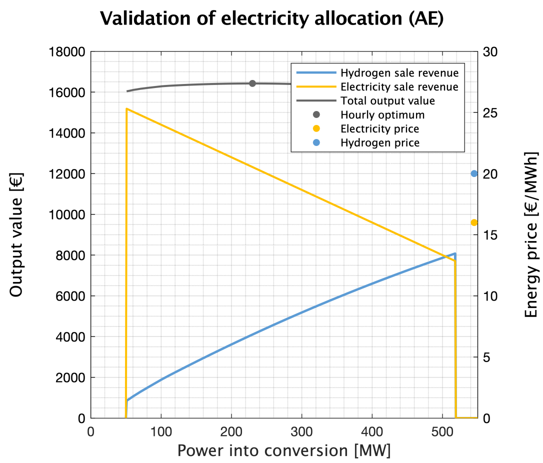


Figure 2-10: Model validation scenario for a 500 MW AE electrolyser at 1000 MW wind power. The model determines the electrolyser part-load that results in the optimal output value from electricity and hydrogen sale. Energy prices are indicated on the right axis.

As observed from the figure, the revenue from electricity sale declines linearly upon an increasing power into conversion. Since electricity is exported to the grid without any additional losses from the OHVS onward, the hourly electricity revenue is simply the available power for

export, multiplied by the electricity price.
Meanwhile, the revenue from hydrogen sale follows from the power sent into conversion, minus the conversion losses that depend on the electrolyser part-load, multiplied by the hydrogen price. Therefore, the revenue from hydrogen sale increases more steeply for lower electrolyser loads, where the part-load efficiency steeply increases. As described in section 2-3-1, from approximately 25% part-load (i.e. 125 MW), the part-load efficiency decreases again, resulting in a less steep increase in hydrogen revenue upon increasing power converted.
The addition of the two curves, presented in grey in the figure, yields an optimum. The optimum is selected on an hourly basis and the electricity is allocated accordingly. The optimum power allocation to conversion in this particular hour is 240 MW, corresponding to a part-load of the electrolyser of 48% of nominal load and a remaining power of 760 MW available for electricity export. The revenue curves illustrate that it is preferable to send less than the nominal electrolyser capacity through the electrolyser to obtain a higher part-load efficiency and sell the remainder of the power as electricity, even when the hydrogen price is slightly higher than the electricity price.

Time series validation - A time series of approximately 50 hours of park operation is presented in figure 2-11 for two hybrid cases: one with an AE electrolyser on the left, and one with a PEM electrolyser on the right. In both cases, a 1000 MW wind park is selected in combination with a 500 MW electrolyser. Essentially, the optimisation as described in the previous paragraph is performed, but this time for a series of hours. Exemplary time series for the wind park output and energy prices that provoke all possible park operations, are selected as input for the model. The figure can be complex to grasp at first sight, so the figure is explained systematically; first it is explained what the lines in the figure represent, followed by an evaluation of the model operation for three distinct moments in time.

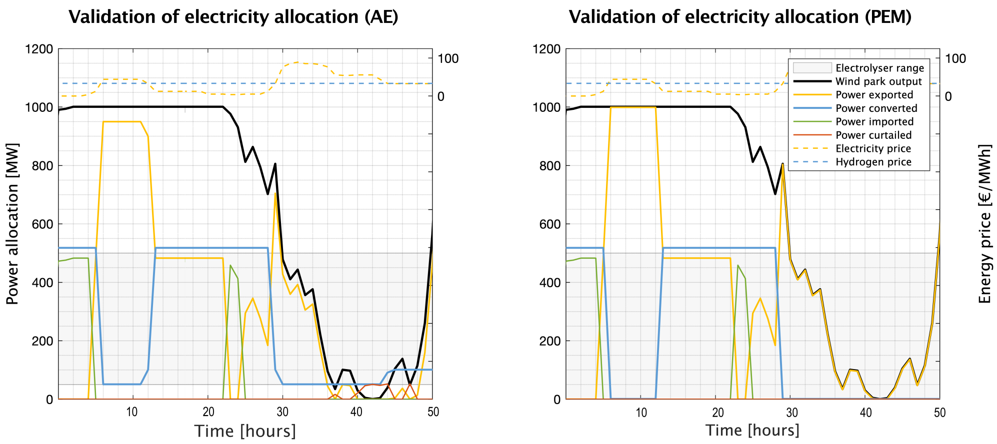


Figure 2-11: Model validation time series for a hybrid wind-hydrogen park with 1000MW installed wind capacity and 500 MW installed electrolyser capacity. Left: AE electrolyser technology, right: PEM electrolyser technology.

The dashed lines in the top of the figures represent the electricity and hydrogen market prices over time, and the black line represents the fluctuating available wind park output. The energy prices and wind park output are equal between the two sub figures.

The yellow, blue, red, and green lines represent the power allocated to electricity export, electricity conversion, electricity uptake, and wind power curtailment, respectively, as optimised by the model. Finally, the grey area represents the electrolyser load range, and indicates a non-zero minimum load for the AE electrolyser in the left sub figure. Three moments in time are interesting to elaborate on.

First, at the 0^{th} hour, plentiful wind power is available, and the electricity price is slightly negative. It is observed from the figure that the model consequently sends maximum power into conversion as indicated by the blue line, and curtails the remaining wind park output as indicated by the green line, to avoid paying the negative electricity price.
Secondly, at the 10^{th} hour, plentiful wind power is still available, and the electricity price is now higher than the hydrogen price. For the PEM electrolyser in the right sub figure, no minimum load has to be considered, and all available electricity is exported. However, for the AE electrolyser in the left sub figure, the model must serve its minimum load. The remaining power is exported as electricity.
Finally, between the 40^{th} and 50^{th} hour, the wind park output is extremely low, and the price of electricity is equal to - or above - the hydrogen price. As a result, the park with the PEM electrolyser chooses to export the little available electricity and convert none. However, in the left-most figure, the model has to serve the AE electrolyser's minimum load. In this case, power is sent into conversion, and electricity is also taken up from the grid to serve the AE electrolyser. The delicacy of the optimisation can be observed in the final hours, where the AE park chooses to import electricity to operate the AE electrolyser on a slightly higher part-load than the minimum load to obtain a higher output value.
The figure shows that, for both the AE and PEM electrolyser, the model selects the economically favourable electricity allocation that satisfies the technical electrolyser constraints. Moreover, it can already be observed from these figures that the minimum load plays a differentiating role in the operation of the AE and PEM electrolysers. An in-depth reflection on the model operation follows in the following chapter.

Chapter 3

Results

In this chapter, the validated model is employed to obtain insight into the design and operation of an offshore hybrid wind-hydrogen park. First, section 3-1 presents the set-up and input parameters of the hybrid wind-hydrogen case study. Moreover, the results for an all-electric reference park are presented to set a benchmark to compare later results with. Subsequently, section 3-2 presents the results of the case study; The operation of a hybrid wind-hydrogen park is showcased in detail, and it is evaluated whether it is economically beneficial to add an electrolyser to the all-electric wind park, and if so, which electrolyser technology and capacity yields the best results. In the final section of this chapter, a sensitivity analysis is performed on the most defining and critical input parameters of the model.

3-1 Set-up of the case study

3-1-1 Introduction to the hybrid wind-hydrogen case study

In the case study, the model is applied to a set of input data that is representative for the scope of this study; A hybrid-wind-hydrogen park from a developer's perspective, located in the North Sea, operating on the Dutch power market, and starting operation in 2030. The location selected for the case study is to the north-west of the Netherlands, and is approximately 150 km from shore. According to [20], this location fits well into the North Sea's spatial wind park planning beyond 2030, and an existing offshore pipeline infrastructure could potentially be retrofitted to a hydrogen export infrastructure. A visualisation of the spatial wind park planning, pipeline infrastructure, and the selected location can be found in appendix A-3. The wind park capacity remains constant throughout the case study and is selected to be 1000 MW. The electrolyser technology and capacity are varied in the case study to obtain insight into how the parks' operations and economics alter upon the various designs.
Moreover, the technical and financial parameters of the model components have been assigned a value for the purpose of the case study and are presented in table 3-1 and 3-2. All values used in the case study serve an indicative purpose and result from literature and manufacturer data. An analysis of the sensitivity of the case study results to alterations in the parameter values is performed in section 3-3.
Finally, a time series of hourly values for the wind park power output and electricity and hydrogen prices have been inserted in the model. In the following section, these time series are discussed in detail.

Table 3-1: Indicative values from literature for the relevant parameters of the AE and PEM electrolyser. [1] efficiency as $\%_{HHV}$ and scaled to the part-load efficiency curve presented in appendix A-2. [2] electrolyser capex reference values for a 20 MW electrolyser, scaled according to equation 2-5 presented in section 2-3-1

Input parameter	AE	PEM	Unit	Source
Nominal efficiency[1]	82	80	% of HHV	[8, 13, 14]
Load range	10-100	0-100	% of nominal load	[8, 12]
Output pressure	30	80	bar	[8, 46]
Electrolyser CAPEX[2]	475	650	k€/MW$_{electrolyser}$	[13, 14]
Electrolyser OPEX	2	2	%/y/cpx	[13, 14, 46]

Table 3-2: Indicative values from literature for the relevant parameters of the desalinator, compressor, platform, transformer and cabling. [1] distance from OHVS to electrolyser platform

Input parameter	Value	Unit	Source
Wind park capacity	1000	MW	[-]
Wind park CAPEX	2.0	M€/MW	[24]
Wind park OPEX	3.0	%/y/cpx	[24]
Desalinator SEC	4.0	KWh/m^3	[15, 85]
Desalinator CAPEX	9.5	k€/MW$_{electrolyser}$	[31, 59]
Desalinator OPEX	2.5	%/y/cpx	[31]
Compressor SEC	0.72	KWh/kg	[16, 56]
Compressor CAPEX	20	k€/MW$_{electrolyser}$	[33, 52]
Compressor OPEX	3.0	%/y/cpx	[33, 52]
Grid pressure	100	bar	[33]
Platform CAPEX	165	k€/MW$_{electrolyser}$	[40]
Platform OPEX	1.0	%/y/cpx	[86]
Transformer CAPEX	70	k€/MW$_{electrolyser}$	[84]
Transformer OPEX	1.0	%/y/cpx	[84, 86]
Cable distance[1]	20	km	[-]
Cable CAPEX	220	k€/km	[86]
Cable OPEX	1.0	%/y/cpx	[86]

3-1-2 Wind park and power market input data

Wind park - The wind park power output series used in this study are generated by Eneco's wind park model, which uses the IEA 15 MW reference turbine, and includes wake-losses and inter-array losses up to the OHVS. The wind data used in Eneco's model is taken from the Dutch Offshore Wind Atlas (55 °N , 4 °W), and the representative wind year of 2012 has been selected and repeated for the full lifetime of the park [87]. Figure 3-1 presents the load duration curve of the representative wind year used in the model.

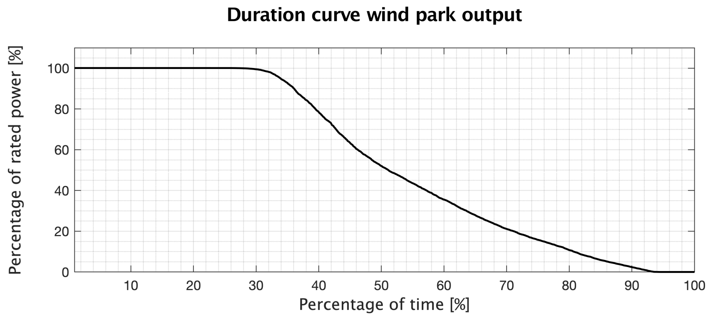


Figure 3-1: Wind park output characteristics for wind year 2012. Sourced by Eneco.

Power market - The price series used in this study are generated by Eneco's power market model and provide the hourly wholesale price for electricity as well as hydrogen. The Eneco power market model considers a large quantity of input parameters, such as the nationally installed renewable capacity and electrification of demand. Moreover, the hydrogen price results from the natural gas and carbon price in the model, with as underlying assumption that Steam Methane Reforming (SMR) and the corresponding costs of carbon emission determine the hydrogen market price.
Several price scenarios have been generated for the purpose of this study, including a *target transition scenario*, *slow-going transition scenario* and a *swift transition scenario*. In the *target transition scenario*, the energy transition unfolds in accordance with the existing Dutch climate targets for 2030 and 2050. In the *slow-going transition* scenario, little renewable capacity is added to the energy system and the electrification of demand, and the CO_2 price remain low; As a result, the climate targets are not met. Oppositely, in the *swift transition* scenario significant renewable capacity is installed, and the electrification of demand and the CO_2 price take off swiftly. The target scenario is presented in figure A-7. The electricity price of the target scenario falls well in line with publicly available price scenarios that provide guidance on annual average electricity prices towards 2050 [33, 88, 89]. The slow-going and swift transition scenarios are presented in appendix A-4.

For the remainder of this chapter, only the target transition scenario is elaborated on, since the conclusion on the other scenarios is straightforward; in the slow-going energy transition scenario, the carbon price remains low, and hydrogen is not sufficiently valued to provide a solid return on the hybrid park under any conditions. On the contrary, in the swift energy transition scenario, the hydrogen price significantly overtakes the electricity price, and the

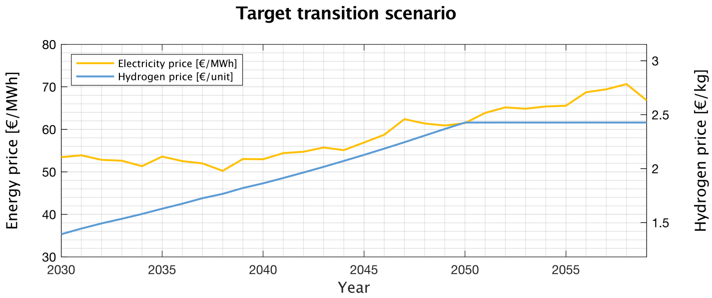


Figure 3-2: Target transition price scenario. The prices presented are annual averages. The hydrogen price is indicated in [€/MWh] on the left axis and in [€/kg] on the right axis; The hydrogen price in [€/kg] is determined on the basis of the Higher Heating Value (HHV), as in accordance with Eneco standards and [17, 18, 19].

addition of an electrolyser becomes favourable under virtually all conditions. The scenario in between is the most likely scenario to come to realisation and the most interesting to apply the model to.
For the objective of this study, it is interesting to provide insight into which factors determine the performance of the hybrid wind-hydrogen park on a gradual scale instead of in discrete scenarios, and how these findings can be related to the design and operation of the hybrid wind-hydrogen park. A systematic variation in the electricity and hydrogen prices will therefore be applied in section 3-3. To ensure a correlation between the wind data and power prices, the aforementioned representative wind year of 2012 has also been used as input to the power market model. A figure displaying the correlation between wind and power price data can be found in appendix A-5.

3-1-3 All-electric reference case

The all-electric reference case is used to compare the performance of the model to a real-world wind park, and to set a benchmark to compare the results of the hybrid wind-hydrogen park to in the following section. For the all-electric reference case, the model is applied to a 1000 MW wind park with no electrolyser capacity. Moreover, the electric export capacity equals the park's rated power and thus poses no limit.
Four metrics are used to perform an objective comparison of the reference park with a real-world wind park: the Levelised Costs Of Electricity (LCOE), Internal Rate of Return (IRR), Capacity Factor (CF), and Capture Value (CV).
The capture value metric expresses the ratio of the average price obtained by the wind park over the average price in the power market as a whole in the same time period. In other words, it presents the share of the average power price that the wind park *captures*. As presented in appendix A-5, the wind park output and electricity price are negatively correlated, which means the average electricity price decreases at increasing wind availability. Wind parks therefore generally generate much power when electricity prices are low and little power when electricity prices spike. This puts wind parks in a disadvantageous position compared to energy assets that can respond more astutely to market dynamics, such as potentially a hybrid wind-hydrogen park. Figure 3-3 presents the CV of the all-electric reference case and shows its significant decline over time, due to the introduction of more renewable capacity.

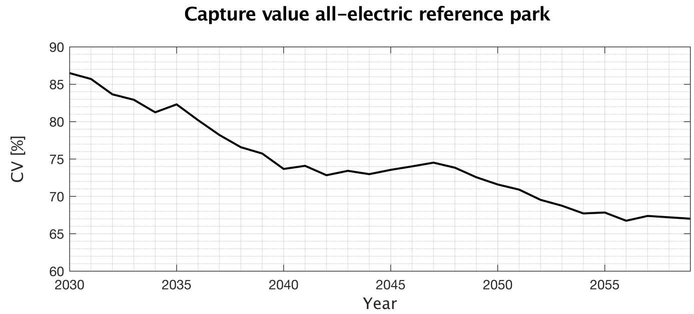


Figure 3-3: Capture value of the all-electric reference wind park. The capture value is calculated for each year from 2030 to 2060, by taking the average electricity price obtained in a particular year by the reference wind park and dividing it by the average electricity price in the same year.

The values of the comparison metrics for the all-electric reference case are presented in table 3-3. The LCOE and CF values correspond well to the recent projection from IRENA for offshore wind in 2030 of 30-50 €/MWh and 36-58%, respectively [90]. Moreover, the IRR of the all-electric wind park is in line with what can be expected from a real-world wind park, albeit slightly on the low end since only merchant revenues are considered. These results presented below will be used as a reference for comparison against the hybrid wind-hydrogen case in the following section.

Table 3-3: Input parameters of the reference case and resulting performance metrics. The LCOE is on the basis of produced electricity and a real interest rate of 4.8 % [21, 22, 23].

Input parameter	Value	Source	Performance	
Wind park capacity	1000 MW	[-]	LCOE	39.5 [€/MWh]
Export capacity	1000 MW	[-]	IRR	5.5%
Wind park CAPEX	2 M€/MW	[24]	CV	74.0%
Wind park OPEX	3%/y/cpx	[24]	C_f	53.0%

3-2 Results of the case study

The objective of the case study is two-fold. First of all, it aims to provide inside into the operations of a hybrid wind-hydrogen park for the AE as well as PEM electrolyser under the default parameter settings of the case study. Secondly, the case study aims to present how the park operations are reflected in the economics of the parks. Hereafter, it can be concluded whether it is economically beneficial to add an electrolyser to the all-electric wind park under the default parameter settings, and if so, which electrolyser technology and capacity.
To this end, the park is studied from two angles. First, a detailed review of the operations of a single park configuration over time is presented, for which a 1000 MW wind park with a 500 MW AE or PEM electrolyser is selected. Once it is understandable how a single park configuration operates, the review is zoomed out to higher level and it is presented how the parks operate over a range of installed electrolyser capacities. Where possible, the benchmark of the all-electric reference park is presented along with the results of the hybrid wind-hydrogen park.

3-2-1 Electricity export

As described in section 2-3-6, the model disposes of four possible operations: the sale of electricity, the conversion of electricity and subsequent sale of hydrogen, the import of electricity and the curtailment of wind power. For each of these operations, the model outcomes are presented over the course of a year to provide insight into how the parks operate individually, and to inter compare the operations of the different parks. An interpretation and contextualisation of the results follows in the discussion chapter.
Figure 3-4 presents the sale of electricity over the year 2030 for the all-electric reference park and two distinct hybrid wind-hydrogen parks. The hybrid parks are accommodated with 500 MW of electrolyser capacity, equating a relative electrolyser capacity of 0.5 compared to the wind park capacity. Moreover, the figure presents the electricity and hydrogen prices to observe how the parks operate under various price conditions.

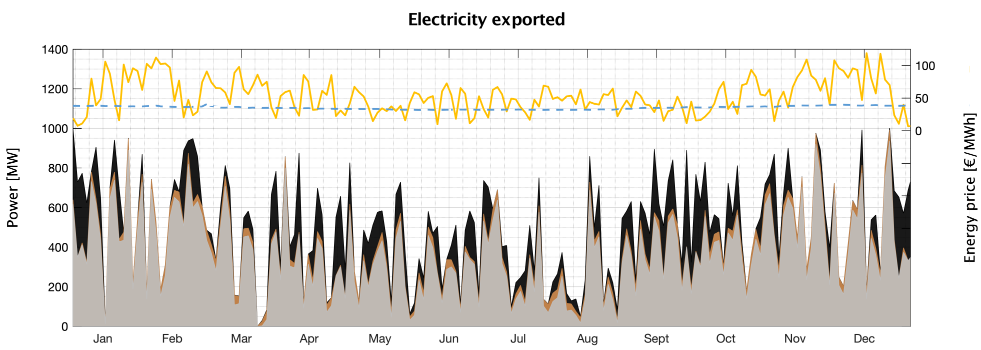


Figure 3-4: Exported electricity over a year of operation for three park designs. Black represents the all-electric reference case, grey represents a hybrid wind-hydrogen park with 500 MW AE electrolyser and brown a hybrid wind-hydrogen park with 500 MW PEM electrolyser. The electricity and hydrogen prices are indicated in yellow and blue, respectively.

First of all, it can be observed from the figure, for example on the outer right or outer left side, that the hybrid parks export less electricity than the all-electric reference park when the electricity price is below the hydrogen price. At these times, conversion of electricity into hydrogen is favourable from an economic perspective and the operations of the AE and PEM electrolyser parks are practically identical.
Secondly, it can be observed from the figure that the hybrid PEM park exports more electricity than the hybrid AE park when the electricity price is above the hydrogen price, i.e. when electricity export is economically favourable. This is because the alkaline electrolyser has to serve its minimum load at all times, which is 50 MW in this particular example. A clear occurrence of such can be observed just ahead of August.

3-2-2 Electricity conversion

Figure 3-5 presents the electricity converted into hydrogen over the year 2030 for the hybrid AE park as well as the hybrid PEM park. In this figure, no all-electric reference can be presented since the conversion of electricity into hydrogen does not occur in the all-electric park.
It can be observed from the figure that for both electrolyser types, conversion spikes occur when the electricity price falls below the hydrogen price. At these times, it favourable to convert electricity into hydrogen from an economic perspective.
Secondly, as is clearly observed just ahead of February and December, the hybrid Alkaline Electrolysis (AE) park converts a base load of electricity into hydrogen over the full time period that corresponds to the minimum load of the AE electrolyser, being 50 MW in this particular example. As a result, the AE electrolyser oftentimes converts more electricity into hydrogen than the PEM electrolyser, at times it is economically unfavourable.

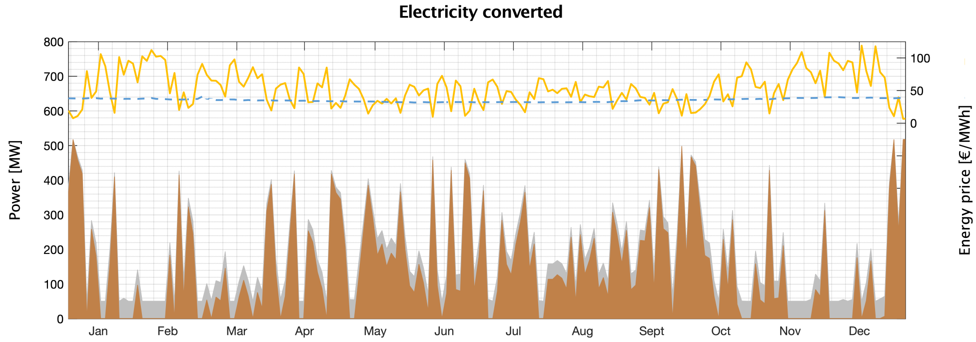


Figure 3-5: Converted electricity over a year of operation. Grey represents a hybrid wind-hydrogen park with a 500 MW AE electrolyser and brown represents a hybrid park with a 500 MW PEM electrolyser. The electricity and hydrogen prices are indicated in yellow and blue, respectively.

3-2-3 Hydrogen production

Figure 3-6 presents the hydrogen produced over the year 2030 for the two hybrid parks, and confirms the observation from the previous paragraph, i.e. the hybrid AE park produces more hydrogen than the hybrid PEM park at times the hydrogen price is below the electricity price. The main distinction between the two figures is that the exported hydrogen is approximately 20% lower than the converted electricity at all times, due to the electrolyser conversion efficiency. The two figures together clearly show the effect that sustaining the AE minimum load has on the operations of the hybrid parks. How this in turn resounds in the economics of the parks is discussed in later results.

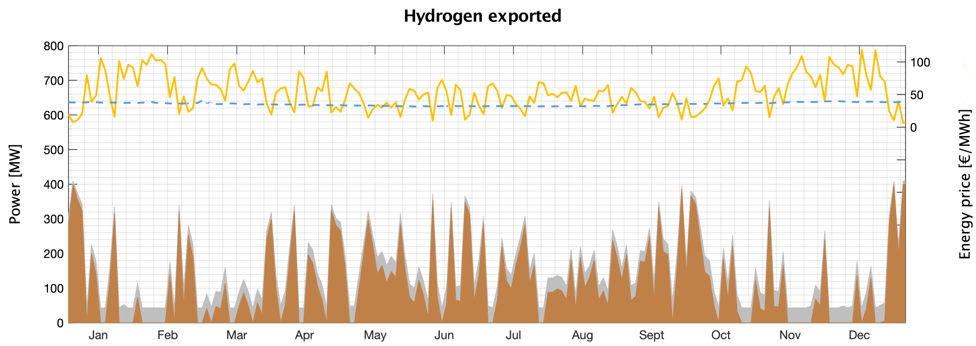


Figure 3-6: Produced hydrogen over a year of operation. Grey represents a hybrid wind-hydrogen park with a 500 MW AE electrolyser and brown represents a hybrid park with a 500 MW PEM electrolyser. The electricity and hydrogen prices are indicated in yellow and blue, respectively.

3-2-4 Electricity import

In figure 3-7, the electricity imported over the year 2030 by the hybrid AE and PEM park is presented. Two observations follow. First, relatively little electricity is imported for both electrolyser types compared to the export of electricity and conversion of electricity into hydrogen. Moreover, it can be observed that the hybrid AE park imports equal or more electricity than the hybrid PEM park at all times. It is also observed that at times that only the AE park imports electricity, the price of electricity is generally higher than the hydrogen price. At these times, electricity import and subsequent conversion into hydrogen is therefore unfavourable from an economic perspective.

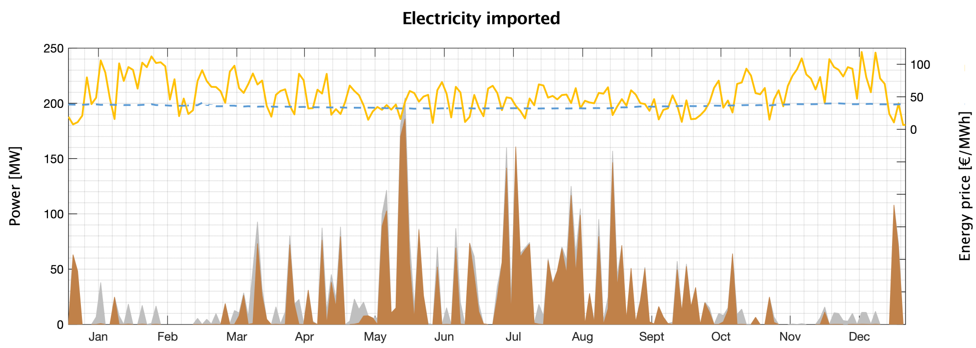
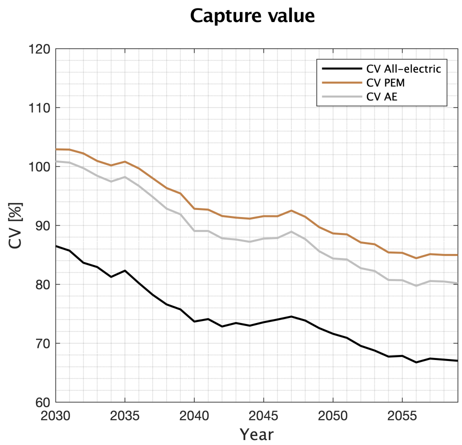


Figure 3-7: Imported electricity over a year of operation. Grey represents a hybrid wind-hydrogen park with a 500 MW AE electrolyser and brown represents a hybrid park with a 500 MW PEM electrolyser. The electricity and hydrogen prices are indicated in yellow and blue, respectively.

3-2-5 Capture value and capture cost rate

A central theme that occurs in the observations is the timing of the various park operations in regard to the electricity and hydrogen market prices. To recall, the goal of complementing the all-electric wind park with an electrolyser of any type is for the park to be able to respond astutely to, and take advantage of, fluctuating market prices. A first metric that expresses the ability of an energy asset to act on market dynamics, being the capture value, was introduced in section 3-1-3. In short, the capture value reflects the average price obtained for the sale of electricity relative to the average market price in the same period of time. A second metric to assess the flexibility of hybrid wind-hydrogen is the Capture Cost Rate (CCR). The CCR can be considered the reverse capture value for electricity import, and reflects the average price paid for the import of electricity relative to the average market price in the same period of time. Therefore, the CCR is only applicable to hybrid wind-hydrogen parks. Figure 3-8 presents the capture value and capture cost rate for the all-electric, hybrid AE and hybrid PEM park.



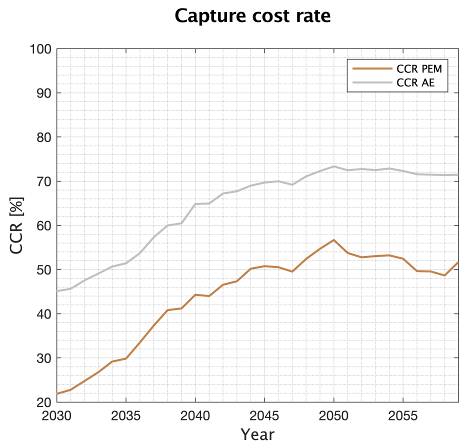


Figure 3-8: Capture value and capture cost rate over the parks' lifetime for three park designs. Black represents the all-electric reference case, grey represents a hybrid wind-hydrogen park with 500 MW AE electrolyser and brown a hybrid wind-hydrogen park with 500 MW PEM electrolyser. The electricity and hydrogen prices are indicated in yellow and blue, respectively.

The general trends that can be observed from the figure are a gradually declining capture value, and a gradually increasing capture cost rate. In both cases, this is explained by the increasing correlation between the wind park output and electricity price over time, which follows from an increase in renewable capacity participating in the power market.

The hybrid parks in this particular example contain 500 MW of electrolyser capacity, which means that if at a particular moment 1000 MW of power is available, plentiful electricity remains after serving the electrolyser's maximum load. This remaining share of electricity is sold for a lower electricity price over time, relative to the average electricity market price, which decreases the CV of the hybrid parks over time.

However, from the left-most figure, it can be observed that the addition of an electrolyser to the all-electric reference park increases the capture value of the park, due to its increased flexibility. In other words, the hybrid wind-hydrogen parks export electricity for a higher average electricity price than the all-electric park. This finding is in line with the observations that followed from figure 3-4 and 3-5. Moreover, it can be observed from the left-most figure that the PEM electrolyser increases the capture value more than the AE electrolyser, which is also in correspondence with earlier observations; a hybrid AE park has to serve its minimum load, which lowers the available electricity for export when the electricity price is high.

The CCR in the right-most figure gradually increases, again, due to the increasing wind-price correlation over time. The moments that an electrolyser takes up electricity is when insufficient power is available to serve the electrolyser by the wind park output alone. Due to the increased correlation, the average price for this uptake increases over time. As can be observed, the difference between the AE and PEM is significantly larger for the CCR than for the CV, which can be explained by the timing of electricity import of both electrolysers and the correlation between the wind park output and electricity price.
For the PEM electrolyser, the electricity import case is simple; the park only imports electricity when it is economically beneficial, and it also has remaining capacity for electricity uptake. For the AE electrolyser, the electricity import case is more complex. The AE electrolyser takes up electricity for two reasons; to generate extra profit, like the Polymer Electrolyte Membrane electrolysis (PEM), and to serve its minimum load in case of too low wind power availability.
The electricity price of the electricity that both electrolysers import to generate profit is generally significantly lower than the average electricity market price. However, the electricity that the AE electrolyser park imports to serve the minimum load in times of too little available wind power is generally more expensive than average, due to the negative correlation between wind power availability and the electricity price. As a result, the CCR of the AE park is significantly higher than that of the PEM park.

Figure 3-9 presents the CV and CCR for the all-electric park and the hybrid AE and PEM park again, but this time expressed as a function of relative installed electrolyser capacity.

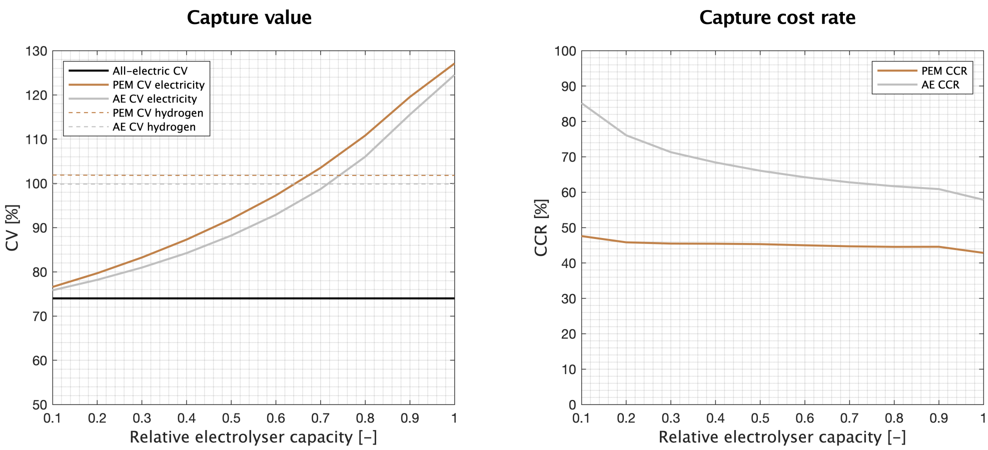


Figure 3-9: Capture value and capture cost rate for all relative installed electrolyser capacities for three park designs: the all-electric reference, hybrid AE and hybrid PEM.

The left-most figure shows that the CV for exported electricity increases rapidly upon increasing relative electrolyser capacity, due to the improved flexibility to switch between electricity

and hydrogen production. The figure also presents the CV for exported hydrogen. Since the hydrogen price is only slightly correlated to the wind park output, as presented in appendix A-5, this CV is approximately 100%. Moreover, the CV for hydrogen is independent of the relative installed electrolyser capacity, since the model only opts to produce electricity when it is economically beneficial, regardless of the electrolyser capacity. The difference between the CV lines for AE and PEM is again explained by the AE minimum load, which results in a base load of hydrogen production regardless of the hydrogen price, and reduces the electricity available for export when the electricity prices are high.
The most striking observation is that, in the right-most figure, the CCR increases steeply for lower relative installed AE electrolyser capacities. The reason for this is two-fold; Upon a decreasing relative installed electrolyser capacity, less often too little wind power is available to serve the minimum electrolyser load. However, when this occurs, extremely little wind power is available, and the electricity price is consequently very high due to the correlation between the wind park output and electricity price. As a result, the AE electrolyser occasionally imports very pricey electricity, which increases the CCR at lower relative AE electrolyser capacities. Secondly, at lower relative installed electrolyser capacities, the AE electrolyser also less often has remaining capacity available to take up additional electricity, decreasing the relative share of cheap electricity in the total electricity taken up by the AE, and increasing the CCR.

3-2-6 Grid exchange

This study is centred around the developer's perspective. It is optimised what the optimal output value is that a developer can obtain by allocating electricity astutely, while assuming an existing infrastructure. However, the results can also be consulted to reflect on the requirements of a future hybrid offshore infrastructure. Figure 3-10 presents the electricity and hydrogen grid exchange for the all-electric park as well as the hybrid parks. The left-most figure shows the effects of seasonality on the grid export, and the right-most figure presents the annual averages of the left-most figure, presented over the lifetime of the park.

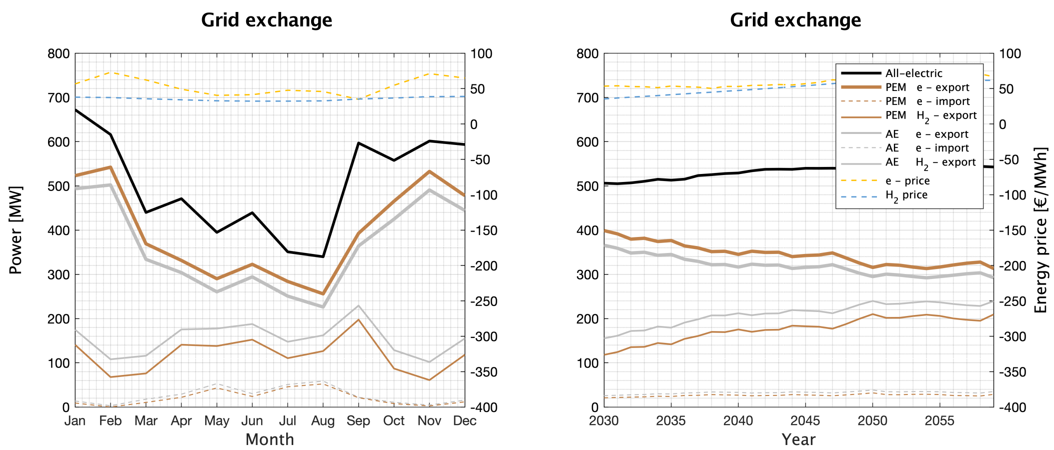


Figure 3-10: Grid exchange over time for the all-electric, hybrid AE, and hybrid PEM park.

The figure shows that the electric grid utilisation declines for the hybrid parks upon an increase in hydrogen price relative to the electricity price. Besides, it shows that electricity import occurs only little over time, and predominantly in summer months. For this reason, it is interesting to study how limiting the electricity uptake affects the economics of the parks in the sensitivity analysis later on. The grid utilisation is extensively discussed in section 3-3. Moreover, it is observed from both figures that the AE electrolyser park exports less electricity and more hydrogen than the PEM electrolyser park, across the seasons and years. The difference is consistently around 50 MW, which can largely be explained by the AE electrolyser minimum load. In addition, the AE efficiency is 2pp higher at nominal load than the PEM efficiency in the default case study parameters, which also results in a slightly increased hydrogen production for the AE electrolyser.

Figure 3-11 shows the lifetime average export and import capacity factors over the range of relative electrolyser capacities for AE as well as PEM. The capacity factors are defined differently for the different lines in the figure, as described below.
The hydrogen export capacity factor is defined as the percentage of nominal electrolyser output, and equals approximately 44% and 53% for the PEM and AE electrolyser, respectively. The lines remain relatively horizontal, since the electrolyser efficiency curve is independent of the electrolyser capacity, and the capacity factor is expressed in proportion to the installed electrolyser capacity. The higher capacity factor for the AE electrolyser is partly explained by the minimum load constraint; The AE park has to serve its 10% minimum load at all times, but often opts to operate the electrolyser at a higher part-load to obtain a higher efficiency, as can be observed from appendix A-2. Besides, the slightly higher AE efficiency at nominal load also contributes to the higher hydrogen export capacity factor.
The electric export capacity factor is expressed as percentage of the electric grid connection, which equals the wind park capacity in this case study. It can be observed that the utilisation of the electric export capacity decreases steeply upon increased electrolyser capacity.
Finally, the electric import capacity factor is defined as the percentage of the rated electrolyser capacity, and increases upon increasing electrolyser capacity. This is simply because at smaller relative electrolyser capacities, more often sufficient wind power is available to feed the electrolyser, resulting in less electricity uptake.

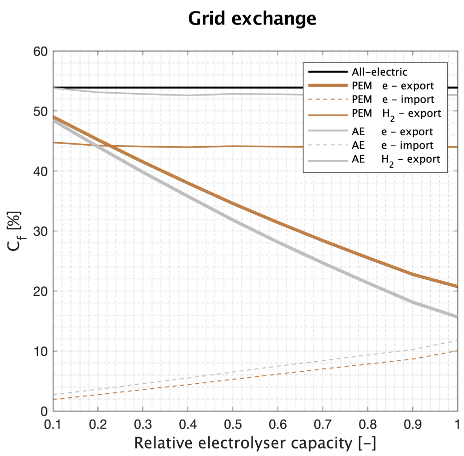


Figure 3-11: Grid exchange capacity factors for the range of relative electrolyser capacities

3-2-7 Internal rate of return

Figure 3-12 finally shows how the park operations are reflected in the economics of the hybrid parks under review in this case study. The IRRs of the two hybrid wind-hydrogen parks are presented alongside the reference IRR of the all-electric wind park. For the particular example of this case study, it can be observed from the figure that whether to add an electrolyser to the all-electric park depends on the electrolyser technology as well as installed capacity.
The addition of an AE electrolyser is not beneficial from an economic standpoint for the park under review, and the business case only worsens upon larger relative installed electrolyser capacities. The specific reason for this is revealed in section 3-3-3 of the sensitivity analysis. However, the addition of a PEM electrolyser does yield an improved IRR compared to the all-electric reference, from a relative electrolyser capacity of 0.4 onward. Interestingly, in the default parameter settings for this case study, the PEM electrolyser is approximately 30% more expensive per installed MW when compared directly to the AE electrolyser. However, even though the PEM electrolyser is significantly more expensive than the AE electrolyser, the difference in total CAPEX of the hybrid wind park per installed wind park capacity is much more moderate. For illustration purposes, the figure provides the total CAPEX per installed wind park capacity at a relative electrolyser capacity of 0.8.
In the next section, it is researched how the IRRs of the hybrid wind-hydrogen parks are affected by the uncertainty in the most significant and important input parameters.

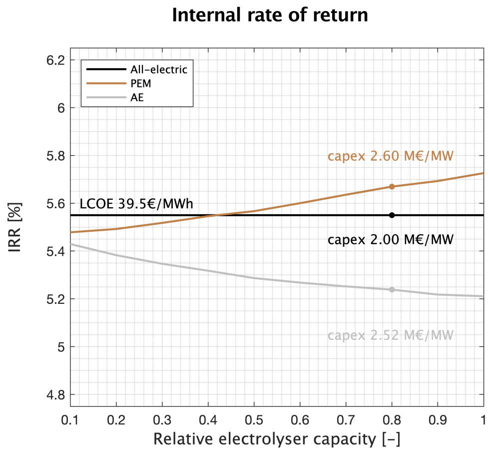


Figure 3-12: IRR over the range of relative electrolyser capacities for the all-electric reference, hybrid AE, and hybrid PEM park.

3-3 Results of the sensitivity analysis

In this section, it is researched how variations in the most significant and critical input parameters resound in the operations and economics of the parks. To this end, a gradual variation is applied over the input parameters one by one, and the results are presented for the hybrid AE and PEM parks. In case the variation in the input parameter also affects the all-electric wind park, the all-electric wind park is re-evaluated, and the updated result is present alongside the hybrid parks. The sensitivities under review are the CAPEX values of the wind park, electrolyser and platform, the prices for electricity and hydrogen, the minimum load and output pressure of the alkaline electrolyser, and finally a reduction in electric import and export capacity.

3-3-1 CAPEX sensitivity

Figure 3-13 presents the resulting IRRs under the application of a $\pm 10\%$ wind park CAPEX variation. An IRR spread for the all-electric wind park is presented in the background of the figure, since a change in the wind park CAPEX also affects the IRR of the all-electric park. The figure also presents the LCOE of the new all-electric parks, which remain within the LCOE range mentioned in section 3-1-3. The first observation from the figure is that a variation in wind park CAPEX results in a very significant variation in IRR, for the all-electric park as well as for the hybrid AE and PEM park.
A second observation is that the addition of an electrolyser to the wind park, for AE as well as PEM, becomes less favourable at lower wind park CAPEX, and more favourable at higher wind park CAPEX. This can be noticed when comparing the upper lines of the all-electric and hybrid areas for the former case and the lower lines for the latter. Finally, the more electrolyser capacity is installed, the lower the sensitivity becomes to wind park CAPEX variations. This follows logically from the fact that at large electrolyser capacities, the wind park CAPEX contribute relatively less to the overall CAPEX.

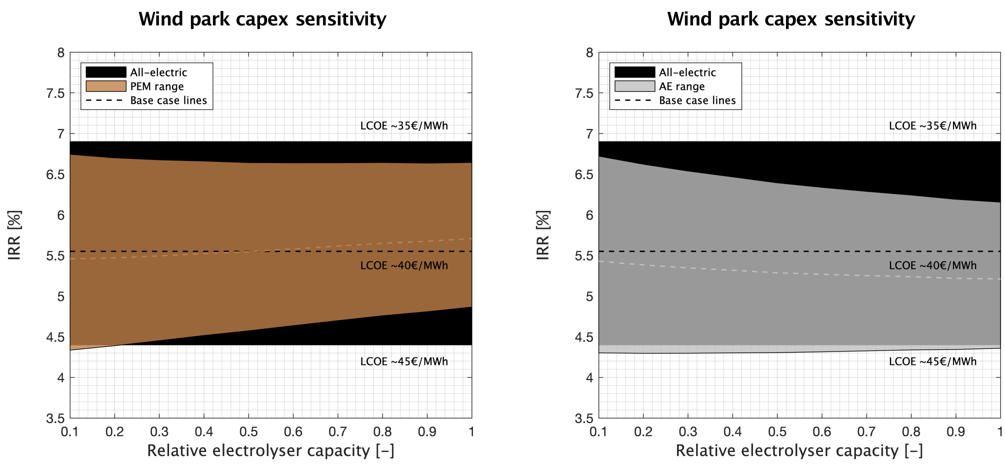


Figure 3-13: Sensitivity of the parks' IRR to a change in wind park CAPEX for three park designs: the all-electric reference, hybrid AE and hybrid PEM.

Other interesting CAPEX sensitivities to review are the electrolyser CAPEX and platform CAPEX, since these components contribute most significantly to the overall CAPEX of the conversion equipment of the hybrid parks. Figure 3-14 presents the electrolyser and platform CAPEX sensitivity for the AE and PEM parks.

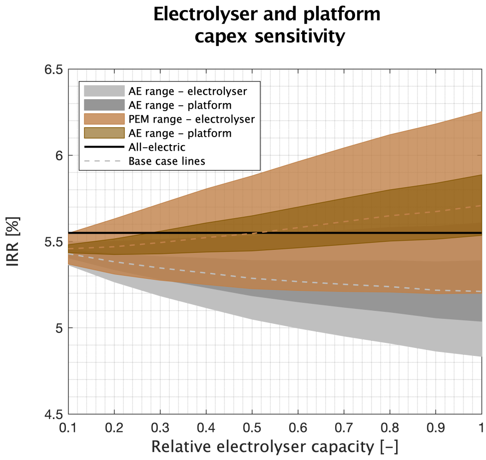


Figure 3-14: Sensitivity of the parks' IRR to a change in electrolyser CAPEX and platform CAPEX for three park designs: the all-electric reference, hybrid AE and hybrid PEM.

The darker areas in the figure represents the ±30% platform CAPEX range. It can be observed that the effect of the platform CAPEX variation remains fairly limited. More interesting is to reflect on the electrolyser CAPEX variation of ±30%, represented by the lighter area in the figure. For the PEM electrolyser, the CAPEX spread determines whether or not the addition of the electrolyser to the all-electric park is favourable from an economic perspective, when keeping the remaining parameters unchanged. Moreover, it is observed that the PEM electrolyser park shows a larger sensitivity to the electrolyser CAPEX variations, as can be expected from its larger CAPEX in the first place. Finally, it is interesting to observe that the PEM electrolyser that is increased 30% in CAPEX follows approximately a similar IRR line as the AE electrolyser at its base case line.

3-3-2 Energy price sensitivity

Figure 3-15 presents the sensitivity of the parks' IRR to a ±30% variation in the electricity and hydrogen prices. To this end, each of the values from the hourly electricity and hydrogen price series have been multiplied by a factor of 0.7 and 1.3. Moreover, in the background of the figure, a spread for the variation in electricity prices for the all-electric park's IRR is presented.
The foremost observation from the figure is that the addition of any electrolyser to an all-electric wind park decreases the park's sensitivity to alternative realisations of the electricity price scenarios, but increases the sensitivity to alternative realisations of the hydrogen price scenarios.
Secondly, the figure shows that the hybrid wind-hydrogen parks are less sensitive to a decline in prices than to an increase in prices, especially in the higher relative installed electrolyser capacity range. This effect can be attributed to the flexibility that the electrolyser provides; the parks can capitalise on a price increase by simply exporting the electricity and fend off a price decrease by converting a larger share of the available electricity into hydrogen.

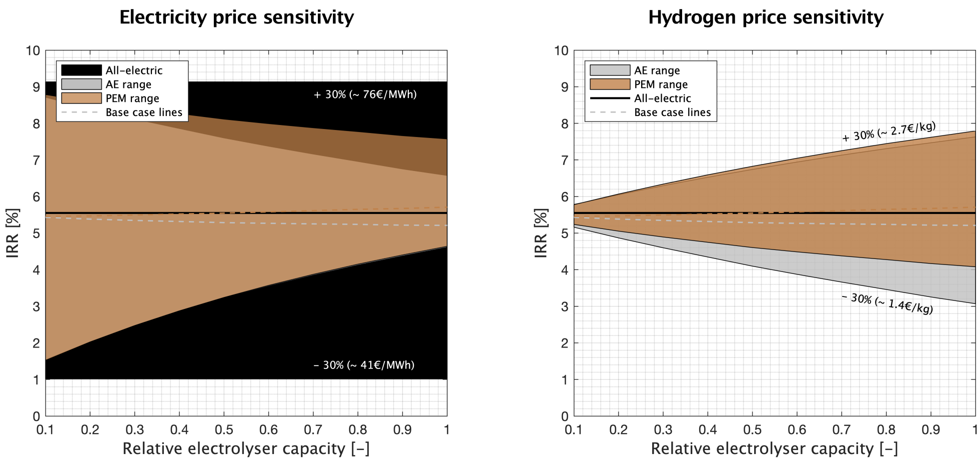


Figure 3-15: Sensitivity of the parks' IRR to a change in energy prices for three park designs: the all-electric reference, hybrid AE and hybrid PEM. A price range of ±30% is indicated in the figure. The case study prices for electricity and hydrogen are 58.7 €/MWh and 2.04 €/kg.

Effect on grid exchange - A variation in the electricity and hydrogen market prices not only affects the economics of the park configuration, but also the operations. In the end, it is the market prices that determine whether the park exports the available electricity, converts it, takes up electricity, or curtails the available wind power. In turn, this resounds in the grid exchange of the hybrid parks. Table 3-4 presents how the capacity factors for electricity export, hydrogen export and electricity import change upon the variation in the aforementioned electricity and hydrogen market prices.
The first observation from the table is that the capacity factor of electric grid export is highly sensitive to the hydrogen price. In case the hydrogen price increases significantly, and a large relative electrolyser is installed, the capacity factor for electric grid export decreases to approximately 12%, compared to 53% in the all-electric reference case.

Table 3-4: Sensitivity of the grid exchange capacity factors to a ±30% change in the electricity and hydrogen prices, compared to the target transition scenario.

	AE		PEM	
Hydrogen price range	(-30%)	(+30%)	(-30%)	(+30%)
C_f electricity export	50%	9%	53%	12%
C_f hydrogen export	36%	67%	28%	62%
C_f electricity import	2%	20%	1%	19%

	AE		PEM	
Electricity price range	(-30%)	(+30%)	(-30%)	(+30%)
C_f electricity export	25%	40%	30%	40%
C_f hydrogen export	72%	38%	67%	30%
C_f electricity import	7%	5%	5%	4%

3-3-3 AE technical sensitivity

In the results presented up till here, the economics of hybrid park with the AE electrolyser fell short to the economics of the hybrid park with PEM electrolyser in all cases. Therefore, it is interesting to look in more detail at the technical parameters of the AE electrolyser that determine its economic performance. In section 2-3-1, two technical challenges of the AE electrolyser were mentioned that research and development efforts specifically focus on: the minimum electrolyser load and the hydrogen output pressure. The minimum electrolyser load also was a recurring topic in the observations on the electrolyser operations in the case study results. Figure 3-16 presents the sensitivity of the IRR of the hybrid AE park to a variation in the minimum load and the output pressure.

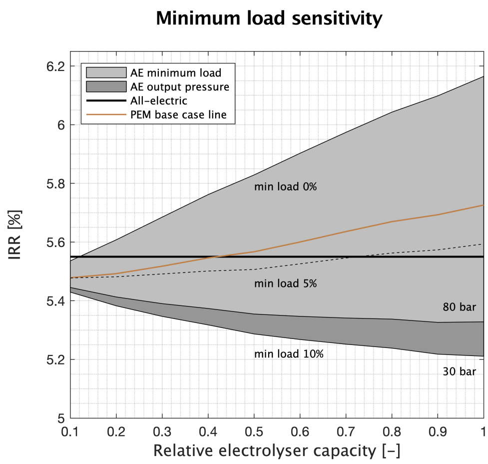


Figure 3-16: Sensitivity of the AE park's IRR to a change in AE min. load and output pressure.

The foremost observation from the figure is that a variation in the minimum electrolyser load has a significant impact on the park's IRR. A minimum load of 10%, the default value in the case study, is presented as lower boundary of the range. At a minimum load of 5%, the hybrid AE park's IRR approaches the all-electric reference IRR. Even more, at a minimum load of 0% the hybrid AE park outperforms the hybrid PEM park in terms of IRR. What this result means is interpreted in the discussion chapter.
Secondly, it can be observed from the figure that the electrolyser output pressure affects the IRR of the park as well, but to a much lesser extent than the minimum load variation. Even in case the output pressure is increased to 80 bar, the IRR of the park with the AE electrolyser will still come out lower than the IRR of the all-electric and hybrid PEM park.

3-3-4 Electric import and export reduction sensitivity

A final interesting result to present is the sensitivity of the IRRs to a limitation in the electric import and export capacity.

Export reduction - Reducing the electric export capacity of the hybrid parks corresponds to overplanting the wind park in reality, i.e. installing a larger wind park capacity than the export grid connection capacity. Due to overplanting of the wind park relative to the electric export capacity, more curtailment occurs in an all-electric park, and not all power can be exported at the rated capacity of the wind park. Since the wind park CAPEX cost remain equal and the cost savings for the smaller export infrastructure are outside the scope of the developer, the IRR of the all-electric park worsens upon reducing the export capacity.
Figure 3-17 presents the sensitivity of the IRR to a 10% reduction in electric export capacity. It can be observed from the figure that the IRR ranges for the hybrid parks are significantly smaller when compared to the all-electric park; The electricity that is to be curtailed at rated power in the overplanted all-electric park can be converted in hybrid parks, and additional revenue can be generated by the sale of the produced hydrogen.

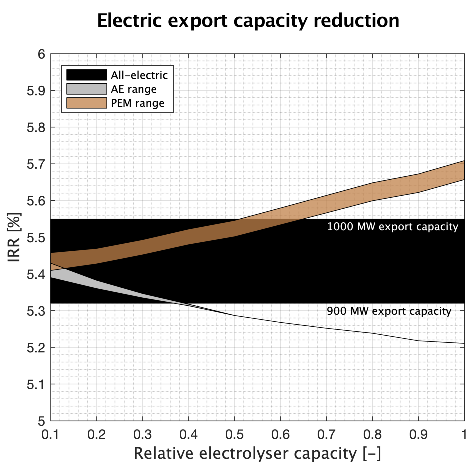


Figure 3-17: Sensitivity of the parks' IRR to a reduction in electric export capacity for three park designs: the all-electric reference, hybrid AE and hybrid PEM.

Import reduction - As observed from figure 3-10 and table 3-4 in the previous sections, oftentimes relatively little electricity is imported by the hybrid parks, even in the case that the electricity price is low and the hydrogen price is high. To research to what extent the electricity uptake affects the economics of the hybrid parks, a sensitivity was performed on the electric import capacity; The electric import capacity was reduced to 0.1 times the electrolyser capacity for the AE as well as PEM hybrid park, to allow the hybrid AE to serve the electrolyser minimum load, and to compare the two parks fairly. Limiting the electric import capacity to only 0.1 times the electrolyser capacity for the AE as well as PEM hybrid park only resulted in a decrease in IRR of 0.3pp, which is of similar magnitude as a 5% variation in the hydrogen market price.

Chapter 4

Discussion

The research objective of this study is to provide high-level insight into the techno-economic optimisation of the design and operation of an offshore hybrid wind-hydrogen park. To this end, it is studied how various design and operational choices resound in the economics of the park for a particular case study. Moreover, it is studied how the economic out-turn of the park changes when the conditions of the case study are altered. In the previous chapter, the plain results from the case study and sensitivity analysis are presented.
This chapter reflects on what the afore presented results essentially mean for the design and operation of a hybrid wind-hydrogen park, how these findings fit into the existing knowledge base, and what topics of interest are for future research. To this end, the chapter reviews four key design topics best comprised in a single question; Should an electrolyser be added to an offshore wind-hydrogen park, and if so, which electrolyser technology and capacity, and how does the individual park fit into the transmission infrastructure and the larger energy system?

4-1 Hybrid wind-hydrogen parks

The results of the study point out that the addition of an electrolyser to a wind park is clearly beneficial from a flexibility perspective, which is in line with the general belief in literature. To be more specific, the results from the study quantify to what extent the addition of an electrolyser increases the average price obtained for the sale of electricity, as expressed by the capture value. The hybrid wind-hydrogen park hereby addresses one of the key challenges that a conventional wind park faces at the introduction of more renewable capacity to the energy system.
A few high-level factors are important drivers for the economic feasibility of a hybrid wind-hydrogen park. As can be logically expected, a decrease in average electricity price or increase in average hydrogen price positively affect the hybrid park's economic feasibility relative to an all-electric wind park. Moreover, a reduction in electrolyser CAPEX relative to wind park CAPEX favours the addition of electrolyser capacity to a wind park. However, this effect can be counteracted by a much smaller wind park CAPEX reduction relative to electrolyser CAPEX, since the wind park CAPEX is more than four times higher per installed capacity than the electrolyser CAPEX. In other words, the predominant external conditions that determine the economic feasibility of a hybrid wind park are the prices for electricity and hydrogen and the CAPEX of the electrolyser relative to the wind park. The results of this study show that the addition of an electrolyser already seems economically beneficial at the

average hydrogen price of 2.04 €/kg in the target transition scenario, assuming an existing hybrid export infrastructure.
According to the recent North Sea Energy (NSE) study, offshore hybrid wind-hydrogen parks could be profitable from a hydrogen price of 1.75 - 2.25 €/kg onward, in case the electrolyser CAPEX is 600 k€/MW, the costs of hydrogen transport is for the developer, and the developer is compensated for savings on the public electricity grid by 1.5 €/kg H_2 when no more electric grid is required. To compare the NSE study to the findings in this study, the compensation for the public grid saving must be subtracted from the price range of 1.75 - 2.25 €/kg, and the savings on hydrogen transport must be added.
Since the majority of the electric infrastructure remains required for a hybrid wind hydrogen park, a hypothetical grid saving of 0.5 €/kg H_2 is assumed for the hybrid park under review, and added to the price range from the NSE study. Moreover, the costs of hydrogen transmission, which DNVGL estimates to be 0.25 €/kg H_2, are covered by a centralised public infrastructure in this study, and therefore subtracted from the range [17]. Considering these adaptations in export infrastructure costs, the break-even green hydrogen range from North Sea Energy range would amount to 2.0-2.5 €/kg, which corresponds well to the results of this study of 2.04 €/kg.

4-2 Electrolyser technology selection

Considering the input conditions underlying the results, PEM appears to be the electrolyser technology of choice for a hybrid wind-hydrogen park with dynamic operations, even though the AE electrolyser has a slightly higher efficiency and significantly lower CAPEX. The minimum load of the AE reduces the electricity available for export in times of high electricity prices, as expressed by the Capture Value, and results every so often in the undesired, expensive uptake of electricity in times of little wind availability, as reflected in the Capture Cost Rate.
Although on qualitative basis only, various studies have selected the PEM electrolyser for its superior dynamics [33, 52, 62, 63]. Moreover, plentiful studies mention the significantly lower CAPEX cost for the AE electrolyser, without addressing if this could compensate for the negative effects of its minimum load in dynamic operation. The results of this study add a quantified insight into the extent to which the minimum load constraint resounds in the economics of the hybrid park, and show that the lower CAPEX cannot compensate for the hybrid AE park's minimum load effect. The minimum load constraint must either be reduced by means of research and development, as also suggested by [61, 65, 70], or the solution must be looked for in the operational strategy of the electrolyser, for example by using forecasting to switch off the electrolyser entirely for longer periods of time. For the latter, additional research should be performed on the ability of the AE electrolyser to switch on and off frequently. For example, a wide range of 20 to 120 minutes was found in literature for the start-up time of the AE electrolyser [49, 62, 63, 75, 77]. Finally, the AE output pressure proved to be of lesser relevance compared to the technical minimum load constraint, as the output pressure does not limit the park's production flexibility.

4-3 Electrolyser capacity

The optimum relative electrolyser capacity is more complex to reflect on than the electrolyser technology selection. No single relative electrolyser capacity can be appointed as optimal, since it highly depends on the realisation of many input conditions, such as the electrolyser CAPEX and hydrogen price and the perspective from which the optimum is determined. In case the conditions are favourable to the addition of an electrolyser, it can be interpreted from the results that from an IRR perspective, the full electrolyser capacity should be added. Two effects make that the IRR increases upon increasing relative electrolyser capacity; the electrolyser CAPEX scale favourably and increasing the relative electrolyser capacity increases the park's production flexibility, and therewith increases the capture value.
Other perspectives can be considered as well in determining the optimal electrolyser capacity. For example, the results show that a large relative installed electrolyser capacity increases the parks' sensitivity to alternative realisations of hydrogen price scenarios but decrease the sensitivity to alternative realisations of electricity scenarios. From a developer's risk perspective, opting for a moderate installed capacity can balance these price risks.

4-4 Export and import infrastructure

According to [33], offshore wind parks should be equipped with 78% relative electrolyser capacity from a national grid flexibility perspective. In the case study, a relative installed electrolyser capacity of 78% resulted in an improved IRR for the hybrid PEM park compared to the all-electric park. Consequentially, however, the results show that the electric export capacity factor could be reduced to 12%. From a grid operator perspective, such a low electric grid utilisation rate is undesired, so it would be beneficial to reduce the electric export capacity for hybrid wind-hydrogen parks. The results show that the IRR of a hybrid park is only moderately affected upon a reduction in electric export capacity, while the effect proved significant for the all-electric park. This means that the addition of electrolyser capacity to wind parks allows for a reduction in electric export capacity, without significantly impairing the business case for the developer. A reduction in electric export capacity reduces the net obtained electricity from the wind park, but increases the electric grid utilisation rate.
The results also show that upon the increase of the average hydrogen price over time, the electric grid utilisation is consequently reduced since more often electricity is converted. To respond to this, the grid operator could provide the developer with an electric export connection capacity that declines over time. The capacity that is then released over time could potentially be dedicated to new offshore wind parks.
Regarding electricity uptake, the study showed that in most scenario realisations relatively little electricity is imported from the grid due to the correlation between the wind park output and electricity price. Leaving out the opportunity of electricity import had a minor effect compared to the other sensitivities.
Finally, a socialised hybrid export infrastructure is assumed in this study. However, it is interesting to reflect on whether a developer could potentially cover the cost of hydrogen transport by its merchant revenues. The results show that if hydrogen transport is assumed to cost 0.25 €/kg [17], which corresponds to a 12% reduction of the hydrogen price in the sensitivity analysis, the addition of any electrolyser becomes economically unfavourable, which implies that the developer cannot cover the cost for hydrogen transport by its merchant revenues.

4-5 Shortcomings and recommendation

The main assumption in this study is the existing, socialised hybrid export infrastructure. Little conclusive information was available on the future availability of an export infrastructure, so leaving the infrastructure out of scope and reflect on it with the results of the study appeared the best feasible option. Moreover, a centralised export infrastructure could not be incorporated in the optimisation from a developers perspective.
Following the results of this study, a social cost-benefit analysis should be initiated on a centralised, hybrid offshore export infrastructure, supported by a detailed techno-economic analysis of the infrastructure.

Regarding the design of the park, a comment has to be made on the scope of this study, that consequently proposes a topic for future research. Since electrolysers have only been applied onshore up to date, where weight and space constraints are often absent, little information is available on the electrolyser space and weight specifications. This resulted in a substantial assumption on the platform requirements for offshore conversion. The two platform sources referenced in this study provided different platform requirements and a large CAPEX range, even though the platform has the second most significant CAPEX contribution to the conversion equipment. Additional research into the component requirements, weight, and dimensions of offshore conversion systems, followed by a techno-economic study that re-evaluates the requirements and suitability of new platforms as well as refurbished platforms, will undoubtedly be useful to advance in the field of offshore conversion.

Regarding the control of the park, two comments have to be made on the scope of this study, that consequently propose two topics for future research.
First, the results show that the electricity allocation algorithm often opts to operate the electrolyser at part-load, due to the associated increased efficiency. In this research, the part-load efficiency curve of the electrolysers is based on limitedly available information about the Siemens 6 MW electrolyser, as mentioned in section 2-3-1. To the authors knowledge, this is the most elaborate information available on the practical part-load efficiency curve of electrolysers to date. However, continued research into the part-load efficiency of the AE as well as PEM electrolyser is recommended, due to the limited online knowledge base on the topic.
Secondly, the alkaline electrolyser was assumed to remain operating on minimum load at all times. As mentioned in the discussion, more research into lowering the minimum load from a technical perspective or optimising the electrolyser operation from a control perspective is desired. Reducing the effect of the minimum load is the foremost specification of the alkaline electrolyser that can increase its competitive position with respect to PEM.

Finally, in the case study various defining parameters have been assigned a value for 2030, which have been obtained from literature research. The sensitivity of the results proved to be large to in particular the hydrogen and electricity price, wind park CAPEX, electrolyser CAPEX, and electrolyser minimum load. Continuous research into these topics is advised; The more precise the estimations on these parameters become, the more precise the results of any future techno-economic system optimisation will be.

Chapter 5

Conclusion

The research question central to this study is the following: How can the design and operation of an offshore hybrid wind-hydrogen park be optimised for output value by using electricity and hydrogen market prices, assuming an existing hybrid export infrastructure?

The results of the study point out that the addition of an electrolyser to a wind park is clearly beneficial from a flexibility perspective. The addition of an electrolyser to a wind park significantly increases the average price obtained for the sale of electricity, as supported by the increase in capture value from 74% to 125% in the case study at the addition of a large relative electrolyser capacity.
Moreover, the PEM appears to be the electrolyser technology of choice for a hybrid wind-hydrogen park with dynamic operations, even though the AE electrolyser has a slightly higher efficiency and significantly lower CAPEX. The results of this study add a quantified insight into the extent to which the minimum load constraint resounds in the economics of the hybrid park and show that the lower CAPEX cannot compensate for the hybrid AE park's minimum load constraint. Moreover, the electrolyser output pressure of the AE proved to be of lesser relevance compared to the technical minimum load constraint, as the output pressure does not affect the park's production flexibility.
The results show a less conclusive result for the optimum relative electrolyser capacity, since the optimum highly depends on the realisation of many input conditions, such as the electrolyser CAPEX and hydrogen price and the perspective from which the optimum is determined. However, when the conditions are favourable to the addition of any electrolyser capacity, the results show that from an IRR perspective the addition of the full electrolyser capacity is optimal. This is due to economies of scale in the electrolyser CAPEX and the increasing flexibility of the park to respond to market prices upon larger installed capacities, in turn increasing the capture value.
From an investment risk perspective, installing a moderate electrolyser capacity could be favourable, since a hybrid park with a large relative installed capacity shows a larger sensitivity to hydrogen price, while a park with little installed electrolyser capacity is more sensitive to the electricity price. Opting for a moderate installed capacity can balance these price risks.
From a grid operator perspective, the relative installed electrolyser capacity is in fact important. Under favourable conditions for hybrid parks, a large relative installed electrolyser capacity is optimal, and the electric grid export capacity factor could be reduced down to 12%. A reduced grid utilisation is unfavourable for the grid operator, since the grid investment is not used to its full potential in that case. For the grid operator, it is therefore beneficial to reduce the electric export capacity for hybrid wind-hydrogen parks. The results show that

under conditions favourable for hybrid parks, reducing the electric export capacity only has a moderate effect on the business case for the developer. Regarding electricity uptake, the study showed that in most scenario realisations, relatively little electricity is imported from the grid due to the correlation between wind availability and electricity price. Limiting the capacity of electricity import to the technically feasible minimum due to the AE minimum load, had a minor effect compared to the other sensitivities.

The results of this study provided insight into the operation and economics of a hybrid wind-hydrogen park that optimises for output value by astute electricity allocation based on market price dynamics. Moreover, the results led to a quantified insight into the suitability of the AE and PEM electrolyser for application in the hybrid park. Finally, the requirements for - and effect on - a centralised export infrastructure from a developer's perspective were reflected on. The study is aspired to help inform researchers, policymakers, and the energy industry in the transition towards hybrid wind-hydrogen parks.

Recommendations - Following the results of this study, a social cost-benefit analysis should be initiated on a centralised, hybrid offshore export infrastructure, supported by a detailed techno-economic analysis of the infrastructure, since this was the largest underlying assumption in this study. Other topics of interest for future research are the conversion components' weight and dimension specifications and the subsequent platform optimisation, the part-load efficiency behaviour of electrolysers, and the optimisation of the operational strategy for an AE electrolyser with minimum load constraint. Finally, the results proved to be sensitive to in particular the hydrogen and electricity price, wind park CAPEX, electrolyser CAPEX, and electrolyser minimum load. Continuous research into these topics is advised; The more precise the estimations on these parameters become, the more precise the results of any future techno-economic hybrid system optimisation will be.

Appendix A

Appendix

A-1 Electrolyser part-load efficiency

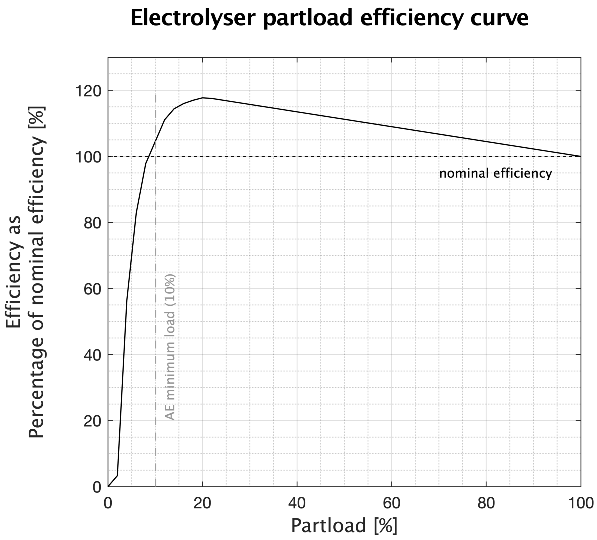


Figure A-1: Part-load efficiency curves used in this study for the PEM and AE electrolyser. The black line indicated the AE part-load efficiency curve used in the sensitivity analysis.

A-2 Aggregate conversion losses

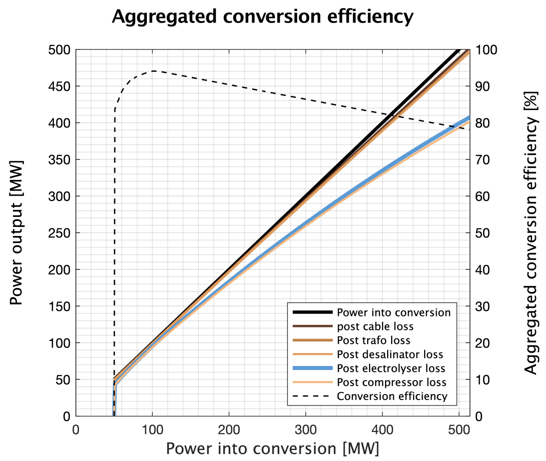


Figure A-2: Individual and aggregate conversion losses of the hardware components over the load range of the AE electrolyser. The figure is exemplary for an installed electrolyser capacity of 500 MW and the x-axis is limited from $conversion_{min}$ to $conversion_{max}$.

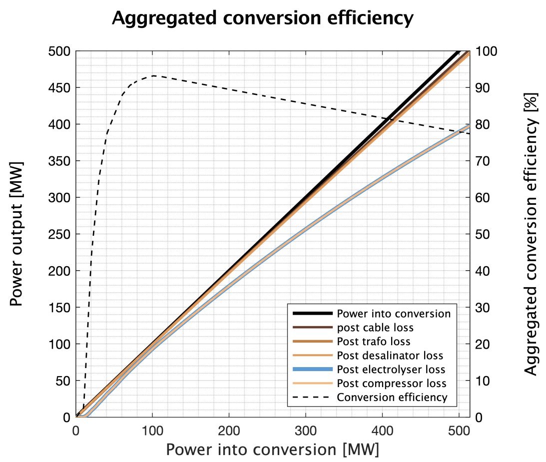


Figure A-3: Individual and aggregate conversion losses of the hardware components over the load range of the PEM electrolyser. The figure is exemplary for an installed electrolyser capacity of 500 MW and the x-axis is limited from $conversion_{min}$ to $conversion_{max}$.

A-3 Location of the case study park

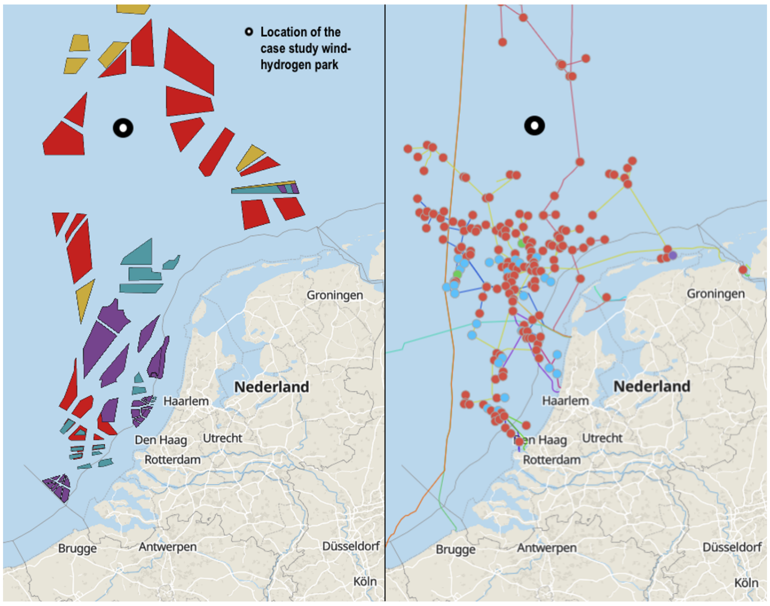


Figure A-4: A map of the North Sea with a marker on the location of the offshore hybrid wind-hydrogen park from the case study. Left: wind park deployment expected until 2050 under various transition paces. Right: offshore platform and pipeline infrastructure potentially suitable for conversion into an offshore hydrogen infrastructure. Maps obtained from the North Sea Energy Atlas [20].

A-4 Price scenarios

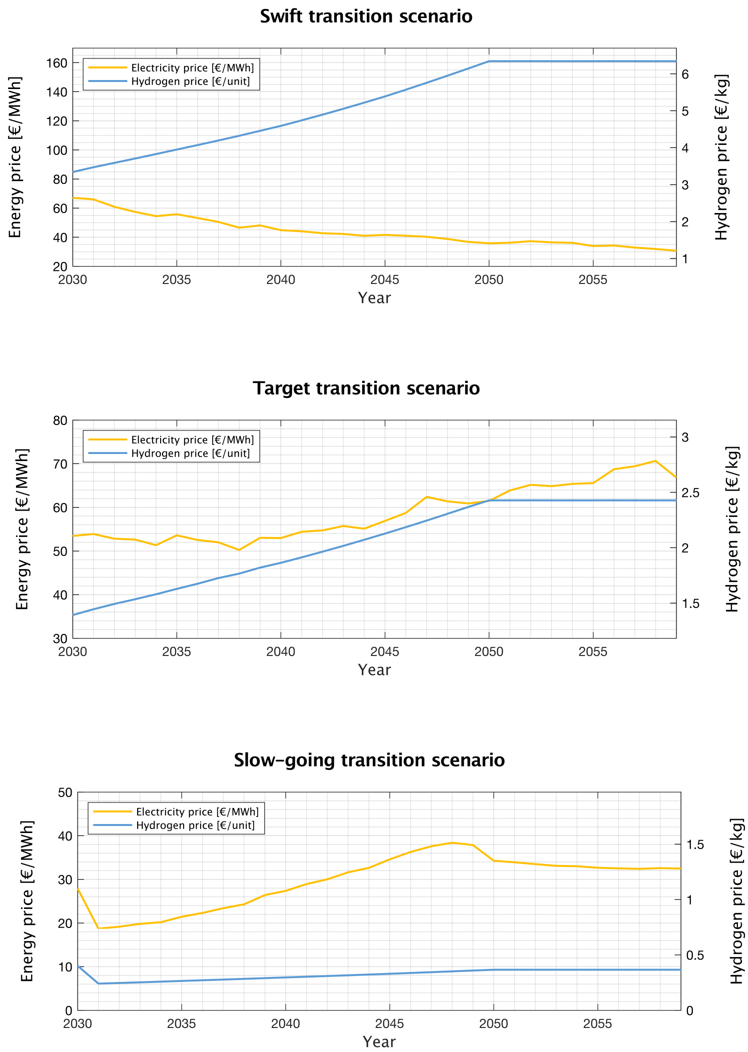


Figure A-5: Three energy price scenario's. Top: swift transition price scenario, middle: target transition price scenario, bottom: slow-going transition scenario. The prices presented are annual averages. The hydrogen price is indicated in [€/MWh] on the left axis and in [€/kg] on the right axis; The hydrogen price in [€/kg] is determined on the basis of the Higher Heating Value (HHV), as in accordance with Eneco standards and [17, 18, 19].

A-5 Wind park output - electricity price correlation

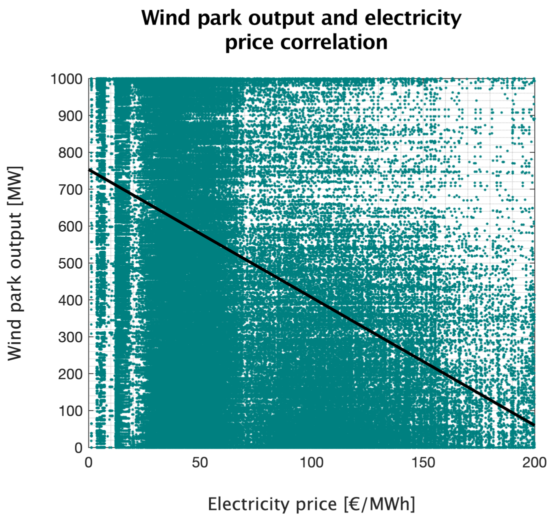


Figure A-6: Correlation between wind park output power and electricity price for the case study input series. Based on Eneco's wind park output and electricity price series.

A-6 Wind park output - hydrogen price correlation

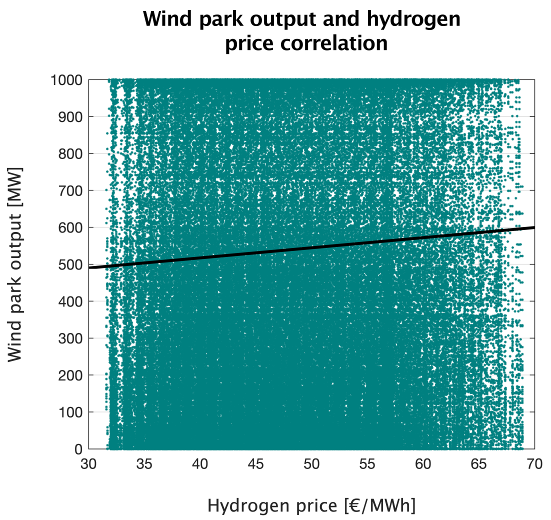


Figure A-7: Correlation between wind park output power and hydrogen price for the case study input series. Based on Eneco's wind park output and electricity price series.

A-7 Wind park capex and opex breakdown

Table A-1: Wind park CAPEX and OPEX assumptions: values are based on Catapult's guide to an offshore wind farm [24].

Type of expense	Costs $k€/MW]$
Development and project management	**50**
Development and consenting services	42
Geological and hydrological surveys	4
Engineering and consultancy	4
Turbine	**1.000**
Nacelle	400
Rotor	190
Tower	70
Other (assembly, warranty, etc.)	340
Balance of plant	**455**
Cables	170
Turbine foundation	280
Operations base	5
Installation and commissioning	**365**
Foundation installation	100
Turbine installation	50
Offshore logistics	3
Other (insurance, contingency, etc.)	212
Decommissioning	**120**
Turbine decommissioning	45
Foundation decommissioning	75

Type of expense	Costs $k€/(MW * annum)]$
Operation, maintenance and service	**55 k**
Operations	14
Maintenance and service	41

Bibliography

[1] North Sea Wind Power Hub Consortium, "Industry Engagement Program," no. June, pp. 0–17, 2019.

[2] M. D. W. d. K. J. R. Hans Cleijne, Mats de Ronde, "NOORDZEE ENERGIE OUTLOOK," tech. rep., 2020.

[3] H. Fennema and M. van Beek, "Infrastructure Outlook 2050," tech. rep., Gasunie & TenneT, 2019.

[4] "B. Het Akkoord voor de Noordzee.pd," tech. rep., 2020.

[5] TKI Wind op Zee, "The Netherlands ' Long-Term Offshore Wind R & D Agenda," no. October, 2019.

[6] RVO Nederland, "Programmalijnen Wind op Zee." 2019.

[7] M. van Schot and C. Jepma, "A vision on hydrogen potential from the North Sea," tech. rep., 2020.

[8] IEA, "Offshore Wind Outlook 2019," tech. rep., 2019.

[9] Ministerie van Economische Zaken en Klimaat, "Routekaart windenergie op zee 2030," 2018.

[10] S. T. R. K. P. Böhm, H; Zauner A.; Goers, "Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimization: report on experience curves and economies of scale," Tech. Rep. 691797, 2019.

[11] P. Lettenmeier, "Efficiency - Electrolysis," tech. rep., 2019.

[12] A. Zauner, H. Böhm, D. Rosenfeld, and R. Tichler, "Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimization: analysis on future technology options and on techno-economic optimization," Tech. Rep. 691797, 2019.

[13] IRENA, *Hydrogen From Renewable Power: Technology outlook for the energy transition.* No. September, 2018.

[14] "Fuel Cells and Hydrogen Joint Undertaking (FCH JU)," 2020.

[15] J. Kim, K. Park, D. R. Yang, and S. Hong, "A comprehensive review of energy consumption of seawater reverse osmosis desalination plants," *Applied Energy*, vol. 254, no. August, p. 113652, 2019.

[16] J. O. Jensen, A. P. Vestbø, Q. Li, and N. J. Bjerrum, "The energy efficiency of onboard hydrogen storage," *Journal of Alloys and Compounds*, vol. 446-447, pp. 723–728, 2007.

[17] DNVGL, "Hydrogen electricity value chain," 2019.

[18] Fuel Cells and Hydrogen, "Early business cases for H2 in energy storage and more broadly power to H2 applications, Final Report, Fuel cells and hydrogen joint undertaking, P2H-BC/4NT/0550274/000/03, 2017," no. June, 2017.

[19] A. Van Wijk and F. Wouters, "Hydrogen, The Bridge between Africa and Europe," no. September 2019, p. 31, 2019.

[20] North Sea Energy, "An interactive atlas of the North Sea," 2020.

[21] DNVGL, "Cost of offshore transmission," *Dnv Gl*, no. June, 2019.

[22] C. Kost, T. Schlegl, J. Thomsen, S. Nold, J. Mayer, N. Hartmann, C. Senkpiel, S. Philipps, S. Lude, and N. Saad, "Fraunhofer ISE: Levelized Cost of Electricity - Renewable Energy Technologies, March 2018," *Fraunhofer ISE: Levelized Cost of Electricity - Renewable Energy Technologies*, no. March, 2018.

[23] FS-UNEP Collaborating Centre for Climate & Sustainable Energy F and Inance, "Renewable Energy in Hybrid Mini-Grids and Isolated Grids: Economic Benefits and Business Cases," *Fs_Unep*, p. 88, 2015.

[24] Catapult, "guide-to-an-offshore-windfarm," 2020.

[25] "Kosten windenergie op zee," Tech. Rep. september, Algemene rekenkamer, 2018.

[26] H. Schermeyer, C. Vergara, and W. Fichtner, "Renewable energy curtailment: A case study on today's and tomorrow's congestion management," *Energy Policy*, vol. 112, no. October 2017, pp. 427–436, 2018.

[27] S. Impram, S. Varbak Nese, and B. Oral, "Challenges of renewable energy penetration on power system flexibility: A survey," *Energy Strategy Reviews*, vol. 31, no. September 2018, p. 100539, 2020.

[28] J. Cochran, M. Miller, O. Zinaman, M. Milligan, D. Arent, B. Palmintier, M. O'Malley, S. Mueller, E. Lannoye, A. Tuohy, B. Kujala, M. Sommer, H. Holttinen, J. Kiviluoma, and S. K. Soonee, "Flexibility in 21st Century Power Systems," tech. rep., 2014.

[29] ISPT, "Final report Integration of Hydrohub GigaWatt Electrolysis Facilities in Five Industrial Clusters in The Netherlands," p. 147, 2020.

[30] "Powering a climate-neutral economy: An EU Strategy for Energy System Integration EN," tech. rep., 2020.

[31] C. Jepma and M. Van Schot, "On the economics of offshore energy conversion: smart combinations," no. February, 2017.

[32] A. v. Wijk and J. Chatzimarkakis, "Green Hydrogen for a European Green Deal. A 2x40 GW Initiative," *Hydrogen Europe*, 2020.

[33] C. Jepma, G.-J. Kok, M. Renz, M. van Schot, and K. Wouters, "Towards sustainable energy production on the North Sea - Green hydrogen production and CO 2 storage: onshore or offshore?," tech. rep., 2018.

[34] Hydrohub, "Integration of Hydrohub GigaWatt Electrolysis Facilities in Five Industrial Clusters in The Netherlands," tech. rep., 2020.

[35] T. Kato, M. Kubota, N. Kobayashi, and Y. Suzuoki, "Effective utilization of by-product oxygen from electrolysis hydrogen production," *Energy*, vol. 30, no. 14, pp. 2580–2595, 2005.

[36] BNEF, "Hydrogen Economy Outlook," tech. rep., 2020.

[37] P. de Laat, "Overview of Hydrogen Projects in the Netherlands," 2020.

[38] D. G. Caglayan, N. Weber, H. U. Heinrichs, J. Linßen, M. Robinius, P. A. Kukla, and D. Stolten, "Technical potential of salt caverns for hydrogen storage in Europe," *International Journal of Hydrogen Energy*, vol. 45, no. 11, pp. 6793–6805, 2019.

[39] R. Peters, J. Vaessen, and R. Van Der Meer, "Offshore hydrogen production in the north sea enables far offshore wind development," in *Proceedings of the Annual Offshore Technology Conference*, vol. 2020-May, pp. 1–14, 2020.

[40] A. van den Noort, W. Sloterdijk, and M. Vos, "Verkenning waterstofinfrastructuur," Tech. Rep. November, DNV-GL, 2017.

[41] KIWA, "Betrouwbaarheid van gasdistributienetten in Nederland Resultaten 2017," no. 01, pp. 14–15, 2018.

[42] TenneT, Gasunie, and DNVGL, "Power-to-Hydrogen IJmuiden Ver Final report for TenneT and Gasunie," p. 79, 2018.

[43] "Siemens investeert in windturbine voor offshore waterstofproductie," 2020.

[44] T. K. I. Tes, "Wind-to-Hydrogen -TKI systeemintegratiestudie," tech. rep., 2018.

[45] "Discussions with a PDEng researcher from TNO on integrating electrolysis in offshore wind," 2020.

[46] BNEF, "Hydrogen: The Economics of Production From Renewables," pp. 1–88, 2019.

[47] IEA, "The Future of Hydrogen," tech. rep., 2019.

[48] A. CHRISTENSEN, "Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe," tech. rep., 2020.

[49] A. Buttler and H. Spliethoff, "Current status of water electrolysis for energy storage, grid balancing and sector coupling via power-to-gas and power-to-liquids: A review," *Renewable and Sustainable Energy Reviews*, vol. 82, no. September 2017, pp. 2440–2454, 2018.

[50] A. Wang, K. van der Leun, D. Peters, and M. Buseman, "European Hydrogen Backbone," Tech. Rep. July, Guidehouse, 2020.

[51] B. den Ouden, "Een Waterstofbeurs voor het Klimaat," tech. rep., 2020.

[52] J. J. Catrinus and M. Van Schot, "On the economics of offshore energy conversion: smart combinations," no. February, 2017.

[53] M. v. d. L. H. d. L. B. P. K. P. Rene Hermkens, Sjoerd Jansma, "Toekomstbestendige gasdistributienetten," tech. rep., 2018.

[54] Hydro-Pac, "Hydrogen Gas Compressors Brochure," 2020.

[55] R.E. Roobeek, *Shipping Sunshine*. PhD thesis, 2020.

[56] O. S. Burheim, *Hydrogen for Energy Storage*. 2017.

[57] K. M. Zohdy and M. A. Kareem, "Hydrogen Production Using Sea Water Electrolysis," *Hydrogen Production Using Sea Water Electrolysis*, vol. 3, no. 1, pp. 1–7, 2010.

[58] V. G. Gude, "Energy consumption and recovery in reverse osmosis," *Desalination and Water Treatment*, vol. 36, no. 1-3, pp. 239–260, 2011.

[59] U. Caldera and C. Breyer, "Learning Curve for Seawater Reverse Osmosis Desalination Plants: Capital Cost Trend of the Past, Present, and Future," *Water Resources Research*, vol. 53, no. 12, pp. 10523–10538, 2017.

[60] S. McDonagh, S. Ahmed, C. Desmond, and J. D. Murphy, "Hydrogen from offshore wind: Investor perspective on the profitability of a hybrid system including for curtailment," *Applied Energy*, vol. 265, no. September, p. 114732, 2020.

[61] R. Loisel, L. Baranger, N. Chemouri, S. Spinu, and S. Pardo, "Economic evaluation of hybrid off-shore wind power and hydrogen storage system," *International Journal of Hydrogen Energy*, vol. 40, no. 21, pp. 6727–6739, 2015.

[62] G. Gahleitner, "Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications," *International Journal of Hydrogen Energy*, vol. 38, no. 5, pp. 2039–2061, 2013.

[63] J. Chi and H. Yu, "Water electrolysis based on renewable energy for hydrogen production," *Cuihua Xuebao/Chinese Journal of Catalysis*, vol. 39, no. 3, pp. 390–394, 2018.

[64] M. M. Rashid, M. K. A. Mesfer, H. Naseem, and M. Danish, "Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis," *International Journal of Engineering and Advanced Technology*, no. 3, pp. 2249–8958, 2015.

[65] J. Brauns and T. Turek, "Alkaline water electrolysis powered by renewable energy: A review," *Processes*, vol. 8, no. 2, 2020.

[66] P. Hou, W. Hu, Z. Chen, and P. Enevoldsen, "Operational optimization of wind energy based hydrogen storage system considering electricity market's influence," *Asia-Pacific Power and Energy Engineering Conference, APPEEC*, vol. 2016-Decem, pp. 466–471, 2016.

[67] F. Micelli, "No Title," 2020.

[68] C. A. A. MaCedo, A. A. De Albuquerque, and H. F. Moralles, "Analysis of economic and financial viability and risk evaluation of a wind project with monte carlo simulation," *Gestao e Producao*, vol. 24, no. 4, pp. 731–744, 2017.

[69] A. Z. C. van Leeuwen, "Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation: report on the costs involved with PtG technologies and their potentials across the EU," Tech. Rep. 691797, 2018.

[70] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, and S. Few, "Future cost and performance of water electrolysis: An expert elicitation study," *International Journal of Hydrogen Energy*, vol. 42, no. 52, pp. 30470–30492, 2017.

[71] J. Koponen, *Review of water electrolysis technologies and design of renewable hydrogen production systems.* PhD thesis, 2015.

[72] T. R. F. P. Bentvelsen, *Modeling and Scheduling of a Controllable Electrolyser in an Industrial Grid.* PhD thesis, 2019.

[73] J. Eichman, K. Harrison, M. Peters, J. Eichman, K. Harrison, and M. Peters, "Novel Electrolyzer Applications : Providing More Than Just Hydrogen Novel Electrolyzer Applications : Providing More Than Just Hydrogen," *NREL Report*, no. September, pp. 1–24, 2014.

[74] D. Schönberger, S. Ag, and P. D. L. D. Hy, "P2G durch Elektrolyse – eine flexible Speicherlösung Die Energiewende und die Integration erneuerbarer Energien ... werden die Energiebranche herausfordern," tech. rep., 2016.

[75] Nel Hydrogen, "The World ' s Most Efficient and Reliable Electrolysers," 2020.

[76] H2B2, "Electrolyser characteristics," 2020.

[77] Hydrogen Europe, "Strategic research and innovation agenda," no. July, p. 157, 2020.

[78] K. Meier, "Hydrogen production with sea water electrolysis using Norwegian offshore wind energy potentials: Techno-economic assessment for an offshore-based hydrogen production approach with state-of-the-art technology," *International Journal of Energy and Environmental Engineering*, vol. 5, no. 2-3, pp. 1–12, 2014.

[79] G. V. Kuik and W. Bierbooms, "Introduction to wind turbine design," *Eindhoven: Delft University Wind Energy {...}*, pp. 1–16, 2002.

[80] G. Parks, R. Boyd, J. Cornish, and R. Remick, "Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs: Systems Integration," *Related Information: Independent review published for the U.S. Department of Energy Hydrogen and Fuel Cells Program*, no. May 2014, p. Medium: ED; Size: 74 pp., 2014.

[81] J. Zou, N. Han, J. Yan, Q. Feng, Y. Wang, Z. Zhao, J. Fan, L. Zeng, H. Li, and H. Wang, "Electrochemical Compression Technologies for High-Pressure Hydrogen: Current Status, Challenges and Perspective," *Electrochemical Energy Reviews*, vol. 3, no. 4, pp. 690–729, 2020.

[82] D. Thomas, "COST REDUCTION POTENTIAL FOR ELECTROLYSER TECHNOLOGY," No. 2, pp. 1–1, 2018.

[83] M. Ruth, A. Mayyas, and M. Mann, "Manufacturing Competitiveness Analysis for PEM and Alkaline Water Electrolysis Systems," *Fuel Cell Seminar and Energy Exposition*, pp. 5–11, 2017.

[84] The Crown Estate & Catapult, "A Guide to an Offshore Wind Farm," Tech. Rep. April, 2019.

[85] Lenntech, "Seawater desalination units," 2017.

[86] N. Sea, W. Power, and H. Consortium, "Cost Evaluation of North Sea Offshore Wind Post 2030," no. February, 2019.

[87] DOWA, "Dutch Offshore Wind Atlas," 2021.

[88] K. Schoots and P. Hammingh, "Klimaat en Energieverkenning 2019," tech. rep., 2019.

[89] DNVGL, "CO 2 Reductie Roadmap van de Nederlandse raffinaderijen," Tech. Rep. november, 2018.

[90] IRENA, "Future of Wind: Deployment, investment, technology, grid integration and socio-economic aspects," tech. rep., 2019.

Glossary

List of Acronyms

AE	Alkaline Electrolysis
PEM	Polymer Electrolyte Membrane electrolysis
SOEC	Solid Oxide Electrolyser Cell electrolysis
OHVS	Offshore High Voltage Station
TSO	Transmission System Operator
TDS	Total Dissolved Solids
RO	Reverse Osmosis
SWRO	Sea Water Reverse Osmosis
HHV	Higher Heating Value
NPV	Net Present Value
AC	Alternating Current
DC	Direct Current
IEA	International Energy Agency
BNEF	Bloomberg New Energy Finance
FCH JU	Fuel cell and Hydrogen Joint Undertaking
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
LHV	Lower Heating Value
LCOE	Levelised Costs Of Electricity
CV	Capture Value
CCR	Capture Cost Rate
SEC	Specific Energy Consumption
SMR	Steam Methane Reforming
CF	Capacity Factor