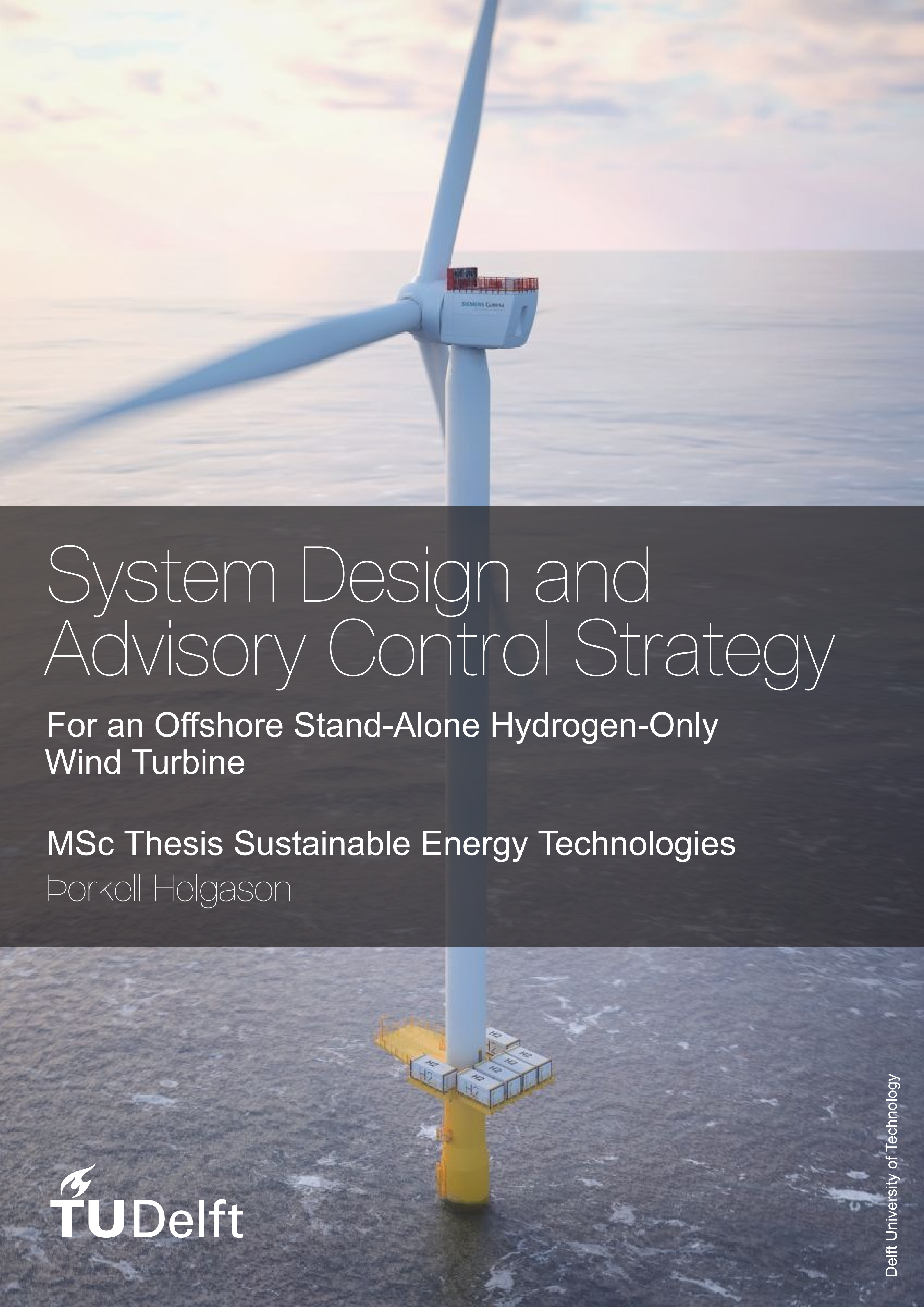

System Design and Advisory Control Strategy

For an Offshore Stand-Alone Hydrogen-Only Wind Turbine

MSc Thesis Sustainable Energy Technologies

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Cover Image: Unlocking the green hydrogen revolution, Siemens Gamesa, 2021, https://www.siemensgamesa.com/en-int/products-and-services/hybrid-and-storage/green-hydrogen/unlocking-the-green-hydrogen-revolution

TU Delft

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Þorkell Helgason
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Abstract

Producing hydrogen from renewable energy sources will play a pivotal role in the energy transition. It can reduce emissions in hard-to-abate sectors and be used for grid balancing services. The energy industry is looking into multiple different system configurations to produce green hydrogen. One such system is an offshore stand-alone wind turbine with the sole purpose of producing hydrogen. The reason for this interest is due to decreasing offshore wind costs, electrolyzer capital expenditure requirements are dropping, and such a system will have high electrolyzer operating hours. Further cost reductions can be achieved by substituting the electrical infrastructure in offshore wind farms as well as on the wind turbine, for hydrogen infrastructure.

When directly connecting an electrolyzer to a non-grid connected fluctuating power source, it will be hard to prevent frequently turning the electrolyzers on and off. That has been found to accelerate component degradation, thereby reducing the system lifetime.

This report aims to address how the system design and the advisory control strategy can increase hydrogen production while decreasing the number of electrolyzer turn-offs. The investigated system comprises a 20 MW wind turbine directly connected to PEM electrolyzers, a desalination system, a water tank, and a battery. Two PEM electrolyzer configurations were compared, namely 4x5 MW and 2x10 MW. Furthermore, two interesting system additions were analyzed. Firstly, the inclusion of a weather forecast to aid the advisory control with making decisions on when to turn electrolyzers on. Secondly, an additional storage element that could keep the last electrolyzer idling during a period of low wind speeds.

The individual components of the system were firstly modeled and then connected to get a representative system model. Two different advisory control strategies, which operate the components, were then designed to simulate the system behavior with regard to hydrogen production and the number of turn-offs, among other key performance indicators.

This thesis project was done in collaboration with Vattenfall, who provided access to 5-second resolution power output data from a single offshore wind turbine. Using that data, different system designs and versions of the two advisory control strategies were simulated with the aim of selecting the best system design and advisory control strategy.

The results showed that the system design and advisory control could significantly reduce the number of electrolyzer turn-offs while producing close to the highest potential of hydrogen. The weather forecast and additional storage element brought substantial benefits regarding the electrolyzer turn-offs but did not largely impact the hydrogen production.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
ABWF	Aberdeen bay wind farm
AC	Alternating current
ASE	Additional storage element
CAPEX	Capital expenditures
crf	Capital recovery factor
DC	Direct current
FLH	Full load hours
HHV	Higher heating value
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
MAFP	Minimum acceptable forecasted power
MPC	Model predictive control
OPEX	Operational expenditures
RO	Reverse osmosis
SOC	Status of charge
SAHO	Stand-alone hydrogen-only

Symbols

Symbol	Definition	Unit
$ASE_{SOC,Max}$	Maximum storage capacity of the ASE	[Minutes]
ASE_{SOC}	Status of charge of the ASE	[Minutes]
$Battery_{\text{OM}}$	The operating mode of the battery	[-]
C	Energy consumption parameter of electrolyzer	[kWh/kg]
$E_{Des,Max}$	Desalination energy consumption per cubic meter of desalinated water	[kWh]
E_{Max}	Maximum energy capacity of the battery	[kWh]
$Elec_{MaxRamp}$	Maximum ramp rate of an electrolyzer	[%/s]
E_{WT}	Energy output from the wind turbine	[kWh]
m_{H_2}	Mass of hydrogen	[kg]
$\dot{m}_{\text{H}_2}$	Mass flow of hydrogen	[kg/s]
P_{Aux}	Auxiliary power	[kW]
$P_{Charge,Max}$	Battery maximum charge rate	[kWh/Δt]
P_{Des}	Desalination power consumption	[kW]
$P_{Des,Max}$	Desalination rated power consumption	[kW]
P_{elec}	Electrolyzer power consumption	[kW]
$P_{elec,min}$	Minimum operating point of electrolyzer	[kW]
$P_{elec,max}$	Maximum operating point of electrolyzer	[kW]
P_{input}	Power input	[kW]
P_{WT}	Power from the wind turbine	[kW]
SOC_{Battery}	The status of charge of the battery	[%]
$SOC_{P_{Aux}}$	Battery SOC equivalent of the auxiliary power consumption	[%]

Symbol	Definition	Unit
$SOC_{\text{WaterTank}}$	The status of the volume left in the water tank	[%]
$\dot{V}_{\text{Water, Des}}$	Desalination volumetric flow rate	[m^3/hour]
$\dot{V}_{\text{Water, Max, Des}}$	Desalination maximum volumetric flow rate	[m^3/hour]
$V_{\text{WaterTank, max}}$	Volumetric storage capacity of the water tank	[m^3]
α	Power Law Exponent	[-]
δ_{Battery}	Boolean variable stating whether the battery has performed an action	[-]
$\delta_{Filling}$	Boolean variable stating whether the desalination system is on or off	[-]
δ_{Idling}	Boolean variable stating whether there is an electrolyzer in idle or not	[-]
$\delta_{Startingup}$	Boolean variable that takes the value of 1 or 0 depending stating whether there is an electrolyzer starting up or not	[-]
Δt	Simulation time step	[s]
ϵ_{sys}	System level efficiency	[%]
ρ	Density	[kg/m^3]
η_{Round}	Battery round trip efficiency	[%]

1
Introduction

This chapter will provide an introduction to this thesis project. The relevant background information is summarized in Section 1.1, explaining the recent interest in stand-alone offshore hydrogen-only wind turbines. The problem analysis is described in Section 1.2, followed by the research questions in Section 1.3. The approach to answer the research questions is described in Section 1.4. Lastly, in Section 1.5, the layout and chapter division is shown.

1.1. Background

The global energy system requires a significant transformation to keep global warming below the 1.5°C, or even 2°C. IRENA has claimed that anything short of radical and immediate action could eliminate any chance of staying below those levels [1]. The required changes have been summarized in the following six key steps [1]: (1) Significant increase in renewable energy generation, (2) improvements in energy efficiency, (3) electrification in end-use sectors, for example electric vehicles, (4) clean hydrogen, (5) bioenergy and lastly (6) carbon capture and storage.

A couple of end-use sectors are hard to fully electrify due to economic and technical challenges, such as shipping, aviation, iron, and steel production, and heavy-duty trucking, among others [2]. This is where the role of hydrogen comes into play. Hydrogen is seen as the leading option for reducing emissions in these hard-to-abate sectors because it can be stored, combusted, and used in chemical processes in similar ways as natural gas, oil, and coal [3].

With increasing renewable energy generation, fluctuating power sources such as wind and solar energy will make up a large portion of the power generation [1]. It will therefore become essential to balance out the electricity supply and demand by storing energy when there is excess power for later use when there is excess demand. Hydrogen can be stored for both long and short-term duration, making it also an interesting option for balancing services [3].

Hydrogen must be produced in a low-carbon way to achieve its emission reduction potential. In 2019, 75% of the produced hydrogen was from natural gas, and 23% from coal [3]. Hence, less than 2% of hydrogen was produced as clean hydrogen. Recently, colors have been used to identify the different ways of hydrogen production [3]. High emission productions, such as from coal and natural gas, have been labelled as black and grey hydrogen, respectively. Blue hydrogen is used for hydrogen production from fossil fuels when combined with carbon capture and storage. Then there is green hydrogen, which is when the hydrogen is produced from renewable electricity. Green and blue hydrogen are the preferred ways of production, with green hydrogen as the ultimate end goal [1].

Green hydrogen is currently 2-3 times more expensive than fossil-based hydrogen in most locations [4], which is hindering its large-scale diffusion. It is expected that before 2030, the cost of green hydrogen could be equal to the cost of fossil-based hydrogen in optimal locations [2, p.12], and there are three main contributing factors [2]. Firstly, the price of renewable electricity, which is a major cost component for green hydrogen, is drastically decreasing. Secondly, the capital expenditure (CAPEX) requirements for electrolyzers are dropping due to economies of scale in electrolyzer production and increased electrolyzer learning rates. The third factor is that electrolyzer operating hours are increasing because of integrated renewable hydrogen production projects. Systems with high operating hours and access to cheap renewable electricity can decrease the cost of green hydrogen substantially [4, p. 17-18]. That is why large-scale integrated, renewable hydrogen projects can become very cost-effective.

A recent interest within the energy industry in such a system is in offshore stand-alone hydrogen-only (SAHO) wind turbines. These are non-grid connected wind turbines with the sole purpose of producing hydrogen. Each wind turbine can have the hydrogen production facility in containerized units located at the base of the offshore wind turbine, next to the tower. There are a few reasons for this interest in offshore SAHO wind turbines.

One of the reasons is that by producing hydrogen locally, it is not required to transport the electricity over long distances through cables resulting in lower power losses and a substantial decrease in the capital expenditures of the system [5]. The decrease in capital expenditures is because the electricity transport infrastructure is substituted for hydrogen infrastructure, which is estimated to be cheaper [5][2, p.20]. For example, the array cables, offshore substation, export cables, and the onshore substation, are substituted with pipelines or hydrogen storage units and shipping transportation.

Another key reason for the interest in offshore SAHO wind turbines is that the cost of offshore wind energy has drastically decreased in the last 11 years, as can be seen below in Figure 1.1. In 2021 the global weighted-average Levelized Cost Of Energy (LCOE) for offshore wind was around 75 USD/MWh compared to roughly 190 USD/MWh in 2010 [6, p.32]. In Europe, the weighted average LCOE was 65 USD/MWh [6, p.119]. Comparing that with the energy costs of fossil fuels in Figure 1.1, which are between 60 - 150 USD/MWh, it can be seen that offshore wind has become highly competitive. Combining local hydrogen production with high operating hours and cheap electricity from offshore wind, the cost of producing green hydrogen could become very competitive.

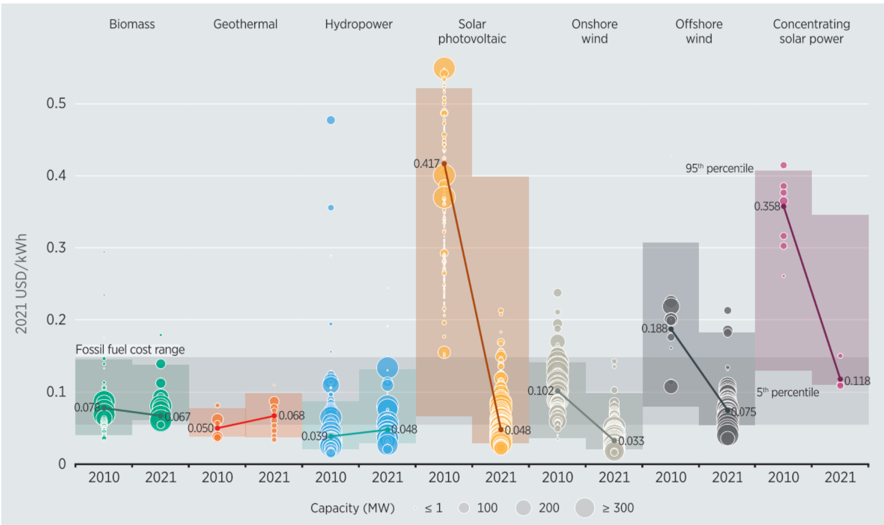

Figure 1.1: Comparison of LCOE for different energy sources, showing trends between 2010 and 2021.

Multiple new projects have been initiated to increase the knowledge of offshore hydrogen-only wind turbines and speed up their commercialization. For example, Vattenfall has announced its plan for the world's first hydrogen-producing offshore wind turbine to start production in 2025 [7]. Other examples are the Oyster project [8] and the H2Mare initiative [9]. The Oyster project will run until 2024 to investigate the feasibility and potential of directly combining an offshore wind turbine with an electrolyzer and transporting renewable hydrogen to shore. The H2Mare initiative plans to research and develop an offshore hydrogen-only wind turbine and deploy a full-scale offshore demonstration plant by 2025/26 [10].

1.2. Problem analysis

Due to the increased interest in green hydrogen, many academic and industry papers have been published on the operation and system design of coupling electrolyzers to renewable energy generation. Most of these papers, however, have been focusing on grid-connected systems where the operational strategy considers whether to sell electricity to the grid or produce hydrogen. The papers on off-grid systems have focused on using hydrogen as a storage element combined with a fuel cell to make a self-sustainable microgrid. There is a gap in the literature on operational strategies and system design for stand-alone systems with the sole purpose of producing hydrogen.

The few publications that have considered stand-alone systems have either been lab-scale demonstration plants or simulated the system performance with a time resolution of 1 hour. The publications with a time resolution of 1 hour only simulate the system with on/off operating modes, ignoring the impact of the idling operating mode, which is important to consider when designing a dynamic advisory control strategy. Smaller time scale simulations are required to address the knowledge gap on specific key issues when coupling hydrogen production with renewable energy sources. For example, how often are the electrolyzers being turned on and off due to the fluctuating nature of wind energy. Frequently turning electrolyzers on and off has been found to accelerate component degradation and increase component failure. Therefore, it is important to understand how often the electrolyzers are being turned on and off. Furthermore, with smaller time scale simulation it can clearly be seen how well the electrolyzers manage to keep up with the fluctuations in the power output.

1.3. Research questions

The main research question of this project is:

> **"How does the system design and advisory control strategy impact the overall system performance in relation to hydrogen production and turning electrolyzers frequently on and off?"**

The sub-research questions can be seen below, and the answers to them help answer the main research question:

1. **How does the electrolyzer system configuration, with regards to the number of electrolyzer units and their respective sizes, impact the system performance in relation to hydrogen production, frequently turning electrolyzers on and off as well as the levelized cost of hydrogen?**
2. **How does the inclusion of a secondary storage element which is capable of keeping electrolyzers idling affect the system performance?**
3. **How does the inclusion of a weather forecast affect the system performance?**

1.4. Approach

This thesis will develop and test advisory control strategies for the offshore SAHO wind turbine with the aim of increasing hydrogen production, considering that the electrolyzers should not be turned on and off too often. This thesis was done in collaboration with Vattenfall, which provided 5-second resolution time series data of the power output from an 8.8 MW wind turbine. A developed simulation model will use this high-resolution data to simulate the system when operated with different advisory control strategies. That will clearly show the impact of coupling electrolyzers with a fluctuating power source, how different strategies can impact the hydrogen production and how often the electrolyzers are turned on and off. Two different electrolyzer configurations will be tested. Firstly 4x5 MW electrolyzers, and secondly, 2x10 MW electrolyzers, both directly coupled to a 20 MW wind turbine. That will show how different system designs can impact the hydrogen production and turning electrolyzers on and off.

1.5. Layout

This report is structured as follows: Chapter 2, gives a big picture overview of the system and individual component descriptions. This is followed by the model implementations in Chapter 3. Next, the case study is described in Chapter 4, where the system sizing and component selection can be seen. Then Chapter 5 goes over the developed advisory control strategies. Chapter 6 discusses the results of the control strategies and the different system configurations. In Chapter 7, additional features were tested to improve the system performance, such as the inclusion of a weather forecast and adding a second storage element capable of keeping an electrolyzer in idle through periods of low wind. The different performances of the systems were summarized in an economic assessment in Chapter 8, where the levelized cost of hydrogen was estimated. Lastly, the conclusions of this project are given in Chapter 9, followed by recommendations for further research in Chapter 10.

2

Offshore Hydrogen-Only Wind Turbine Overview

This chapter will provide a big picture overview of the system, alongside a description of the individual components that make up the system. Under each component description, a brief literature review is provided summarizing important background information.

2.1. System overview

The main setup of the system is an offshore wind turbine, with multiple containerized units located on the wind turbine platform. Those units are the hydrogen production units, battery, water tank, desalination system, and control unit. The additional weight of these systems needs to be considered when designing the wind turbine's support structure. There are multiple types of support structures, such as a monopile, jacket foundation, or floating support structure. These different types of support structures and their effect on the system design are left out of the scope of this thesis as well as the weight consideration of the components.

In Figure 2.1, a top-down view of the system can be seen along with the flow of electricity, water, and hydrogen. The wind turbine produces power that can be used for three purposes:

- Produce hydrogen via electrolysis
- Store the energy in the battery
- Desalinate seawater to the desired purity level for the electrolyzers

If none of the above three systems can use the power, the power needs to be curtailed since the system is not connected to the grid.

To produce hydrogen via electrolysis, the electrolyzers take electricity and water as an input to produce hydrogen and oxygen. Figure 2.1 shows that the hydrogen is assumed to be transported from the wind turbine platform via pipeline, but the transportation of the hydrogen is not within the scope of this thesis.

The battery can both store and supply power, as is shown in Figure 2.1. Since the system is not connected to the grid, the battery will need to supply energy to the critical auxiliary components when the wind turbine is not producing power. The battery takes direct current (DC) power, while the wind turbine produces alternating current (AC) power. Hence, there is an AC to DC conversion step when storing the power from the wind turbine in the battery. When the battery then supplies power to critical auxiliary components, the power goes through a conversion step from DC to AC.

The desalination system takes seawater and electricity as input to desalinate the seawater to the acceptable purity level of the electrolyzers and is then stored in a water tank on the platform. This tank is then connected to the electrolyzers, which draw water from the tank when producing hydrogen. It is important to have a water tank to provide a buffer between the water requirement of the electrolyzers and the output of the desalination system.

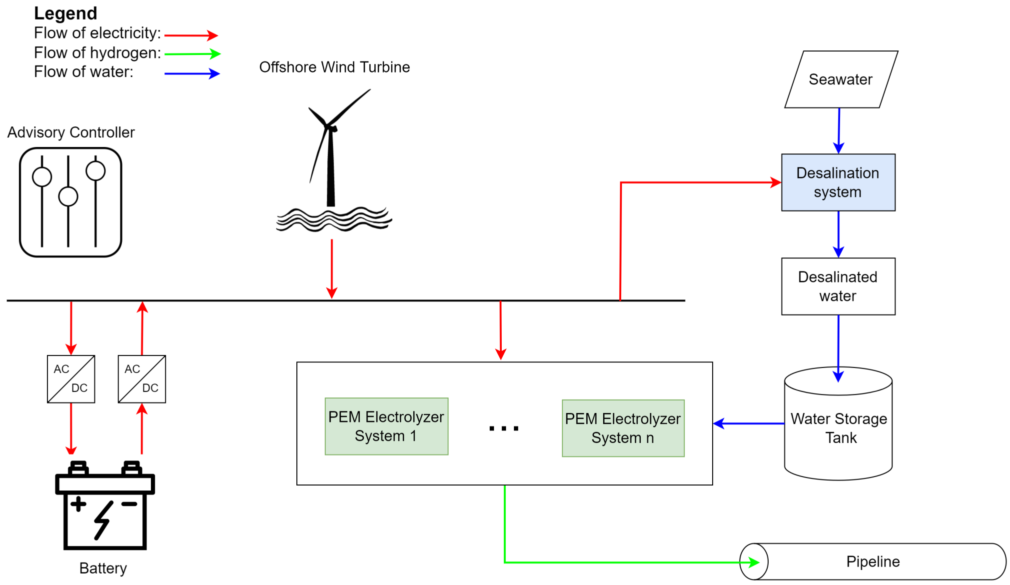

Figure 2.1: Flows of electricity, water and hydrogen within the system

Then there is the advisory control which governs how the different components in the system operate together. The advisory control will attempt to optimally distribute the wind turbine's fluctuating power output to the other system components.

Lastly, there is the additional storage element (ASE), but the ASE is not shown in Figure 2.1. It is left out of the system figure as it is unknown whether an additional storage element should be included in the system design or not. The additional storage element would store energy from the wind turbine, hence that energy is not used for hydrogen production. That energy is used later when the wind turbine power output is low and cannot keep an electrolyzer idling. Then the additional storage element can use the stored energy to keep the electrolyzer idling. The meaning of idling will be explained in Section 2.3.

In the following sections, these different components will be described in greater detail.

2.2. Wind turbine

The main role of the wind turbine is to convert the kinetic energy of the wind into electrical energy. As the system is non-grid connected, the wind turbine is the only power source in the system.

The average size of offshore wind turbines has grown rapidly over the last two decades and is expected to keep growing, as is shown in Figure 2.2. Wind turbines are expected to reach a size of 20 MW around 2025-2030 [11]. Therefore, SAHO wind turbines will likely be of large sizes, such as 15-20 MW.

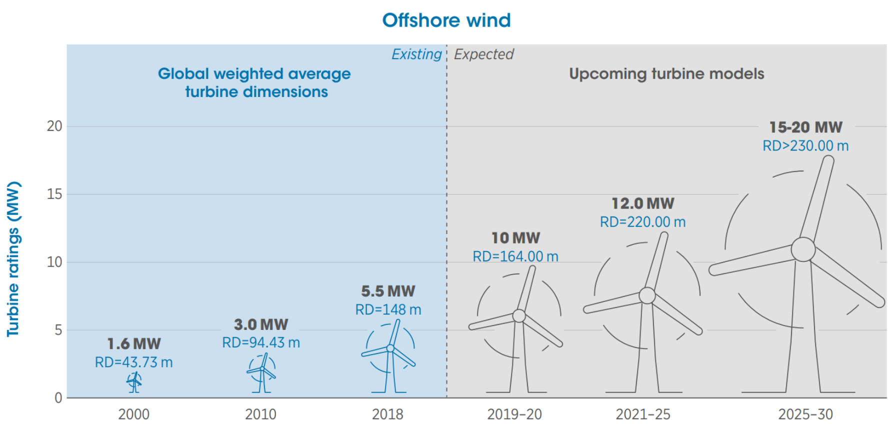

Figure 2.2: Average size of offshore wind turbines; Currently existing and expected. Source: [11]

Some of the key benefits of increasing wind turbine capacity are;

- There are greater wind speeds at higher altitudes. That results in greater annual energy production, and lower wind speed areas can be better exploited [11].
- Fewer wind turbines are required to reach a certain wind farm capacity, resulting in fewer maintenance visits [11]. This might become an important benefit as it is unknown how the operation and maintenance of a SAHO wind turbine will be compared to a regular wind turbine.
- Economies of scale are an important benefit. Wind farms with larger wind turbines have an overall lower cost per MW of capacity [11]
- Larger wind turbines have increased inertia, leading to slower short-term fluctuations. The time constant, which characterises how fast the wind turbine power output changes due to changes in the wind speed, has been estimated to be linearly proportional to the wind turbine inertia, which is proportional to the rotor radius squared [12]. Hence, a larger wind turbine will have fewer fluctuations, which is desirable as the electrolyzers will need to follow the power output from the wind turbine dynamically.

2.3. Electrolyzer

The role of the electrolyzer is to capture and use the fluctuating power output from the wind turbine to split water (H_2O) into hydrogen (H_2) and oxygen (O_2), thereby converting most of the electrical energy into hydrogen as H_2. This process is called electrolysis and is performed within a system called an electrolyzer.

There are three main types of electrolyzers; Polymer electrolyte membrane (PEM) electrolyzers, Alkaline electrolyzers (AE), and Solid oxide electrolyzers (SOE). Multiple in-depth reviews on the working principle of these different types of electrolyzers have been performed [13, 14, 15]. For this thesis project, it is not important to understand in detail the working principle of these electrolyzers. It is, however, good to understand the main differences between these three electrolyzer types in terms of commercialisation and capabilities to be directly connected to a fluctuating power source. The following paragraphs will address this.

Alkaline electrolysis is a mature technology that has been used in large-scale industrial processes since the 1920s [3]. The benefits of alkaline electrolyzers are that they are durable, readily available in MW scale [14], and have low capital costs compared to PEM and SO electrolyzers [16]. Current alkaline electrolyzers consume roughly 52 kWh of electricity to produce 1 kg of hydrogen [17, p.53]. The main drawbacks of alkaline electrolyzers when considering direct coupling to an offshore SAHO wind turbine, as well as other renewable energy systems, are the following:

- Their dynamic operation with regards to fluctuating power input is limited [16], and frequent turn-on/turn-off behavior accelerates component degradation, reducing the expected system lifetime [15].
- They have a low operating pressure [16]. Therefore, an external compression system would likely be required on the offshore wind turbine platform.
- They have a low current density, which alongside the low operating pressure, causes the AE to have a large area requirement [3].
- They are also heavy compared to PEM electrolyzers which is an issue for offshore installation [18]

Alkaline electrolyzers are mainly considered for large-scale base-load hydrogen production [17]. They are still under development, however, focusing on pressurized systems to make alkaline electrolyzers more suitable to be combined with renewable energy [17].

PEM electrolyzers were first introduced in the 1960s to overcome the drawbacks of alkaline electrolyzers. The main benefits of PEM electrolyzers are:

- They can rapidly respond to changes in the power input, making PEM electrolyzers very suitable to follow power input from renewable energy technologies [14].

- They operate at high pressure [14], which eliminates the need for external compression when pipeline transport to shore is not too long.
- PEM electrolyzers have high current density and compact design [14], making them suitable to be located on the support structure of an offshore wind turbine.

PEM electrolyzers have established a strong position in the electrolyzer market and are considered the leading technology for direct coupling with renewable energy along with pressurized alkaline electrolyzers [17]. Current PEM electrolyzers consume roughly 53 kWh of electricity to produce 1 kg of hydrogen[17, p.53]. The disadvantage of PEM electrolyzers is that it is a less mature technology than AE and uses precious metals, both of which cause PEM electrolyzers to be more expensive than alkaline electrolyzers [16]. In addition, PEM electrolyzers have only recently been available in MW sizes and will require a steep learning curve [17].

SO electrolyzers have only recently reached a commercial stage and are far behind alkaline and PEM electrolyzers in terms of scale and maturity [17]. The advantage of SO electrolyzers is that they can operate at much higher temperatures than PEM and alkaline electrolyzers, which allows them to reach higher electrical efficiency [13]. On the other hand, the high operating temperature poses a challenge for material stability leading to a lower system lifetime [13]. SO electrolyzers can also operate in reverse, thereby converting hydrogen back to electricity [3] making them an interesting option for balancing services for the power grid.

By request of Vattenfall, this research will only focus on PEM electrolyzers. The above comparison also showed why PEM electrolyzers are considered ideal for direct coupling with renewable energies.

PEM electrolyzers have three operating modes [19]:

- They can be on where they are consuming power and producing hydrogen.
- They can be off where they are not consuming any power and no hydrogen is produced.
- They can be idling (sometimes referred to as stand-by), where they are consuming a small amount of power to be kept operational and ready but not producing hydrogen [19]. In this state, they can rapidly turn on, taking < 10 seconds to start producing hydrogen [20, p.11]

When directly coupling a PEM electrolyzer to a fluctuating power source, it is hard to avoid turning electrolyzers on and off as the power input fluctuates. This problem has been highlighted in multiple publications [21, 22, 19]. Even though PEM electrolyzers are specifically designed to operate under dynamic conditions, it has been found that frequently turning them on and off has a negative impact on the system lifetime [23, 24]. Frequently turning electrolyzers on and off can increase mechanical and chemical failures in the stack components caused by temperature and pressure fluctuations [23]. Very rapid on/off cycling causes mechanical and chemical degradation due to temperature and pressure cycling, as well as chemical degradation due to uncontrolled stack polarity [23]. Therefore, it is important to operate the electrolyzers with the aim of avoiding turning them on and off frequently.

2.4. Desalination

The desalination system of the SAHO wind turbine is responsible for purifying the seawater to a required purity level before usage by the hydrogen units. PEM electrolyzers typically require 10 kg of ultra pure water to produce 1 kg of hydrogen [25]. Depending on the scope of the system, water requirements differ, however. Many electrolyzer suppliers require tap water as an input because there is an internal purification step within the hydrogen unit that purifies the water from tap quality to ultra high purity. For example, electrolyzers from the companies Cummins and Siemens Gamesa RE require around 13-17 kg of tap water per kg of hydrogen produced [26, 20].

Reverse osmosis (RO) is the most widely adopted technology for desalination [27]. Over the last 30 years, significant advances have been made in membrane technology, more efficient operation and process optimization causing the energy requirement of RO systems to drop from roughly 9-10 kWh/m^3 to less than 3 kWh/m^3 [25]. Comparing that with the energy consumption of the electrolyzers, mentioned in Section 2.3 as roughly 52-53 kWh/kg, it can be seen that the desalination system consumes less than 0.1% of the energy consumption of the electrolyzers[1].

[1] Since electrolyzers require about 15 kg of water per kg of produced hydrogen, equivalent to 0.015 m^3 of water, the desalination system only consumes around 0.045 kWh per kg of hydrogen. That is less than 0.1% of the energy consumption of the electrolyzers, which consume roughly 52-53 kWh/kg.

These technological advances have also decreased the CAPEX and operational expenditures (OPEX) of seawater RO systems significantly and are currently estimated to be around 0.5-1.2 USD per m^3 of water [28]. Sea water RO for hydrogen production only accounts for roughly 0.6% of the levelized cost of hydrogen (LCOH) cost breakdown [25]. Although the desalination system is vital for the operation of the system, this shows that for cost reductions, the desalination system has a low impact.

For this thesis project, the scope of the desalination system will only be focused on sizing the desalination system.

2.5. Battery and additional storage element

The role of the battery is to provide a power supply to components that need access to electricity at all times, regardless of whether the wind turbine is producing power. In literature, this is referred to as the uninterruptible power supply (UPS). When the wind turbine is not producing power, the battery will supply the power to those components. For example, offshore wind turbines' components that need access to electricity at all times are heating loads, ventilation loads, transformer magnetisation loads, navigation lights, and sensors for data measurements [29]. This required power consumption will be called critical auxiliary power consumption. The battery will need to supply the critical auxiliary power consumption to all the components in the system.

Currently, offshore wind turbines are usually equipped with a small diesel generator to ensure that in case of emergency, a power source is available to supply the critical auxiliary components [30]. However, the industry is attempting to reduce the use of fossil fuels and move towards sustainable solutions such as batteries [30].

For this thesis project, a battery will be used as the sole UPS in the system. The battery will therefore need to be sized such that the storage capacity in the battery ensures that it is extremely unlikely that it gets fully drained.

The above-described battery will only be used to supply the critical auxiliary power consumption. It is interesting to investigate whether it is beneficial to have an additional storage element (ASE), such as another battery that can keep electrolyzers idling. If the wind turbine power output decreases such that an electrolyzer needs to be turned off. In that case, the ASE could start supplying power to keep the electrolyzer idling to prevent turning the electrolyzer off. This was highlighted by NREL in [21], that keeping electrolyzers idling increases the energy costs but avoids turning electrolyzers on and off [20, p. 11].

2.6. Compression

As Section 2.3 discussed, PEM electrolyzers operate at a high pressure, with current state-of-the-art electrolyzers running at 30-40 bar [17, 31]. That is sufficient pressure to transport the hydrogen via pipeline when the wind farm is close to shore. For remote offshore wind farms, further compression might be necessary. For the purpose of this research, external compression is assumed to be unnecessary.

2.7. Advisory control

This section will explain the advisory controller, what is expected from such a controller, and why it is important.

The primary purpose of the advisory controller is to control the operation of the components and thus the flow of energy, water, and hydrogen. The advisory control should operate the system such that hydrogen production is maximized while ensuring that the system operates in an acceptable way considering safety, component lifetime, and degradation. For this thesis project, acceptable operation will only be monitored through the number of electrolyzer turn-offs. Section 2.3 highlighted that frequently turning electrolyzers on and off causes accelerated degradation and component failure. The advisory control will therefore attempt to increase hydrogen production while decreasing the number of turn-offs.

Currently, it is not clear how important it is to decrease the number of turn-offs, however. NREL highlighted this issue, stating that further knowledge is required on the impact of frequently turning electrolyzers on and off as well as how operational strategies affect the durability of electrolyzers [21].

In this project, the advisory control receives information from the four main components in the system. For example:

- Wind turbine: Active power output
- Electrolyzers: Power consumption and operating mode
- Battery: Status of charge
- Water tank: Water level in the water tank

The list above only showed a small portion of the required information. The advisory control uses the received information to decide how to distribute the active power in the system between the components and how to operate them. For example, deciding when to turn the electrolyzers, battery, and desalination system on and off.

The individual components will need to be modeled to simulate such a system. A system-level model can then be obtained by connecting the individual components. Together, the system model and the designed advisory control will simulate the system performance under the designed advisory control strategy. The component models are the topic of the next chapter.

3 System Modeling

This chapter will walk through the individual component models, as well as the system model, explaining how they were derived, their level of detail, and provide reasons for why those modeling approaches were selected. This chapter starts with the wind turbine model in Section 3.1, followed by the electrolyzer model in Section 3.2. Then, the desalination model will be explained in Section 3.3. In Section 3.4, the battery model is described, and then the additional storage element model is in Section 3.5. Lastly, the system model is discussed in Section 3.6. For each model, a tabulated summary of the parameters, their units, and a short description is provided.

3.1. Wind turbine

The main role of the wind turbine component is to provide power input to the electrolyzers. There are two main ways to receive the power input. Firstly, by not modeling the power output but rather using real power output data from an operational wind turbine. Secondly, the power output can be modeled as a function of wind speed. Vattenfall could provide data with a 5-second resolution of the active power output from a single wind turbine. That is very suitable for testing the performance of the system model because it shows real power output fluctuations, which the advisory control will need to deal with. Hence it was not required to model the wind turbine power output. The symbol P_{WT} will be used in the following chapters and represents the power from the wind turbine.

For the economic assessment, a model will be needed to convert 1-hour average wind speeds into power output. Typical methods for modeling the power output of wind turbines are either based on (1) the fundamental power equations of power available in the wind or (2) models based on utilizing the power curve of the wind turbine [32]. Vattenfall provided a power curve that could directly translate wind speed to power output.

3.2. Electrolyzers

The main goal of the electrolyzer model is to accurately model the mass flow of hydrogen leaving the electrolyzer units as a function of the input power. It is important to allow the hydrogen generation to fluctuate with the fluctuating power consumption to obtain a dynamic model that can be used to test the designed advisory control strategy.

There are multiple types of electrolyzer models with different degrees of complexity. In literature, the models are often based on the polarization curve, which shows the variation in voltage with current, and the hydrogen production [33]. More complicated models attempt to model the temperature and pressure variations in the anode, cathode, and membrane and their different types of losses in the subsystems [33]. However, that level of detail is not required for this thesis project.

One of the most straightforward approaches is to assume a linear relationship between hydrogen production and the power consumption of the electrolyzer. This approach was used in a recent report which analyzed the viability of a dedicated hydrogen-producing windfarm [34]. It used the energy consumption of each produced kilogram of hydrogen as the primary modeling parameter, a number provided by most electrolyzer suppliers. For example, in the datasheet of an electrolyzer from Cummins, it is stated that the electrolyzer specific energy consumption at rated power is less than 54 kWh per kg of produced hydrogen [26]. A ballpark estimate can then be obtained by modeling the hydrogen production as

$$m_{H_2} = \frac{E_{WT}}{C} \tag{3.1}$$

where m_{H_2} is the accumulated mass flow of hydrogen for the simulated time period, E_{WT} is the accumulated energy from the wind turbine, and C is the energy consumption parameter. For the case of the HyLYZER500, C would be 54 kWh/kg [26]. It does not matter whether the energy from the wind turbine is used or the power. If the energy is used, accumulated mass output over time is obtained, but if power is used, the mass flow [kg/s] is the output.

The drawback of this method is the assumption that the efficiency of the electrolysis process is constant, which is not the case. The efficiency of an electrolysis process depends on the electrolyzer power consumption. This model can therefore be improved by making the energy consumption parameter C change as a function of the power consumption.

3.2.1. Electrolysis efficiency

When referring to the efficiency of an electrolysis process, it is essential to include the system boundary that is being referred to. For example, it is possible to refer to the overall system efficiency, or the DC efficiency also called stack efficiency. The system efficiency is the ratio of the usable energy of the hydrogen exiting the system compared to the energy required to produce the hydrogen. This overall efficiency of the process is the desired outcome of the model. The system efficiency is expressed as

$$\epsilon_{sys} = \frac{\dot{m}_{H_2} * HHV_{H_2}}{P_{input}} \tag{3.2}$$

where $\dot{m}_{H_2}$ is the mass flow of hydrogen in [kg/s], HHV_{H_2} is the higher heating value (HHV) of hydrogen which is a constant equal to 39.39 [kWh/kg]. Lastly, P_{input} is the power input into the system boundary.

In Figure 3.1, the typical shape of a system efficiency curve can be seen as the black curve. The system efficiency is the combined efficiency of the DC and auxiliary systems, shown in purple and pink respectively. Figure 3.1 shows that those two efficiencies have an opposite trend.

The DC efficiency refers to the ratio of the energy input to an electrolyzer stack, in the form of DC, and the energy output of the technically usable hydrogen that is outputted from the stack [35]. The system boundary can then be increased to include other sub-systems. For example, the rectifiers are required to convert the AC power from the wind turbine to DC power which the stacks run on. On the other side of the system, there is the balance of plant, which includes the sub-systems that post-process the hydrogen leaving the stacks, such as drying, cooling, purifying, and compressing. By increasing the system boundary to include all these sub-systems, it can be expected that the system efficiency should be lower than the DC efficiency as all these auxiliary services require energy and have some energy losses. That is exactly shown in Figure 3.1, with the system efficiency being lower than the DC efficiency.

To summarize the key message of Figure 3.1, the system efficiency increases rapidly with increasing electrolyzer power consumption, referred to as load on the x-axis in Figure 3.1, as the auxiliary losses are very high at low loads even though the DC efficiency is high. As the electrolyzer power consumption, or load, increases, the operating point moves along the x-axis, resulting in a corresponding system efficiency (in the black curve). Then the system efficiency reaches an optimal efficiency, typically around 25-40% power consumption, where the DC efficiency and the auxiliary system efficiency cross. After that, the system efficiency steadily decreases towards the nominal load (also called rated power). That is because the decrease in DC efficiency is greater than the gain in efficiency from the auxiliary equipment. Furthermore, Figure 3.1 shows that by assuming a linear relationship between the power consumption and the hydrogen output, the increase in efficiency at partial load is neglected, which makes the model less accurate.

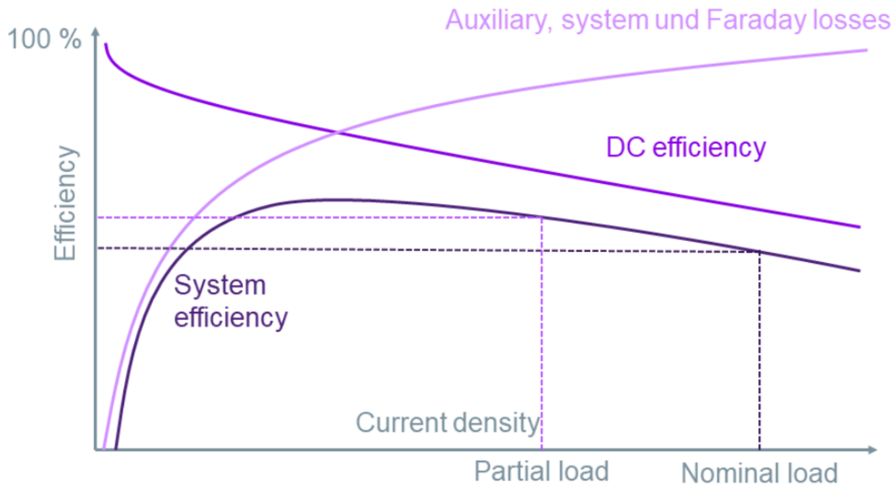

Figure 3.1: System efficiency [35]

The shape of the system efficiency curve is important because it shows that it is more efficient to operate electrolyzers at partial load and that there is a sharp increase in efficiency from the minimal operating point towards around 20-25% power consumption. The advisory control will attempt to maximize hydrogen production while decreasing the electrolyzer turn-offs, and the system efficiency curve plays a vital role in designing the advisory control strategy.

3.2.2. PEM electrolyzer model implementation

The electrolyzer model for this thesis project takes the active AC power output from the wind turbine as input and the mass flow of hydrogen in [kg/s] as the output. In Figure 3.2 the system boundary of the PEM electrolyzer model is shown as the dashed line surrounding the green box. Figure 3.2 shows that the only input is the AC power (the water intake is considered in the water tank model), and that the system efficiency curve should include losses from the AC/DC rectification, and all losses from the sub-systems in the balance of plant. The electrolyzer model is therefore the function

$$f(P_{elec}) = \epsilon_{sys} \tag{3.3}$$

which outputs the system efficiency, ϵ_{sys} for a given electrolyzer power consumption, P_{elec}. The hydrogen output can then be calculated using Equation 3.2, when solving for $\dot{m}_{\mathrm{H}_2}$, as

$$\dot{m}_{H_2}\ \text{[kg/s]} = \frac{f(P_{elec}) * P_{elec}\text{[kJ/s]} * \frac{1\ \text{[kWh]}}{3600\ \text{[kJ]}}}{HHV_{H_2}\frac{\text{[kWh]}}{\text{[kg}}} \tag{3.4}$$

The output is then multiplied by $\Delta t[s/\text{simulation time step}]$ to consider the length of the simulation time step. This modeling approach is very modular and allows each electrolyzer to operate individually, which is important as there will be multiple electrolyzer units on the turbine platform.

The function f will therefore need to be created such that a power input can be directly translated to a hydrogen output. A recent report from IRENA showed an efficiency curve from a PEM production plant in Germany, connected to an onshore wind farm [31, 36]. The green curve shows the efficiency of the system with respect to the higher heating value of hydrogen, and the black curve shows the volumetric hydrogen output. The HHV efficiencies in this graph include all auxiliary components such as transformers, rectifiers, compressors, pumps, and cooling units [36]. This system-level efficiency curve also includes compression to an output pressure of 22.5 MPa [36], however, which is not included in the scope of the system for this thesis project. This system-level efficiency curve will be used as a reference and will be tailored to a system-level efficiency of an electrolyzer which applies to the system of this thesis.

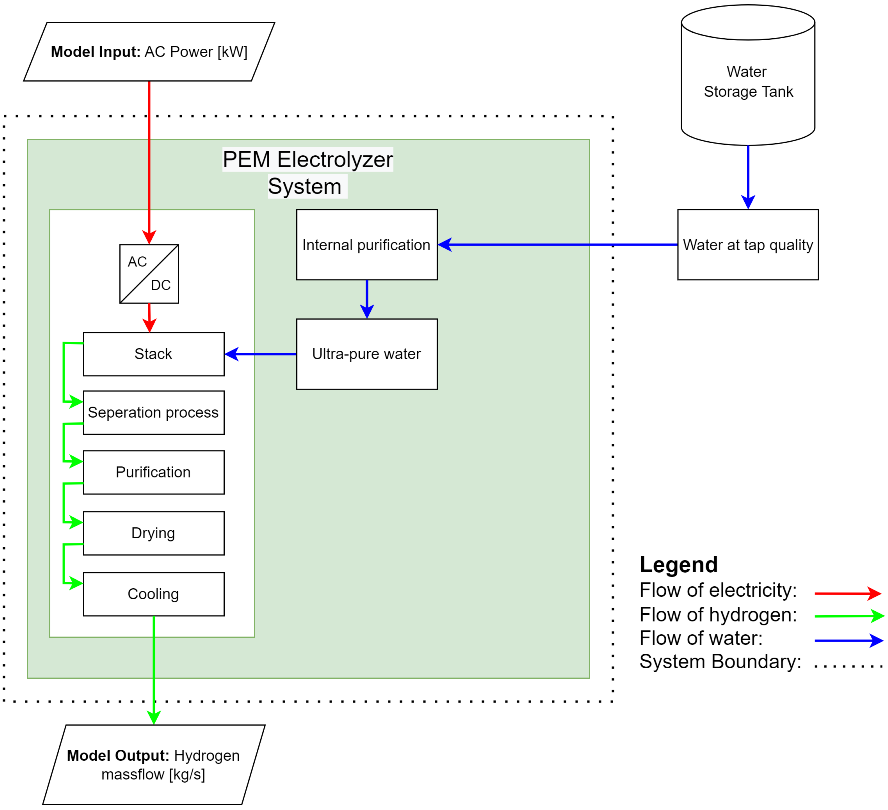

Figure 3.2: System boundary of the PEM electrolyzer model

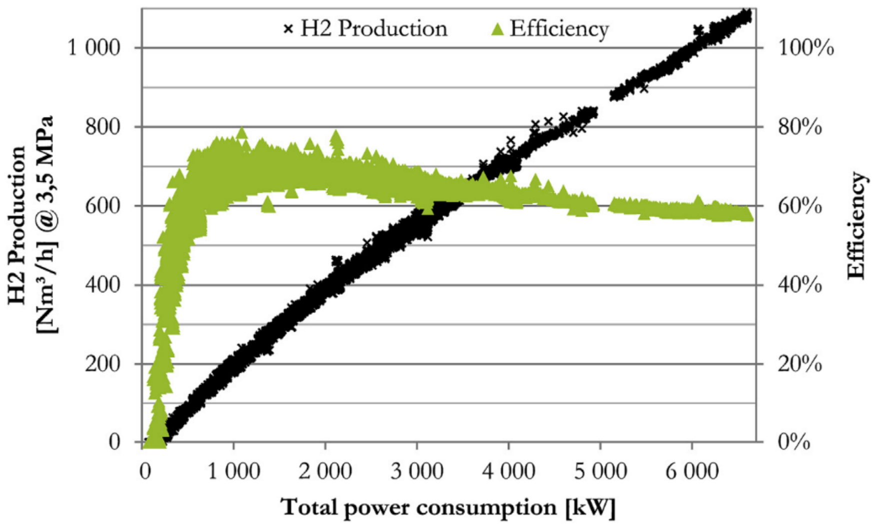

Figure 3.3: System level efficiency curve of the Energipark Mainz electrolysis system [36]

With the electrolyzer model able to translate power consumption to hydrogen output, there are only a few more important aspects to consider. The model needs to be dynamic and able to react to the dynamics of the fluctuating power output from the wind turbine. For example, when the active power output from the wind turbine increases, the increase in the power consumption of each electrolyzer unit should be constrained by a maximum ramp rated, $Elec_{MaxRamp}$ with the unit [%/s]. Furthermore, the electrolyzers have a minimum operating point, $P_{elec,min}$, and a maximum operating point, $P_{elec,max}$. It is important to take into account that turning electrolyzers on both consumes power and takes time. The parameter $\Delta t_{\text{Off-To-On}}$, will be the time it takes to turn an off electrolyzer on, and $P_{\text{elec,starting-up}}$ is the starting up power consumption. As described in Section 2.3, electrolyzers have three operating modes, namely on, off, and idle. On meaning the electrolyzer is consuming power and producing hydrogen, off meaning it is shut down and not consuming any power, and idle meaning that the electrolyzer is kept on stand-by, such that it consumes certain power to keep it warm and ready to ramp up within a short period of time. That is why the parameters $\Delta t_{\text{Idle-To-On}}$ and $P_{\text{elec,idling}}$ are required as well. All these parameters are summarized below in Table 3.1.

Table 3.1: Electrolyzer model parameters

Parameter	Unit	Description
$P_{elec,rated}$	[kW]	The rated power of the electrolyzer
$P_{elec,min}$	[kW]	The minimum operating point of the electrolyzer
$P_{elec,max}$	[kW]	The maximum operating point of the electrolyzer. Often that is higher than the rated power.
P_{elec}	[kW]	Dynamic variable, which stores the power consumption of the electrolyzer at a given simulation time step. Can take a value from $[P_{elec,min}, P_{elec,max}]$
$Elec_{MaxRamp}$	[%/s]	The maximum ramp rate of the electrolyzer, given in % of the rated power, per second.
$Elec_{OM}$	[-]	The operating mode of the electrolyzers. Electrolyzers have three operating modes, namely on, idle, and off, which this parameter stores and feeds to the advisory control.
$Elec_{\text{Water Requirement}}$	[kg H_2O/kg H_2]	The required water consumption of the electrolyzer to produce one kg of hydrogen.
$\Delta t_{\text{Off-To-On}}$	[minutes]	The time it takes to turn an electrolyzer from off to on. A cold start.
$\Delta t_{\text{Idle-To-On}}$	[seconds]	The time it takes to turn an electrolyzer from idle to on. A warm start.
$P_{\text{elec,starting-up}}$	[kW]	The starting up consumption. A power consumption that needs to be delivered to the electrolyzer, for a duration of $t_{\text{Off-To-On}}$ minutes, such that the electrolyzer can turn on.
$P_{\text{elec,idling}}$	[kW]	The idle consumption. A power consumption that needs to be delivered to an idling electrolyzer such that it can keep idling.
δ_{Elec}	[-]	A dynamic state variable which considers whether the electrolyzer has performed an action or not within a single simulation time step. Each electrolyzer can only perform one action per simulation time step.

3.3. Desalination system and water tank

The desalination model aims to estimate the power consumption of the desalination system, as well as to model the volumetric flow rate of water, from the desalination system, into the water tank. The power consumption is important to model, as the power will be withdrawn from the wind turbine power output and hence not used for hydrogen production. The water flow rate is important for modeling how the water tank storage changes with time.

The desalination model is separate from the water tank model and will firstly be described. The desalination model has six parameters, which are summarized below in Table 3.2.

The rated power consumption of the desalination system can be calculated based on the selected energy consumption per cubic meter, $E_{Des,Max}$, and the maximum volumetric flow rate, $\dot{V}_{\text{Water, Max, Des}}$, as

$$P_{Des,Max} = \dot{V}_{\text{Water, Max}} * E_{Des,Max} \tag{3.5}$$

The volumetric flow rate is then assumed to linearly vary, depending on the power consumption as

$$\dot{V}_{\text{Water, Des}} = (\frac{P_{\text{Des}}}{P_{\text{Des, Max}}}) * \dot{V}_{\text{Water, Max, Des}} * \frac{1[s]}{3600[s/hour]} \tag{3.6}$$

and is divided by 3600 to get the volumetric flow rate in the unit m^3 per second. $\frac{P_{\text{Des}}}{P_{\text{Des, Max}}}$ can take any value in range between 0 and 1, as the explanation of the P_{Des} in Table 3.2 shows. The outcome is then multiplied by $\Delta t[s/\text{simulation time step}]$. $\dot{V}_{\text{Water, Des}}$ is then an input to the water tank model, along with the hydrogen output of the electrolyzer models.

Table 3.2: Desalination model attributes

Parameter	Unit	Description
$E_{Des,Max}$	[kWh/m^3]	The rated energy consumption per m^3 of desalinated water.
$P_{Des,Max}$	[kW]	Rated power consumption.
P_{Des}	[kW]	Dynamic variable, which stores the power consumption of the desalination system at a given simulation time step. Can take any value in the range from [0, $P_{Des,Max}$]
$\dot{V}_{\text{Water, Max, Des}}$	[m^3/hour]	The maximum volumetric output flow rate. When operating at rated power.
$\dot{V}_{\text{Water, Des}}$	[m$^3/s$]	Dynamic variable which stores the volumetric output flow rate of the desalination system at a given simulation time step.
$\delta_{Filling}$	[-]	An on/off state variable. A dynamic variable that is used to communicate with the advisory whether the desalination system is on or off.

The water tank model has only three attributes which are summarized below in Table 3.3.

Table 3.3: Water tank model attributes

Parameter	Unit	Description
$V_{\text{WaterTank, max}}$	[m^3]	Volumetric storage capacity of the water tank
$V_{\text{WaterTank}}$	[m^3]	Dynamic variable which stores the current volume of water in the water tank
$SOC_{\text{WaterTank}}$	[%]	The status of the volume left in the water tank, as a percentage of the $V_{\text{WaterTank, max}}$

The water tank model takes two inputs, the $\dot{V}_{\text{Water, Des}}$ from the desalination system which is entering the tank, and also the $\dot{m}_{H_2}$ from the electrolyzer models, which is the total hydrogen mass flow leaving the electrolyzers. From the electrolyzer model, the water requirement for the production of one kilogram of hydrogen is used to convert the $\dot{m}_{H_2}$ into $\dot{V}_{\text{Water, Requirement for Hydrogen}}$ as

$$\dot{V}_{\text{Water, Requirement for Hydrogen}} = \frac{\dot{m}_{H_2} * \text{Elec}_{\text{Water Requirement}}}{\rho_{\text{H}_2\text{O}}} \tag{3.7}$$

, where $\rho_{\text{H}_2\text{O}}$ is assumed to be 1000 kg/m^3. The water tank storage then changes in each simulation time step as

$$V_{\text{WaterTank}}(t + \Delta t) = V_{\text{WaterTank}}(t) + \dot{V}_{\text{Water, Des}} - \dot{V}_{\text{Water, Requirement for Hydrogen}} \tag{3.8}$$

The variable $SOC_{\text{WaterTank}}$ is then calculated as

$$SOC_{\text{WaterTank}} = \frac{V_{\text{Water tank}}}{V_{\text{WaterTank, max}}} \tag{3.9}$$

3.4. Battery

The battery model needs to capture how the stored energy in the battery changes as it gets charged and discharged over time. A very straightforward approach is to model the battery with the eight main attributes, shown in Table 3.4.

Table 3.4: Battery model attributes

Parameter	Unit	Description
E_{Max}	[kWh]	Maximum energy capacity of the battery
E	[kWh]	This is a dynamic variable that stores the current energy available in the battery. It changes when energy is charged/discharged.
$P_{Charge,Max}$	[kWh/Δt]	The maximum energy that the battery can capture in each simulation time step. It is given in kWh and not kW as the simulation time step is greater than one second
η_{Round}	[%]	Round trip efficiency, to consider the energy losses between storing the energy and then using it.
SOC_{Battery}	[%]	The status of charge of the battery as a percentage of the E_{Max}.
$Battery_{\text{OM}}$	[-]	The operating mode of the battery, which can be on, or stand-by.
δ_{Battery}	[-]	A dynamic state variable which considers whether the battery has performed an action or not within a single simulation time step. The battery can only perform one action.
P_{Aux}	kW	The auxiliary power consumption that the battery will need to provide energy when the battery is operating the critical components. Assumed to be a constant value.

The status of charge of battery at any moment, can be calculated as

$$SOC = \frac{E}{E_{Max}} \tag{3.10}$$

, where the SOC can range from 0 to 1, with 0 meaning the battery is fully drained and 1 meaning the battery is fully charged.

The battery has two operating modes. Firstly, it can operate the system autonomously, meaning it is supplying power to single-handedly operate all auxiliary components. Secondly, it can be on stand-by, which will be regarded as its default operating mode when the wind turbine is producing power. In stand-by mode, a default power consumption is required to operate the battery's control unit. This is further explained in Section 4.5.

When the battery is operating the system autonomously, it delivers the energy to the auxiliary components for the wind turbine, electrolyzers, desalination, and itself. It will be assumed that these consumptions are constant, although, in reality, there will be peaks and troughs. For example, there might be spikes in energy consumption if the battery needs to yaw the wind turbine or pitch the blades, but those consumptions are for short durations. The average power consumption will therefore be used. In each simulation time step, the SOC changes as:

$$SOC(t + \Delta t) = SOC(t) - SOC_{P_{Aux}} \tag{3.11}$$

where P_{Aux} is the combined consumption of all the components in the system and $SOC_{P_{Aux}}$ is the equivalent SOC impact of that consumption, calculated as

$$SOC_{P_{Aux}} = \frac{P_{AUX}}{E_{Max} * 3600} \tag{3.12}$$

3.5. Additional storage element

The aim of the additional storage element model is to capture the benefit in system performance of having an additional storage element. The ASE will not be modeled using energy as the main parameter, like the battery, but will rather be modeled using the time it can operate the electrolyzers. The reason is that the advisory control will not be designed to consider when and how to operate the additional storage element. The results will only indicate the potential gain of having an additional storage element. The ASE has four attributes which are shown below in Table 3.5.

Table 3.5: Additional storage element model attributes

Parameter	Unit	Description
$ASE_{SOC,Max}$	[Minutes]	Maximum storage capacity of the ASE, in minutes that it can keep an electrolyzer in idle or starting up.
ASE_{SOC}	[Minutes]	A dynamic variable that tracks the time that the ASE has left to keep the operating electrolyzers in idle or starting up.
δ_{Idling}	[-]	Boolean variable that takes the value of 1 or 0 depending on whether there is an electrolyzer in idle or not, respectively.
$\delta_{Startingup}$	[-]	Boolean variable that takes the value of 1 or 0 depending on whether there is an electrolyzer starting up or not, respectively.

The SOC is a dynamic parameter that is evaluated in each simulation timestep. The SOC can increase and decrease depending on whether the ASE is being used or charged but is constrained by the SOC_{Max}. If the ASE is being used, the SOC changes as

$$ASE_{SOC}(t + \Delta t) = ASE_{SOC}(t) - \Delta t * \delta_{Idling} - \Delta t * \delta_{Startingup} \tag{3.13}$$

where Δt is the simulation time step in minutes. Therefore, if there is an electrolyzer idling or starting-up, then time is withdrawn from the SOC.

If the ASE is not being used and the wind turbine is producing hydrogen, the SOC is being charged

$$SOC(t+1) = SOC(t) + \Delta t_{SimulationTimeStep} \tag{3.14}$$

The reasoning behind that is that if the system is producing hydrogen, then that energy could also have been directed to the ASE. Then by monitoring the amount of energy that the ASE used throughout a simulation, the equivalent hydrogen production of that energy can be estimated. For example, if the ASE used 1000 kWh of energy to operate the electrolyzers, then that is equivalent to 18.5 kg of hydrogen[1]. That equivalent hydrogen production can then be withdrawn from the total hydrogen production. This will be further explained when the results with the ASE are shown, in Section 7.3.

3.6. System level model

Now that all the models have been explained, this section will provide an overview of the required inputs from all the component models to be able to simulate the system. They are summarized below in Table 3.6.

In this thesis project, the advisory control is the last piece that connects all these models together. The advisory control uses the models presented so far to simulate the system's behavior. For each simulation time step, the advisory control will receive the inputs in Table 3.6, from which it will decide how to operate the system.

How the advisory control will use this information will be explained in detail in the advisory control chapter in Chapter 5. Before moving on to that chapter, the case study will be described next. There, the component selection and sizing are discussed.

Table 3.6: Required information at each simulation times step to simulate the system

System component	Required Variables/Parameters at each Δt
Wind turbine	Current power output [kW]
Electrolyzers	Number of electrolyzers For each electrolyzer the following information is required: Power rating [kW] Current operating mode [0: off, 1: idle, 2: on] Current power consumption [kW] Maximum ramp rate [%/s] Time to go from off to on [minutes] Time to go from idle to on [minutes]
Battery	Storage capacity [kWh] Current SOC [%] Maximum charge rate [kW] Maximum discharge rate [kW] Threshold to start charging battery [%] Threshold to stop charging battery [%]
Desalination system	Power rating [kW] Maximum volumetric outflow [m^3/s]
Water tank	Volumetric capacity [m^3] Current volumetric level as a function of the total capacity [%] Threshold to start filling water tank [%] Threshold to stop filling water tank [%]

[1]Assuming the production of 1 kg of H_2 consumes 54 kWh

4
Case-Study: Wind Turbine In The Aberdeen Bay Wind Farm

This chapter will provide details on the component selection and sizing. The parameters that were described in Chapter 3 will be quantified. The sizing of the wind turbine, electrolyzers, and desalination will be selected. The sizing of the battery will be site-specific and will be sized using site-specific wind data.

4.1. Site selection

The selected site for the case study is the Aberdeen Bay wind farm (ABWF), located approximately 3 kilometers off the coast of Aberdeen in the United Kingdom [37]. This site was selected because Vattenfall could provide 5-second resolution data from a single 8.8 MW wind turbine from the Aberdeen Bay wind farm.

It is important to note that the findings of this thesis project will not be exclusively site-specific. Although the power output will be site-specific and the sizing of the battery, the sizing methodology and the designed advisory control strategy will work for other locations. Furthermore, the overall findings will be applicable to other site locations.

4.2. Wind turbine

The system was designed as it would be commissioned in 2030 to make this thesis project relevant for future works. Therefore a 20 MW wind turbine will be used as the power source, as the rated capacity of wind turbines is expected to keep increasing (see Figure 2.2).

This selection has one important implication. The power output time series of the 8.8 MW wind turbine in the ABWF will need to be scaled to 20 MW. That was simply done by multiplying the power values in the time series by a factor of (20 MW / 8.8 MW) = 2.27. This makes an important assumption that the power output fluctuations of a 20 MW wind turbine are the same as an 8.8 MW wind turbine which will most likely not be the case, for reasons explained in the wind turbine component description in Section 2.2. Assuming that the fluctuations are the same is a conservative approach, however, and will make an interesting case study to see how well the electrolyzers and the designed advisory control can deal with the power output fluctuations.

For the economic assessment, Vattenfall provided a synthetic 20 MW power curve, meaning that it is a realistic power curve, but not from an actual wind turbine nor from a wind turbine supplier. The power curve is shown below in Figure 4.1

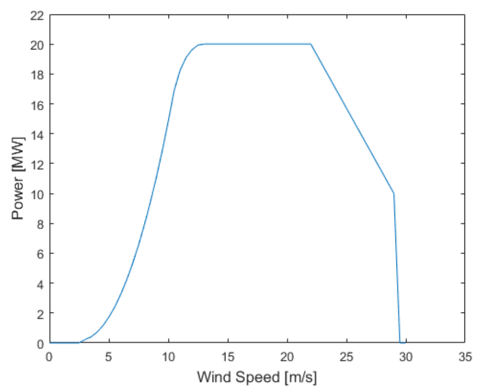

Figure 4.1: 20 MW Wind Turbine - Synthetic Power Curve

Important wind turbine attributes are shown below in Table 4.1. For example, the hub height is required to extrapolate wind data when the data is not from the same altitude as the hub height. In addition, the yearly availability factor becomes important for the economic assessment in Chapter 8.

Table 4.1: 20 MW Wind Turbine Attributes

Hub height [m]	165
Rotor diameter [m]	280
Cut-in wind speed [m/s]	3
Cut-out wind speed [m/s]	29.5
Rated wind speed [m/s]	13
Yearly availability factor [%]	97

4.3. Electrolyzer system

It will be taken as given that the electrolyzers will need to be able to match the wind turbine capacity, although that might not be economically optimal [38]. The two electrolyzer configurations that will be tested are:

- 4x5 MW
- 2x10 MW

In the PEM model implementation section, Section 3.2.2, a reference system-level efficiency curve was shown (Figure 3.3). That system-level efficiency curve cannot be directly used for two main reasons. Firstly, that system is based on a centralized electrolyzer platform connected to a whole wind farm, unlike the topology of this thesis which is hydrogen production at wind turbine level. Secondly, it includes additional compression, which is not included in the system design of the SAHO wind turbine. Therefore, an electrolyzer needs to be chosen to be suitable for offshore conditions and has publicly available information about the system level efficiency.

The most applicable electrolyzer identified was the HyLYZER500, a 2.5 MW electrolyzer from Cummins. It is a compact electrolyzer designed for outside conditions, although it was not specifically stated if it is suitable for offshore conditions. The important system characteristics are summarized below in Table 4.2.

The system specific consumption of $\leq$ 54 kWh/kg is noted to be at rated conditions and includes all auxiliary components such as rectifiers, control system, cooling, compression, and water and hydrogen purification [26]. Using the information that this system-specific consumption includes all auxiliary services, like the efficiency curve from Figure 3.3, that efficiency curve can be tailored to the HyLYZER500. However, based on discussions with Vattenfall experts and outside sources, a few changes were made.

Table 4.2: HyLYZER500 system characteristics [26]

	HyLYZER500
Rated power consumption	2.5 [MW] [39]
System specific consumption	$\leq$ 54 [kg/kWh]
Potable water consumption	13 - 17 [L/kg of H2]
Operating range	5 - 100 [%]
Footprint	18 x 11m
Installation environment	Outdoor 0.61x12.1m ISO container
Product setup	Outdoors (-20°C to 40°C)

Firstly, the minimum operating point was increased to 10% due to the electrolyzer units being larger than the HyLYZER500, 5, and 10 MW [4, p. 65]. Furthermore, the maximum operating point was increased to 120% based on the expectation that this type of PEM system could operate temporarily above its rated capacity in the future, albeit at a lower efficiency. Comparing the system specific consumption of 54 kWh/kg to the HHV value of hydrogen, 39.39 kWh/kg, the HHV efficiency at rated power is 72.3% for the HyLYZER500. The same was done for the system in Figure 3.3, which is comprised of Silyzer200 PEM electrolyzers with a combined rated power of 4 MW [36]. The difference between the Silyzer200 and HyLYZER500 is shown in Table 4.3. It can be seen that the HyLYZER500 has a 13% increase in HHV efficiency compared to the Silyzer200. The difference in efficiency is likely due to the transformers and compression, which are out of the scope of the HyLYZER500 system boundary. They are also not in the scope of the SAHO wind turbine.

Table 4.3: HHV efficiency of the Silyzer200 compared to the HyLYZER500

Electrolyzer	HHV Efficiency [%]
Silyzer200	64
HyLYZER500	72.3

The efficiency curve from Figure 3.3 was manually recreated, as it was not possible to obtain the actual data. The efficiency curve was then scaled to the system-level efficiency of the HyLYZER500. The result is shown below in Figure 4.2, where the x-axis shows the operating point of the electrolyzer compared to its rated power. As the figure shows, the HyLYZER500 only goes to 120%, while the Silyzer200 can operate at 150% of its rated power.

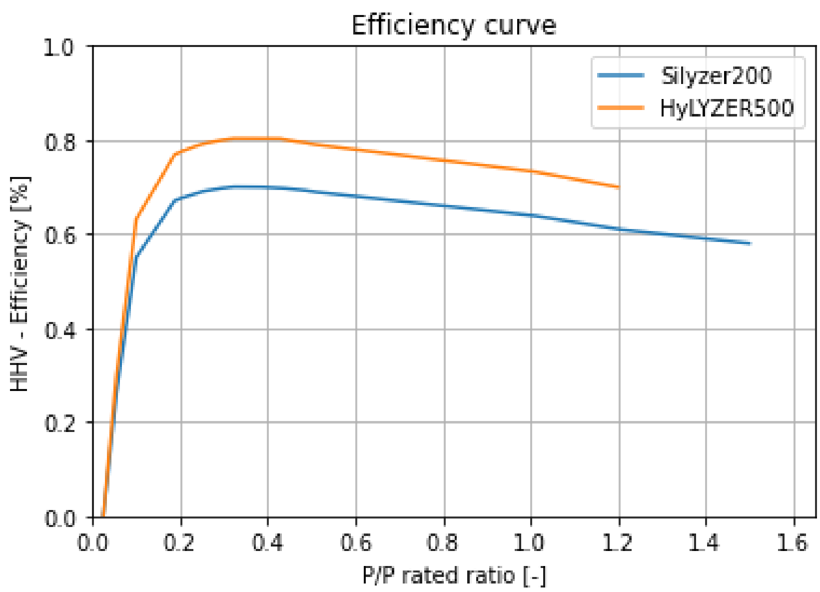

Figure 4.2: Manually created system level efficiency curve for the HyLYZER500

Using the efficiency curve of the HyLYZER500, it is possible to directly translate a power consumption of an electrolyzer to a hydrogen output. A concrete example of how a power input to the electrolyzer is translated to hydrogen output is provided in Appendix A.1.

A summary of the electrolyzer model input can be seen below in Table 4.4. Most of the values in Table 4.4 were found based on public sources such as reports or electrolyzer data sheets. The sources are included in the table. The only exceptions were the $P_{\text{elec,starting-up}}$ and $P_{\text{elec,idling}}$. No information about these values were obtained from public sources, but based on email discussions with an external electrolyzer supplier the value of $P_{\text{elec,starting-up}}$ and $P_{\text{elec,idling}}$ is estimated to be roughly 2% of $P_{\text{elec,rated}}$ [40].

Table 4.4: 5 MW and 10 MW electrolyzer system characteristics

Parameter	Generic value	5 MW electrolyzer	10 MW electrolyzer
$P_{elec,min}$	10% of $P_{elec,rated}$ [41]	500 kW	1000 kW
$P_{elec,max}$	120% of $P_{elec,rated}$	6 MW	12 MW
$Elec_{MaxRamp}$	10% of $P_{elec,rated}$/s [42]	500 kW/s	1000 kW/s
$Elec_{\text{WaterRequirement}}$	15 kg H_2O/kgH_2 [26, 20]	- || -	- || -
$\Delta t_{\text{Off-To-On}}$	5 minutes [4, p. 49] [43]	- || -	- || -
$\Delta t_{\text{Idle-To-On}}$	10 seconds [20]	- || -	- || -
$P_{\text{elec,starting-up}}$	2% of $P_{elec,rated}$ [40]	100 kW	200 kW
$P_{\text{elec,idling}}$	2% of $P_{elec,rated}$ [40]	100 kW	200 kW

4.4. Desalination system and water tank sizing

The rated power of the desalination system will be designed to deliver water to the water tank at the same rate as the electrolyzers withdraw water at their rated power. A 20 MW electrolyzer system, operating at full capacity for 1 hour, will produce roughly 370 kg of hydrogen[1].

$Elec_{\text{Water Requirement}}$ is assumed to be 15 kg per kg of hydrogen. Therefore, at rated power $\dot{V}_{\text{Water, Requirement for Hydrogen}}$ is 5.56 m^3/h[2]. The desalination system will therefore be required to deliver 6 [m^3/h] of desalinated water.

To know the power requirement of the desalination system, the energy consumption needs to be estimated. Water tap quality is roughly 300 Total Dissolved Solids in the units [mg/L] [44]. To reach a water quality of tap water level (300 - 500 mg/L) only a single stage sea water reverse osmosis is required. By adding a second stage, the water quality could be increased further to 15 - 130 mg/L[45, p. 10]. As water quality is vital for a good operation of the electrolyzer system, a two-stage seawater RO will be selected. Efficient two-stage seawater RO can have a specific energy consumption as low as 3 kWh per m^3 of water [45]. For this report, it will be assumed that the energy consumption of the desalination will be 3 kWh/m^3. Using Equation 3.5, the estimated rated power of the system is 18 kW.

The water tank will need to be sized with careful consideration of the loads that the wind turbine support structure can withstand. For the purpose of this thesis, the costs and load considerations of the water tank were not considered. The water tank was sized such that it would take roughly 7 hours to be fully drained. For a water consumption of 5.56 m^3/h, a water tank capacity of roughly 40m^3 was obtained.

Table 4.5: Desalination and water tank sizing

Parameter	Symbol	Sizing
Rated energy consumption	$E_{Des,Max}$	3 [kWh/m^3]
Rated power consumption	$P_{Des,Max}$	18 [kW]
Maximum volumetric flow rate	$\dot{V}_{\text{Water, Max, Des}}$	6 [m$^3/\Delta t$]
Water tank storage capacity	$V_{\text{Water tank}}$	40 [m^3]

[1]Assuming the production of one kilogram of hydrogen consumes 54 kWh
[2]370 kg H_2/hour * 15 kg H_2O/kg H_2 = 5,555 kg H_2O/hour $\approx$ 5.56 m^3 H_2O/hour.

4.5. Battery selection, and sizing

The key question for the battery sizing is how much energy capacity should the battery system have. That will be dependent on the estimated energy consumption of the components when the wind turbine is not producing power. The following sub-section will describe the consumptions of the individual components, which will be followed by the battery sizing.

4.5.1. Auxiliary power consumption

Wind Turbine

As discussed in Section 2.5, offshore wind turbines have components that require access to electricity when the wind turbine is not producing power.

Some public information could be found on the typical auxiliary consumption of wind turbines. For example, a 6 MW wind turbine from REpower, has an average load demand of 42 kW and a peak load demand of 193 kVA [29, p.16]. This is roughly in alignment with data from Vattenfall for wind turbines close to 10 MW. If operated autonomously for 24 hours with a 42 kW consumption, the consumed energy is 1008 kWh, which is quite a large consumption. This is considering grid-connected wind turbines, however. When considering self-sustainable wind turbines, this self-consumption might be optimized to decrease this consumption. In consultation with Vattenfall engineers, it was assumed for the purpose of this study that the daily critical consumption for a 9 MW wind turbine is around 30 kWh per day.

For the case study of a 20 MW wind turbine, the critical auxiliary power consumption will be assumed to be linearly proportional to the energy consumption of a 9 MW wind turbine. Therefore, a value of 67 kWh per day was used[3]. If evenly distributed throughout the day, that results in a constant consumption of 2.8 kW. Take note, that this is an average consumption.

Electrolyzer

Very limited information could be found on the auxiliary power consumption of electrolyzers. Data sheets of PEM electrolyzers from Cummins [26] mentioned auxiliary installed power, but there was no clear trend in how these consumptions scaled with size. A 5 MW indoor unit had 40 kVA, while a 3 MW and 1.5 MW outdoor units both had 125 kVA. Furthermore, it was not clear what exactly this auxiliary installed power stood for and if they were critical to being supplied. Attempts to reach out to electrolyzer suppliers were not successful. For simplicity, it will be assumed that the critical auxiliary power consumption of electrolyzers should be in the same order of magnitude as the wind turbine. Therefore a value of 2 kW was assumed for an electrolyzer configuration with a total capacity of 20 MW.

Battery

A leading Li-ion battery supplier indicated that battery packs have auxiliary power demand as well, to power heating, ventilation, air conditioning and control system functions. Those consumptions need to be supplied at all times. If the wind turbine is producing power, the battery is not supplying the power to the critical auxiliary components of the entire system. In that case, the battery is on stand-by and the consumption for that operating mode is 1 kW for a 281 kWh battery. If the battery is supplying power to the critical auxiliary components, the battery is operational, and then the auxiliary consumption of the battery increases to 2 kW.

Desalination

No information was found on the critical auxiliary power consumption of the desalination system. As a simplification, this has been assumed to be negligible, and the desalination system is treated as an on/off system with no critical auxiliary power consumption.

Component Summary

In Table 4.6, the critical power consumption of all the components in the system is summarized. It can be seen that when the wind turbine is producing power, a 5.8 kW consumption is withdrawn from the available power from the wind turbine. If the wind turbine is not producing power, then the battery is operating the system and a constant power consumption of 6.8 kW is withdrawn from the energy storage capacity in the battery.

[3] 30 kWh * $\frac{20MW}{9MW}$

Table 4.6: System critical auxiliary consumption

System Component	Critical Auxiliary Power Consumption [kW]
Wind Turbine	2.8
Electrolyzers	2
Battery	1-2 (depending on operating mode)
Desalination	0
Total	**5.8 - 6.8**

This sub-section on auxiliary power consumption has shown that a 6.8 kW power source is required from the battery when it is keeping the critical auxiliary components running. For a whole day, a 6.8 kW power consumption is equivalent to withdrawing 163 kWh of energy.

To reach a conclusion on the size of the energy storage in the battery, it is required to get an estimate of the frequency distribution of consecutive idle time, where the battery would need to supply power to the critical auxiliary components. The following sub-section will address this.

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4.5.2. Battery sizing

Consecutive idle time

One method to size the battery is to ensure that the battery can supply power to the critical auxiliary components for a given period, at all times [46]. To estimate the period for which the battery should be able to autonomously supply power, the frequency distribution of the consecutive idle time is required, as well as the worst-case scenario.

Consecutive idle time is when the wind speed is consecutively below the cut-in wind speed, or above the cut-out wind speed. For the 20 MW wind turbine, as described in Table 4.1, the cut-in and cut-out wind speeds were 3 m/s and 29.5 m/s, respectively. The worst-case scenario, will be selected as the 30-year extreme consecutive idle time.

Frequency distribution

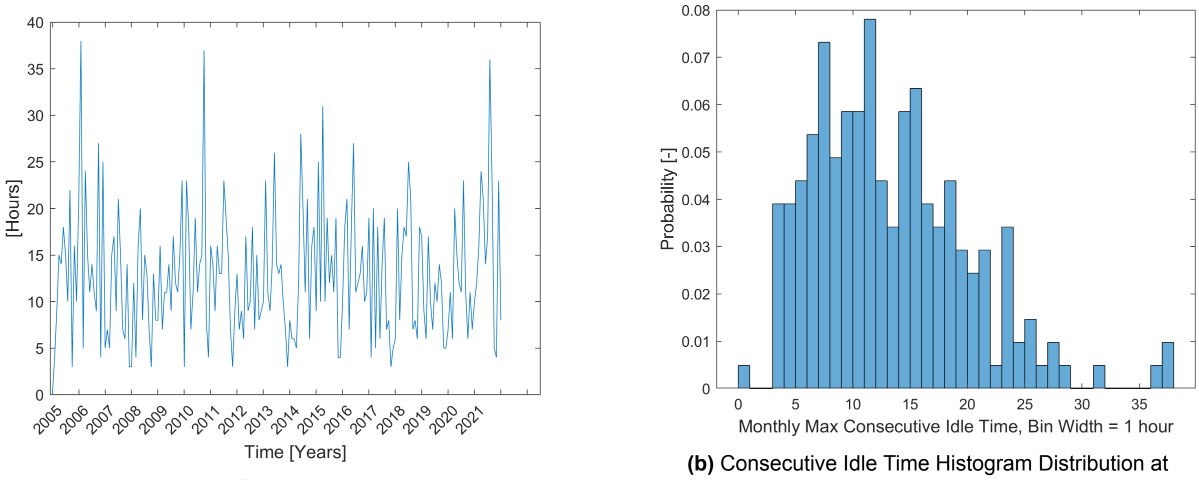
The frequency of consecutive idle time is site-specific, as the local wind climate will determine how often such idle times occur. For the case study of the Aberdeen Bay Wind Farm, Vattenfall provided access to 1-hour resolution data from ERA5 (European Centre for Medium-Range Weather Forecasts, Reanalysis, 5th generation), for a 17-year period, from 2005-2021. The data is based on an altitude of 100m. Therefore, it was required to extrapolate those wind speeds to the hub height altitude of the 20 MW wind turbine.

For altitudes above 100m, the increase in wind speed with height is modeled with the power law, as

$$U(H) = U(H_{ref}) * (\frac{H}{H_{ref}})^{\alpha} \tag{4.1}$$

, where $U(H_{ref})$ is the known wind speed at a reference height H_{ref}, and α is the power law exponent which governs how the wind speed varies with height [47]. The parameter α varies with elevation, time of day, season, and wind speed, just to name a few, and therefore is quite an uncertain parameter [47]. At sea conditions, it is estimated that, on average, α takes a value of around 0.10-0.11 [48]. For the purpose of extrapolating the known wind speed at 100m height to the hub height value of 165, α was set to 0.11.

Using the extrapolated wind speeds, monthly maximum consecutive idle times were stored. In Figure 4.3a, the monthly maximum consecutive idles times from 2005 - 2021 are depicted. The figure shows that not once was the consecutive idle time greater than two days, with the maximum occurred value being 38 hours. The majority of the monthly maxima are between 5 - 25 hours. This can more clearly be seen in a histogram, as is shown in Figure 4.3b. Figure 4.3b, shows that more data points are required to get a higher resolution frequency distribution, but it does show the rough outline of the distribution.



(a) Monthly Maximum Consecutive Idle; 2005 - 2021

(b) Consecutive Idle Time Histogram Distribution at HubHeight = 165m

Figure 4.3: Aberdeen Bay Wind Farm
Consecutive idle time analysis

Another methodology to size the battery is to use statistical methods to estimate the 30-year extreme consecutive idle time. For example, in the wind energy industry, estimating the 50-year extreme wind speed is required for support structure load calculations [49]. In the latest version of the IEC-61400-1 (3rd edition), an extreme wind speed is defined as the value of the highest wind speed, averaged of *t* seconds, with an annual probability of exceedance of 1/N (where N is the recurrence period, in years) [49]. The aim is then to identify the maximum wind speed, which is on average exceeded once every 50 years. This same methodology can be applied to the ERA5 data to determine the maximum consecutive idle time, which is exceeded on average once every 30 years.

As referred to in the IEC standard, annual maxima are usually used, but for this simplified analysis, the monthly extremes will be used instead to increase the number of samples. By sorting the monthly extreme values, in Figure 4.3a, from low to high, a distribution is obtained (can be seen in Figure C.1a). From this distribution, it is possible to estimate the probability of exceedance for the observed values and, from there, the recurrence of the observed monthly maximas. An important assumption is that this distribution is representative of the site, such that any future occurrences do not deviate significantly from the distribution. Using a Matlab script, provided by a TU Delft course along with the permission to use it, the recurrence was firstly calculated, and a line was fitted to the data using the least square method. That is possible because a roughly linear trend is observed when plotting the recurrence with a logarithmic scale, as can be seen in Figure 4.4. A trend line is then fitted to the roughly linear trend, and the resulting linear fit along with the obtained 30-year extreme consecutive idle time can be seen below in Figure 4.4. From Figure 4.4, it can be seen that with a recurrence rate of 360 months on the x-axis, the 30-year extreme is 47 hours. These results indicate that the battery should be sized such that it can operate the system for two days. For a more detailed description of how this 30-year extreme analysis was performed, see Section C.1.

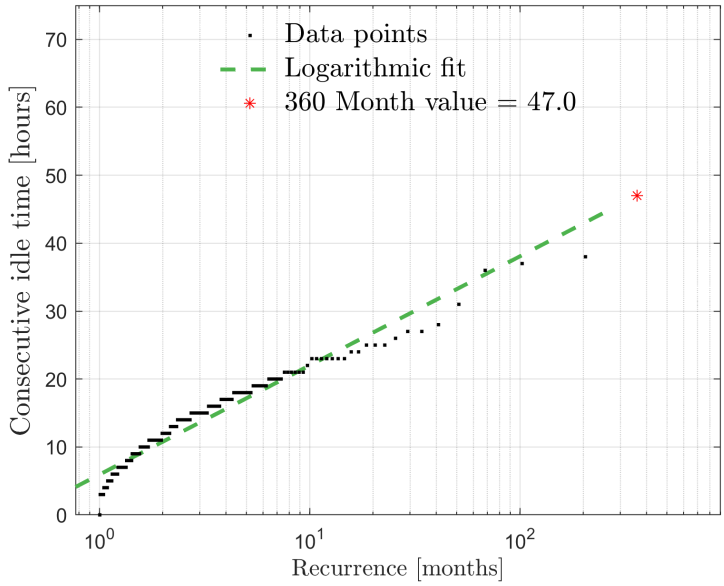


Figure 4.4: Aberdeen Bay Wind Farm: 30-year extreme consecutive idle time

For the battery selection, it was decided to use the characteristics of the NorthVolt Voltpack Mobile. It is a currently available large scale battery which can serve as an interface for auxiliary systems, and has a peak-shaving capability [50]. The characteristics of a single unit can be seen below in Table 4.7.

Table 4.7: NorthVolt Voltpack Mobile characteristics [50]

Installed Capacity [kWh]	281
Max Load Power (Peak Shave) [kW]	275
Dimensions [m]	1.6x2x1.2
Weight [kg]	3000

As the battery system needs to supply 6.8 kW to the critical auxiliary components for up to 2 days, the minimum storage capacity is 326 kWh. Considering that a single NorthVolt battery has a storage capacity of 281 kWh, it is required to use two such batteries resulting in a total storage capacity of 562 kWh.

Now that the case study has been defined, along with the component selection and sizing, the advisory control can be designed. That is the topic of the next chapter.

5 Advisory Control Strategy

This chapter will go over the designed advisory control strategy that was developed for the stand-alone hydrogen-only wind turbine. Firstly, a literature review of the published articles on advisory control strategies for coupling hydrogen to renewable power generation is summarized in Section 5.1. The designed advisory control strategy is then described in Section 5.2. That section will start with a top-level description of the logic and then describe each part of the logic separately except for the electrolyzer operation control. That is discussed in Section 5.3, where two operational strategies are summarized. In Section 5.4, the workings of the entire logic will be shown with the aid of simulation figures.

5.1. Advisory control literature review

The design of the advisory control is one of the main topics of this thesis project. Therefore an extensive literature review was performed on the developed advisory control strategies for coupling hydrogen production with renewable power generation. The literature review was not only focused on stand-alone wind-hydrogen systems but also on grid-connected systems to increase the number of relevant sources. Only the most relevant publications will be summarized here.

Two main methods were identified in the literature. Model Predictive Control (MPC) and rule-based control. MPC is an optimization strategy where for each simulation time step, the controller solves an optimization problem, considering predictions of the future. Rule-based control strategies are simple but robust, using predetermined rules based on some easily measured metric to operate the system, such as the wind turbine power output or the status of charge of the battery.

MPC is considered effective when utilizing forecasts, such as for electricity prices or the weather. In literature, it is mostly used for systems where there are many degrees of freedom, for example, grid-connected systems where the wind farm needs to supply a local load. In such systems, hydrogen is used as energy storage for later use, and the controller aims to maximize revenue by deciding whether to sell electricity to the grid or produce hydrogen. Furthermore, operational aspects such as component degradation, maintenance, and operating costs can be considered. This has been extensively documented and tested by a project called Haelous, in [51, 52, 19]. The results showed that this type of controller could minimize switching times, supply the local load by the wind farm and fuel cells and maximize revenue by selling energy to the grid during times of excess energy when the electricity price is high.

Although current MPC publications on coupling hydrogen and renewable energy have not been focused on pure hydrogen production, it was mentioned by Abdelghany et. al (2021) as a recommendation for future research [19]. One such publication was found for pure hydrogen production based on coupling wind and wave energy to an alkaline electrolyzer [53]. The resulting controller managed to maximize hydrogen production and minimize the switching times. All of the identified MPC publications were found to be based on time steps of 1 hour, however, which raises the question of whether such controllers and the results depicted an accurate result of minimized switching times.

The second methodology, which will be used for this thesis, is to use predetermined rules based on easily measured metrics. The only publications on the operational strategies for stand-alone hydrogen-producing wind turbines were using rule-based strategies and were from Dutton et. al [54], and Valenciaga et. al [55], published in 2000 and 2010 respectively. Both publications used the SOC of the battery as a key operation metric along with the operating limits of the electrolyzer. However, both reports are quite outdated and used very strict operational limits for the alkaline electrolyzers.

A more recent publication on such a strategy, by Fang et. al (2019), researched coupling alkaline electrolyzers with a grid-connected wind farm with the aim of reducing the switching times while increasing the hydrogen production [22]. The hydrogen production units were operated when the wind farm was producing more power than the power demand from the grid. The proposed strategy used thresholds based on the electrolyzer rated capacity that the excess power needed to be surpass before turning electrolyzers on. The philosophy of the designed control strategy is simple and robust, but the results were not compared to other high-performing strategies. Hence it was not clear whether that was the best strategy. Furthermore, a time sampling of 1 hour was used.

Based on the literature review, it became clear that a lot of work has been done on the advisory control strategies for many hybrid renewable energy systems, but there are limited published articles for a stand-alone offshore wind turbine coupled with a PEM electrolyzer. Furthermore, there is a need for a better understanding of how the designed control strategy can deal with instantaneous power output fluctuations, with a time step in the order of seconds. The following sub section will describe the designed advisory control strategy which will be tested in this thesis project.

5.2. Advisory control logic description

This section will describe the designed advisory control strategy. The advisory control controls all the components and thereby governs the flow of energy, water, and hydrogen. Using the component sizes and case study definition in Chapter 4, the advisory control will, for each simulation time step, receive the inputs, summarized in Table 3.6, from which it will take decisions on how to operate the system.

5.2.1. Advisory control high level description

In Figure 5.1, a flowchart is depicted, which illustrates the main workings of the advisory control logic. The following paragraphs will describe step by step what is happening in Figure 5.1.

When all the required inputs, as summarized in Table 3.6, have been provided to the advisory control, the system model can simulate the system performance based on the actions that the advisory control takes. When entering the advisory control logic, the first thing that the controller checks is if the wind turbine is producing active power which is greater than the auxiliary power consumption and electrolyzer idling- and starting up- consumption,

$$P_{WT} > (P_{Aux} - \sum P_{elec,idling} - \sum P_{elec,starting-up}) \tag{5.1}$$

If not, the battery will take over and manage the system autonomously, using the logic *Battery Autonomous Operation Control*. If there is an additional storage element capable of keeping electrolyzers starting up and idling, then the logic *Additional Storage Element Control* is entered, after which this control loop is exited and then restarted in the next simulation time step. In case the wind turbine is producing enough power, the advisory controller withdraws the auxiliary power, and in case an electrolyzer is in idle operation or starting up, those respective consumptions are withdrawn,

$$P_{remain} = P_{WT} - P_{Aux} - \sum P_{elec,idling} - \sum P_{elec,starting-up} \tag{5.2}$$

Next, there are two state variables, $\delta Filling$ and $\delta Charging$, for the water tank and battery, respectively. The value of these state variables are 0 in case these components are not being filled/charged and 1 in case they are. If the water tank storage, $SOC_{\text{WaterTank}}$, goes below a threshold selected by the advisory control, then $\delta Filling$ is set to one, meaning the desalination system is turned on. When the desalination system is turned on, the control logic *Water Tank Control* is entered, which withdraws the required power to run the desalination system from P_{Remain}.

$$P_{remain} = P_{remain} - P_{Des}$$

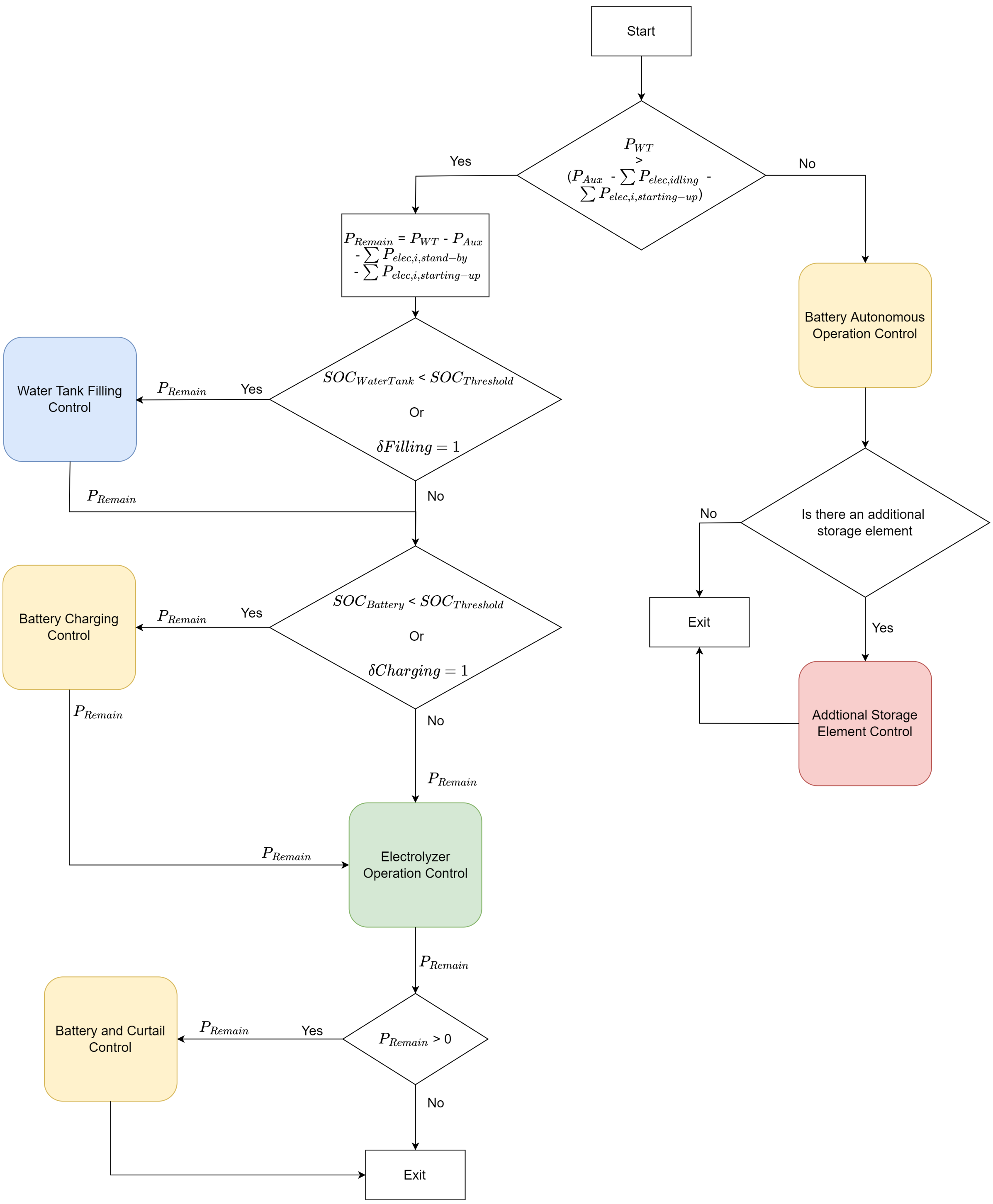


Figure 5.1: Advisory control top view - flow chart

The value of $\delta Filling$ stays equal to one until the water storage level has increased to a desired upper threshold such as 90 or 95% of the water tank storage capacity. The exact same approach is used for the battery. If the SOC goes below a certain threshold, $\delta Charging$ is set to one, and the control logic *Battery Charging Control* is used. The *Battery Charging Control* logic charges the battery and withdraws the required power for charging from P_{Remain} until the selected upper threshold of the SOC_{Battery}

is reached. This is followed by the *Electrolyzer Operation Control*, depicted in the green box. The *Electrolyzer Operation Control* attempts to utilize the remaining active power for hydrogen production. Therefore, most of the time, all the available power within P_{Remain} is consumed by the electrolyzers. There are certain times, however, when the electrolyzers cannot capture all the remaining power. For example, if no electrolyzer is operational to capture the power. After leaving the *Electrolyzer Operation Control*, the advisory control checks if P_{Remain} is greater than zero, meaning there is still remaining power to distribute. If not, the control loop is exited. If there is remaining power, the advisory control enters the *Battery and Curtail Control*, whose purpose is to capture the excess energy in the battery in P_{Remain}. If there is more excess power than the battery can capture, then the remaining power is curtailed.

A few of these control logic blocks will be described in greater detail in the following sub-sections, but for the *Water Tank Filling Control* and *Battery Charging Control* the descriptions above are deemed enough.

5.2.2. Battery autonomous operation

The *Battery Autonomous Operation*, is entered when the wind turbine is not producing enough active power. Then, the battery has the sole purpose of discharging its stored energy to operate the critical auxiliary components, as was described in Section 3.4. If the stored energy in the battery gets fully drained, all components are fully turned off. That is a scenario that the advisory control strategy should ensure does not happen. A flowchart of the *Battery Autonomous Operation* describing the logic can be seen in Figure B.7.

5.2.3. Battery and curtail control

The purpose of the *Battery and Curtail Control* is to capture the excess power in the system. The battery is constrained by three factors. Firstly, it can only perform one action per simulation time-step. Therefore if it has already been charged/discharged during this simulation time-step, it cannot capture the excess energy. Secondly, as explained in Section 3.4, the battery has a maximum charge rate and, lastly, a maximum storage capacity. The battery will only capture excess power up to its maximum charge rate, and it considers how much storage capacity is remaining. A flowchart of the *Battery and Curtail Control* describing the logic can be seen in Figure B.8.

5.3. Electrolyzer operation control: Strategy 1 and 2

One of the key questions to answer for the electrolyzer operation control is how to operate multiple electrolyzer units simultaneously. That task can be divided into two main areas. Firstly, if there is more than one electrolyzer producing hydrogen, how should the advisory control split the P_{Remain} between them. Secondly, the advisory control needs to decide when to turn on the electrolyzers, when to set them to idle, and subsequently turn them off. The next two subsections will shed light on those two aspects.

5.3.1. Distributing power between multiple electrolyzers

An exercise will be performed where different configurations of power distributions will be tested to answer the question of how to split the available power between multiple operational electrolyzers. The example will analyse a 20 MW wind turbine producing 15 MW of power with 4x5 MW PEM electrolyzers. The aim of the exercise is to maximize hydrogen production. An important assumption is made that the efficiency curves of all electrolyzers are the same and will take the shape of the HyLYZER500 electrolyzer efficiency curve shown in Figure 5.2.

In Table 5.1, a comparison is made between four different power distributions between the four electrolyzers and how that affects the hydrogen production. Table 5.1, shows that the more evenly the power is distributed between the electrolyzers, the more hydrogen is produced. The hydrogen production increases because their operating points decrease by evenly splitting the power between the electrolyzers. As already discussed in Section 3.2.1, and shown in Figure 5.2, the maximum efficiency point is in the partial load region of around 25-40% of the rated capacity. That shows that the advisory control should evenly distribute the energy between the electrolyzers in an attempt to operate them together in the partial load region, which has the highest efficiency.

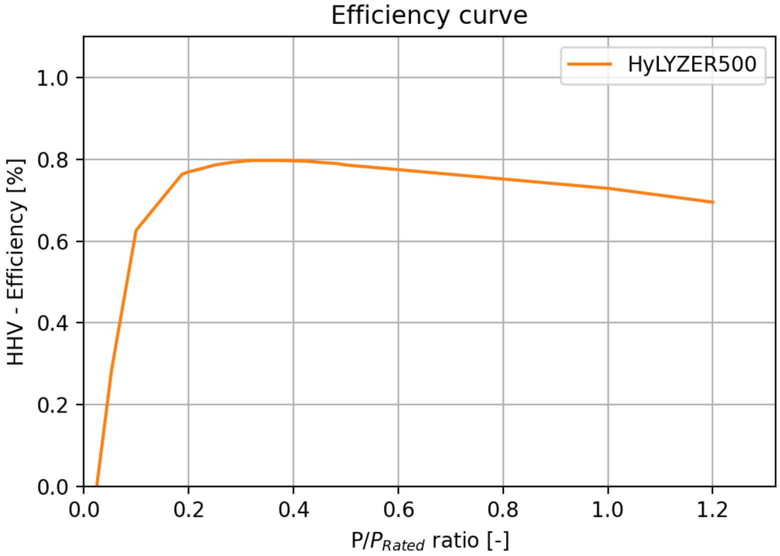


Figure 5.2: Manually created efficiency curve of the HyLYZER500, tailored to the curve from [36]

Figure 5.2 also shows that the efficiency drops steeply as the electrolyzers start operating below 20%. That touches upon the second key question for the electrolyzer operational control, when is it better to turn off an electrolyzer and allow the other remaining electrolyzers to ramp up and obtain higher efficiency. This effect is shown in Table 5.2, where the exercise is considering when the wind turbine is producing 5000 kW and the advisory control can utilize all of that power for hydrogen production, $P_{Remain} = 5000kW$. The results show that running four electrolyzers produces less hydrogen than running three electrolyzers, but only marginally. The key take-away from this small exercise is that when multiple electrolyzers are operating, the advisory control will split the power evenly between the electrolyzers. Then, when the power from the wind turbine is ramping up or down, the advisory control will need to decide whether to turn an electrolyzer on or off or make do with the already operational electrolyzers. That will be the topic of the next subsection.

Table 5.1: Comparing the effect of different power distributions between electrolyzers on hydrogen production - case 1

P_{Remain} [kW]	$P_{Elec,1}$ [kW]	$P_{Elec,2}$ [kW]	$P_{Elec,3}$ [kW]	$P_{Elec,4}$ [kW]	H_2 Production [kg/Hour]
15000	5000	5000	5000	0	277.6
15000	5000	5000	2500	2500	284.8
15000	5000	3333.3	3333.3	3333.3	287.2
15000	3750	3750	3750	3750	288.4

Table 5.2: Comparing the effect of different power distributions between electrolyzers on hydrogen production - case 2

P_{Remain} [kW]	$P_{Elec,1}$ [kW]	$P_{Elec,2}$ [kW]	$P_{Elec,3}$ [kW]	$P_{Elec,4}$ [kW]	H_2 Production [kg/Hour]
5000	5000	0	0	0	92.5
5000	2500	2500	0	0	99.7
5000	1666.7	1666.7	1666.7	0	101.1
5000	1250	1250	1250	1250	99.7

5.3.2. Turning the first electrolyzer on, off and to idle

The main goal of the advisory controller is to maximize hydrogen production and ensure that the system is operated well regarding its lifetime and degradation. It is important to prevent frequently turning electrolyzers on and off as it accelerates component degradation, as was described in Section 2.3. The next sections will describe two different strategies for when to turn electrolyzers on and off. But first, this section will describe how to operate the first electrolyzer as that will be the same for both strategies. Important terminology for the designed advisory control strategies, which will be used extensively throughout this chapter and the rest of the report, is summarized below:

- Turn-on threshold: A threshold that the wind turbine power output or electrolyzer power consumption needs to surpass to turn an off electrolyzer on. That threshold is always lower than the turn-on-from-idle threshold. Therefore it will never happen that an off electrolyzer is turned on if there is already an idling electrolyzer. The idling electrolyzer will first be turned back on.
- Turn-on-from-idle threshold: A threshold that the wind turbine power output or electrolyzer power consumption need to surpass to turn an idling electrolyzer back on.
- Turn-to-idle threshold: If the electrolyzer power consumption drops below the turn-to-idle threshold, the advisory control will set one electrolyzer to idle.
- Turn-off threshold: A threshold that is used when there is only one electrolyzer operational. If the wind turbine power output drops below this threshold, the first electrolyzer is fully shut down.

The first electrolyzer will be turned on when the wind turbine power output exceeds 20% of the electrolyzer rated power. The minimum operating point of a single electrolyzer is estimated to be 10% of its rated capacity, as described in Table 4.4. In case the electrolyzer is off, setting the turn-on threshold of the first electrolyzer to 20% will provide a margin of 10% from the minimum operating point in an attempt to prevent the situation that the wind speed ramps down while the electrolyzer is turning on.

When the electrolyzer has been turned on, it is the only operational electrolyzer. Therefore there is nothing to gain by turning the electrolyzer to idle or off. The first electrolyzer is therefore kept on unless the power consumption drops below the minimum operating point of 10%, after which the electrolyzer has to be set to idle.

If the electrolyzer has been set to idle, there is again nothing to be gained by turning it off. Therefore the electrolyzer is only turned off if the wind turbine power output drops below the idle consumption of 2% of the electrolyzer rated power.

The only remaining consideration is when to turn the idling electrolyzer back on. It was decided to set the turn-on-from-idle threshold of the first electrolyzer to 15% of the electrolyzer rated power. The number of switches from idle to on, and on to idle are assumed to not negatively impact the system lifetime. Therefore, with the aim of producing as much hydrogen as possible, it was decided to lower the turn-on-from-idle threshold to 15% compared to 20% for the turn-on threshold. These values are summarized below in Table 5.3, showing the thresholds that the wind turbine power output need to surpass or drop below for the corresponding actions to happen.

Table 5.3: First electrolyzer operational thresholds

Turn-on threshold	20% of electrolyzer rated capacity
Turn-on-from-idle threshold	15% of electrolyzer rated capacity
Turn-to-idle threshold	10% of electrolyzer rated capacity
Turn-off threshold	2% of electrolyzer rated capacity

When to turn the next electrolyzers on is not as straightforward because there is a trade-off between turning electrolyzers on early to capture efficiency gains and more frequent turn-offs. There are two simple ways for the advisory controller to base its decision on when to turn the next electrolyzer on. Firstly, the controller could measure and analyze the wind turbine's power output as is done for the first electrolyzer. An alternative way is to analyze the power consumption of the electrolyzers as in [22]. The resulting outcomes are exactly the same, and for this thesis project, it was decided to base the decision on the power consumption of the operational electrolyzers. For example, if there are two electrolyzers, the controller will monitor the power consumption of the first electrolyzer to make a decision when to turn the second electrolyzer on. The third electrolyzer will be turned on based on the power consumption of the second electrolyzer and so on for additional electrolyzers. As the operational electrolyzers operate at the same point, that is equivalent to looking at the power consumption of all operational electrolyzers. For a more detailed explanation, see the implementation description in Appendix B.

Before moving on to the description of the two designed strategies, one important clarification needs to be made. It was decided to turn electrolyzers off as a consequence of turning an electrolyzer to idle. The advisory control will decide when to turn electrolyzers to idle operation and then only allow one electrolyzer to be idling as it consumes energy. Therefore, whenever an electrolyzer is set to idle, the advisory control will check whether there is already an idling electrolyzer. If that is the case, the already idling electrolyzer is fully turned off.

The following two strategies will differ on the selected turn-on thresholds that the electrolyzer power consumptions will need to surpass before turning the next electrolyzer on from an off state. This power consumption threshold will be labelled as $P_{NextOneOn}$. The same goes for the turn-to-idle threshold, which will be labelled as $P_{TurnToIdle}$. When the power consumption of the electrolyzers drop below that threshold, an electrolyzer is set to idle.

5.3.3. Strategy 1: Constant thresholds

One of the most simple strategies is to have the turn-on and turn-to-idle thresholds constant. With a higher turn-on threshold, greater power consumption from each electrolyzer is needed before the advisory control turns the next electrolyzer on. That in turn, makes it less likely that an electrolyzer gets turned on, just to be turned to idle again if the wind turbine power output ramps down. An example of this strategy would be a turn-on threshold of 75%. That means that when an electrolyzer´s power consumption has reached 75% of its rated power, the next electrolyzer will be turned on.

Then there is the turn-to-idle threshold. For example, a turn-to-idle threshold of 15% means that one electrolyzer will be set to idle if the power consumption of the operating electrolyzers has dropped below 15% of their rated power. As the electrolyzers all operate at the same point, they will all have dropped below 15% of their rated capacity, but only one electrolyzer will be set to idle. That will allow the other electrolyzers to ramp up above the turn-to-idle threshold because their will be surplus energy available. When an electrolyzer is set to idle, its power consumption will decrease to the idle consumption of 2%, as described in Section 4.3. Therefore, if the turn-to-idle threshold was 15%, there will be a surplus of 13% of the electrolyzer rated power in the system after an electrolyzer is set to idle. If the wind turbine power output keeps ramping down, causing the other operational electrolyzer to drop again below the turn-to-idle threshold, another electrolyzer will be set to idle and the already idling electrolyzer is fully shut off.

Another important consideration is when to turn idling electrolyzers back on when there is more than one electrolyzer operational. Table 5.3 showed that when there is only one operational electrolyzer, and that electrolyzer is idling, it is turned back on when the wind turbine power output surpasses 15% of the electrolyzer rated power. That is a different scenario, however, because when there is more than one operational electrolyzer, some power will be redirected from the turned on electrolyzer to the previously idling electrolyzer such that they will end up with equal power consumption. For all versions of this strategy, the turn-on-from-idle threshold will be set to 50% when there is more than one operational electrolyzer. For example, with one electrolyzer producing hydrogen and one electrolyzer in idle, when the power consumption of the turned on electrolyzer surpasses 50% of its rated power, the idling electrolyzer is turned back on and both electrolyzers will operate at the operating point of 25%. The value of 50% was chosen based on an analysis comparing the effect of different turn-on-from-idle thresholds, which will be explained in Section 5.3.4.

Strategy 1 can have any setup of different turn-on and turn-to-idle thresholds, and that will be referred to as different versions of strategy 1. It is not obvious which version of strategy 1 will perform best. That is, which turn-on threshold coupled with which turn-to-idle threshold will perform the best with regards to hydrogen production while also having few turn-offs. To get a clear view of the performance of different versions, all integer turn-on threshold, $P_{NextOneOn}$, from 60 - 100% will be coupled with turn-to-idle threshold, $P_{TurnToIdle}$, in the range of 10-20%, resulting in 451 different versions that will be tested and compared. This will be explained in more detail in Chapter 6 where the results will be shown.

5.3.4. Strategy 2: Require a certain efficiency gain

Strategy 2 will use the system efficiency curve in an attempt to create a better strategy than strategy 1. To get an understanding of the effect of turning an electrolyzer on, it is possible to analyze the difference in system efficiency of operating different number of electrolyzers. As the modeling chapter showed, the HHV efficiency of a PEM electrolyzer is a function of its power consumption, $f(P_{elec})$. But with multiple electrolyzers, the overall HHV efficiency also depends on the number of operational electrolyzers. When assuming the power is split evenly between the operational electrolyzers, the efficiency can be calculated as

$$\eta_{Production} = f(\frac{P_{Remain}}{N}) \tag{5.3}$$

where N is the number of operational electrolyzers, and P_{Remain} is the remaining power that is left to distribute to the operational electrolyzers. By using Equation 5.3, it is possible to plot the production efficiency curves of different numbers of operational electrolyzers with increasing wind turbine power output. This is shown in Figure 5.3, which compares four 5 MW electrolyzers for a 20 MW wind turbine. It is important to note that each electrolyzer is assumed to be able to operate up to 120% of its rated power capacity. Therefore one 5 MW electrolyzer can operate up to 6 MW.

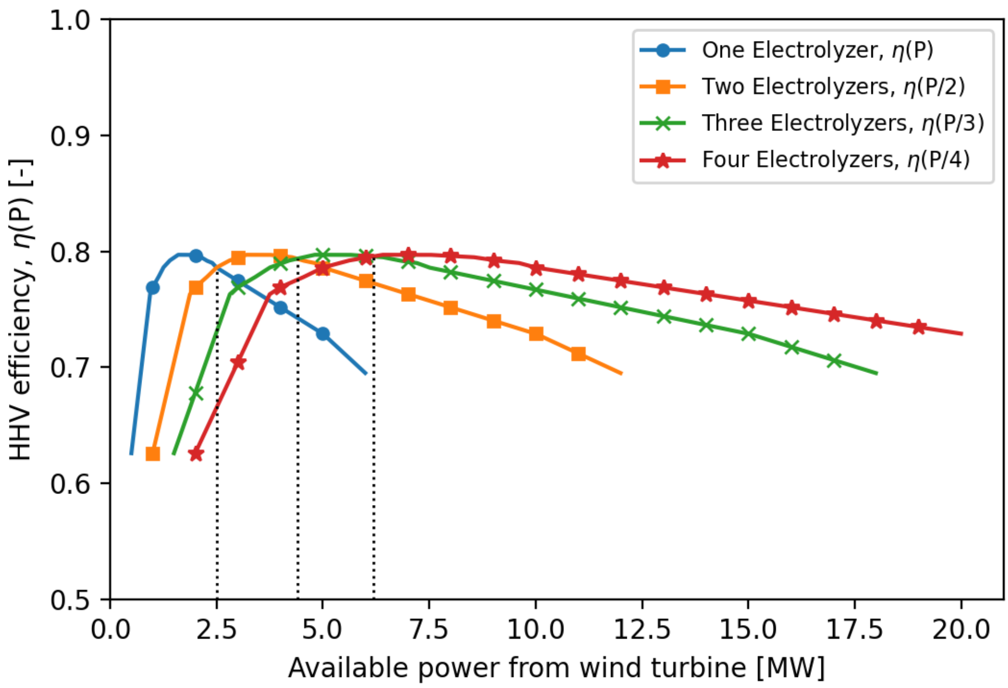


Figure 5.3: Production efficiency with different number of operational 5 MW electrolyzers. Each electrolyzer can operate until 120% of their rated power.

From Figure 5.3, it can be seen that for every power output from the wind turbine, there is an optimal number of operational electrolyzers with regards to the HHV efficiency. The vertical dotted lines show where the efficiency curves of different numbers of operational electrolyzers cross. Figure 5.3, also shows that the magnitude of the difference between the efficiency curves starts to decrease as more electrolyzers become operational. When more electrolyzers become operational, the advisory control will direct power from the other operational electrolyzers towards the newly turned on electrolyzer until all operational electrolyzers are operating at the same point. Each additional electrolyzer will therefore have a smaller relative impact on lowering the operating point [1].

[1] For example, if turning the second electrolyzer on when the first electrolyzer is at 100%, both electrolyzers would operate at 50%. Then if turning the third electrolyzer on, when the first and second electrolyzers are at 100%, all three would operate at 67%.

Strategy 2 will utilize the information that each additional electrolyzer has a lower relative impact and turn electrolyzers on and to idle, depending on how much efficiency is gained by those actions. In Figure 5.4, the efficiency gain of turning an electrolyzer on is shown. For example, the yellow dashed curve shows the efficiency gain of turning the second electrolyzer on (it is the difference in efficiency between the orange curve with squares and the blue curve with circles in Figure 5.3). When the value on the dashed orange line is greater than zero, it is more efficient to run two electrolyzers compared to one, while on the other hand, if the value is negative, it is more efficient to run one electrolyzer. The same logic goes for the green dotted curve in Figure 5.4, which compares the difference between having three operational electrolyzers instead of two from Figure 5.3.

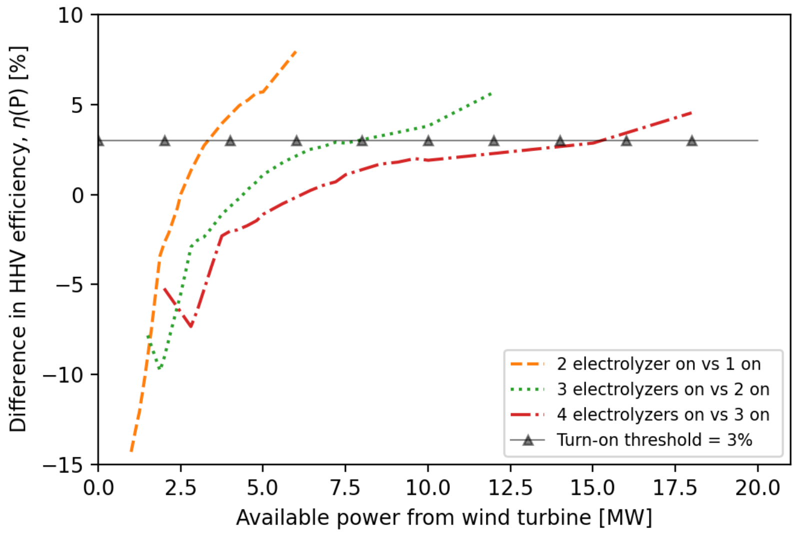


Figure 5.4: Efficiency gain comparison with different number of operational electrolyzers. Each electrolyzer has a rated capacity of 5 MW but can be operated up to 120%

To provide an example of how this strategy will work, consider the vertical line in Figure 5.4. It is the example of requiring a 3% efficiency gain for turning an electrolyzer on. The turn-on thresholds are selected based on where the 3% gain line is crossed. The turn-on thresholds will then become dependent on the number of operational electrolyzers but not constant like in strategy 1. Thereby addressing the fact that as more electrolyzers become operational, each additional electrolyzer will have a lower impact on the efficiency. Therefore, this strategy is only interesting when there are more than two electrolyzers. Hence, this strategy will not be tested for the 2x10 MW but only for the 4x5 MW.

Similarly to strategy 1, multiple turn-on thresholds will be tested using different required efficiency gains. The efficiency gains will be tested from 0% up to 4%, with 0.5% incremental steps. The reason for not going higher than 4% was that turning on the fourth electrolyzer has a maximum efficiency gain of 4.5%, and it happens close to 120% of the electrolyzer rated power. The exact cross-over points for turning on the second, third and fourth electrolyzer, using some of the above mentioned required efficiency gains, are summarized in Table 5.4. Table 5.4, has three main column sections. On the left, the required efficiency gain is shown. Looking at the first row, which shows a version requiring 0% efficiency gain for turning electrolyzers on, it can be seen that the 2nd electrolyzer should be turned on when the 1st electrolyzer is at 50% of its rated power. The 3rd electrolyzer is turned on when the operational electrolyzers reach 43.93% (equivalent to the wind turbine producing 4.39 MW which is then evenly split between two electrolyzers). Lastly, the fourth electrolyzer is turned on when the three operational electrolyzers are operating at 41.17%.

Table 5.4: Turn-on thresholds for different required efficiency gains

Efficiency gain for turning on from off	Electrolyzer operating point 2nd	3rd	4th	WT power production at crossover points [MW]		
Require 0% gain	50.0%	43.9%	41.2%	2.50	4.39	6.18
Require 1% gain	54.7%	49.5%	49.5%	2.74	4.95	7.43
Require 2% gain	60.1%	58.4%	70.2%	3.00	5.84	10.53
Require 3% gain	66.7%	79.0%	101.8%	3.33	7.90	15.27
Require 4% gain	75.6%	102.2%	113.6%	3.78	10.22	17.04

Table 5.4, shows that with increasing required efficiency gain, the turn-on thresholds are increased. Interestingly, versions of strategy 2, which require small efficiency gains, 0 - 1%, decrease their turn-on thresholds for the 3rd and 4th electrolyzers because these versions are attempting to stay very close to the optimal efficiency point. The versions that required an efficiency gain above 2% always increase the turn-on thresholds as more electrolyzers become operational because each additional electrolyzer has a smaller relative impact.

This same approach can be used to decide when to turn an electrolyzer to idle. When an electrolyzer is set to idle, not only does it stop producing hydrogen, but it also consumes power that could otherwise be used for hydrogen production. For example, if there is 3 MW of available power and there are two operational electrolyzers, both electrolyzers are consuming 1.5 MW. The advisory control might decide to set one electrolyzer to idle, but it is important to know that by doing that, the idling electrolyzer will consume 100 kW, and the electrolyzer which was not set to idle will ramp up to 2900 kW power consumption. Table 5.5 shows the results when the effect of idle consumption is included. For a description of how these values were obtained, see Section B.3.

Table 5.5: Turn-to-idle thresholds from on for different required efficiency gains

Efficiency gain for turning to idle from on	Electrolyzer operating point 2nd	3rd	4th	WT power production at crossover points [MW]		
Require 0% gain	18.1%	18.7%	19.4%	1.81	2.80	3.88
Require 1% gain	17.3%	17.8%	17.7%	1.73	2.67	3.54
Require 2% gain	16.5%	16.8%	16.7%	1.65	2.51	3.34
Require 3% gain	15.5%	15.6%	15.7%	1.55	2.34	3.14
Require 4% gain	14.4%	14.4%	14.6%	1.44	2.17	2.91

5.3.5. Turning idling electrolyzers back on

This section will analyze what is an acceptable threshold to turn idling electrolyzers back on. It was decided to make that a constant threshold for both strategy 1 and strategy 2.

The same approach as for strategy 2 is again used to understand what the threshold should be to get a certain efficiency by turning an idle electrolyzer back on. The results are shown in Table 5.5, and a description of how those results were obtained can be seen in Section B.3. Table 5.6 shows that a turn-on-from-idle threshold of around 40-50% is a good approximate value since it results in an efficiency gain of around 2-3% to turn an idle electrolyzer back on. A turn-on-from-idle threshold of 50% was chosen in the end. Decreasing that threshold further had a negligible impact on the hydrogen production, and mainly increased the amount of overall switching to idle and back on.

The selection of which electrolyzer to set to idle is based on the overall operating time of the electrolyzers. The advisory control should attempt to operate the electrolyzers evenly over the lifetime of the project. Therefore the electrolyzers are set to idle depending on their overall operating time.

Table 5.6: Turning on thresholds from idle for different required efficiency gains

Efficiency gain for turning on from idle	Electrolyzer operating point			WT power production at crossover points [MW]		
	2nd	3rd	4th			
Require 0% gain	36.3%	28.0%	25.9%	1.81	2.80	3.88
Require 1% gain	38.7%	37.4%	38.5%	1.93	3.74	5.77
Require 2% gain	46.1%	45.9%	49.9%	2.31	4.59	7.49
Require 3% gain	51.1%	55.3%	88.2%	2.55	5.53	13.24
Require 4% gain	57.3%	85.2%	109.8%	2.86	8.52	16.48

5.3.6. Summary of the two strategies

To summarize, this subsection on electrolyzer operational strategies has provided two different strategies to turn electrolyzers on and off. Firstly a simple but robust strategy with constant turn-on and turn-to-idle thresholds. Secondly, a strategy where the thresholds adapt to the required efficiency gain, which in turn depend on how many electrolyzers are operational. Multiple different versions of those strategies are possible and will be tested in Chapter 6.

5.4. Simulation figures showing the advisory control strategy

The following section will explain how the advisory control strategy works using simulation figures.

This section will walk through advisory control strategy 1, using images to explain it in better detail. This example will be based on a turn-on threshold of 75% and turn-to-idle threshold of 15%. A 5-second resolution active power output profile, of a whole day, from an 8.8 MW wind turbine scaled to 20 MW can be seen in Figure 5.5.

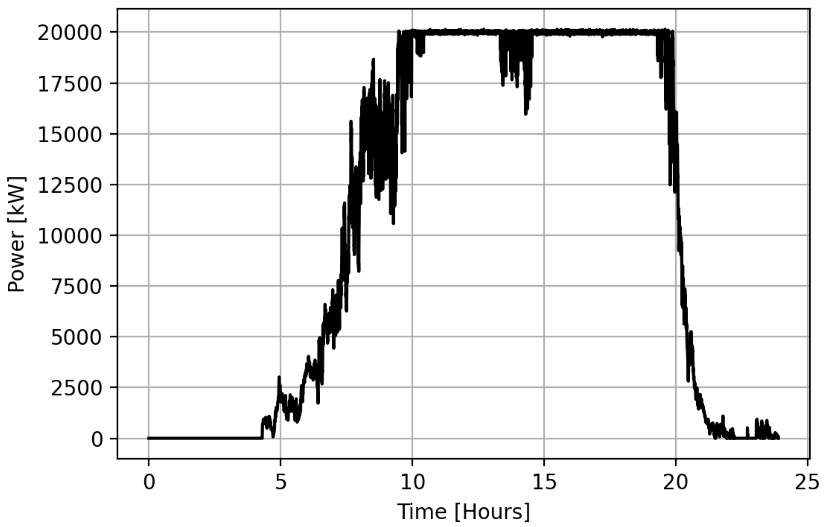


Figure 5.5: 20 MW wind turbine, power output timeseries.

To graphically show the electrolyzer operation, a figure with four subplots will be used. An explanation of how the first electrolyzer is turned on is shown in Figure 5.6. This split of four subplots will be used quite a lot in the following few figures, so a short description will be given. Every plot has a legend on the bottom of the plot, describing the role of different lines in these plots.

Sub plot 1: The first subplot on the top shows the active power output from the wind turbine. The blue dashed line in subplot one is the turn-on threshold when the electrolyzer is off (20% of the electrolyzer rated power). The red dashed line in subplot one is the turn-on threshold when the electrolyzer is idle (15% of the electrolyzer rated power).

Sub plot 2: The second subplot shows the electrolyzer power consumption of the four electrolyzers. The idle consumption is not shown in this graph, but only electrolyzer power consumption for hydrogen production. In Figure 5.6, only the first electrolyzer, shown in a blue curve, is being turned on. The green dashed line in subplot two is the turn-to-idle threshold of the 1st electrolyzer, which is 10% of the electrolyzer rated power. The reason why the legend for the green dashed line says, *Turn-to-idle threshold: one electrolyzer*, is that for only one electrolyzer, the turn-to-idle threshold is the minimum operating point of the electrolyzer. When more electrolyzers are operational, the controller will use the thresholds described in Section 5.3.

It is important to note that in subplot two, the electrolyzer power consumptions are plotted on top of each other. This can clearly be seen in Figure 5.7. When the second electrolyzer is turned on, the yellow profile of the second electrolyzer is plotted on top of the blue power profile. Since the available power is split evenly between them, it appears that the graph only shows the trend of the second electrolyzers. The same applies when the third and the fourth electrolyzers become operational.

Sub plot 3: The electrolyzer operating modes are shown in subplot 3. If an electrolyzer is off, it has a value of 0. When the electrolyzer is turned on, it is shown in the figure as it is in idle mode (meaning a value of 1) until the electrolyzer switching timer shown in subplot 4 reaches zero. Then the electrolyzer is fully operational, and that is shown with a value of 2 on the third subplot.

Sub plot 4: The last subplot shows the electrolyzer switching timer. A timer is used because it takes time and energy to turn electrolyzer systems on. From a cold-start, it takes 5 minutes, and from idle, it takes 10 seconds, as selected in Table 4.4.

To start with, the turning on and setting to idle mechanism will be explained, by simulating the first 6 hours of the profile shown in Figure 5.5. Figure 5.6 shows how the first electrolyzer is turned on when the wind turbine active power output crosses the turn-on threshold in blue. Subplot 3 shows that the electrolyzer has been turned on, and a switching time of 300 seconds is started in subplot 4. The electrolyzer starts producing power when the switching timer drops to zero in subplot 4. After only around 6 minutes of operation, the active power from the wind turbine drops below the minimum operating point of the electrolyzer, shown in the green dashed line in subplot 2, so it is set to idle mode. Then when the active power output from the wind turbine crosses the turn-on threshold for an idle electrolyzer, the red dashed line in subplot 1, the electrolyzer is turned on again. In subplot 4, a small 10-second timer can be seen before the electrolyzer becomes operational.

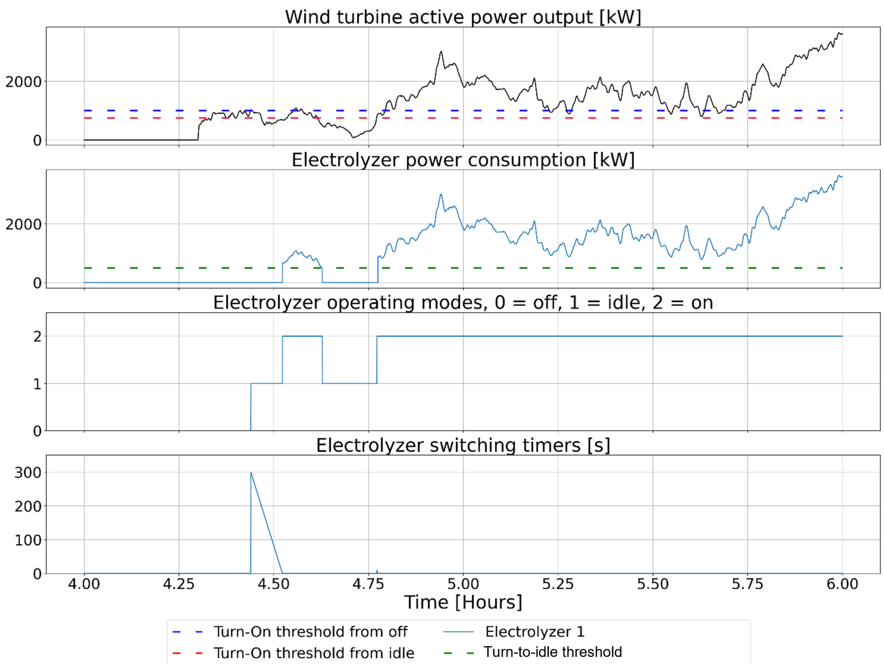


Figure 5.6: Advisory control explanation: First electrolyzer turned on

When the wind turbine power output increases, the advisory control will consider turning on more electrolyzers. The simulation result of the first 8 hours of the power profile from Figure 5.6 can be seen in Figure 5.7. The figure shows the turn-on threshold of 75% in the red dashed line in subplot 2 and how the electrolyzers are turned on one by one when the electrolyzer power consumption surpasses that threshold.

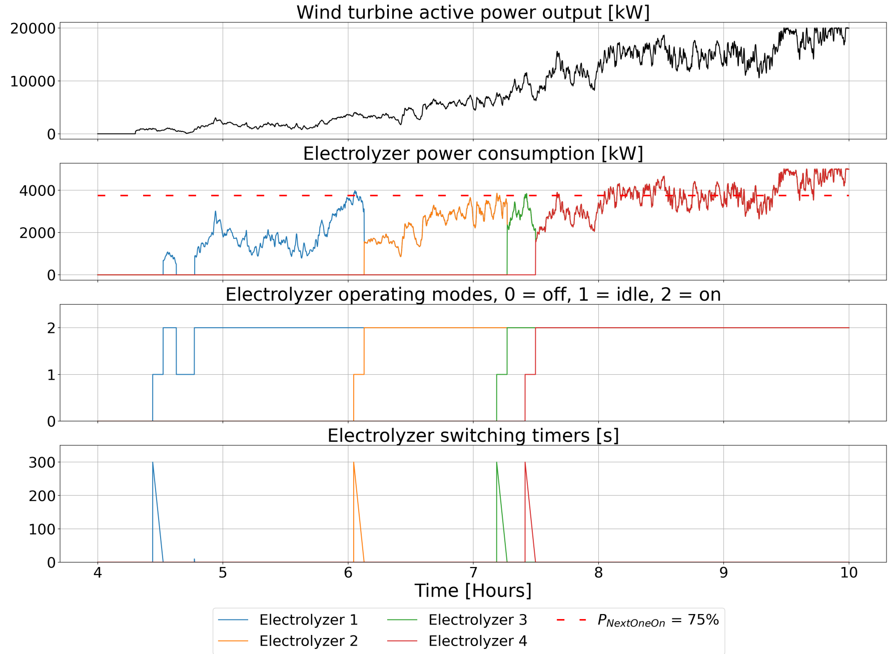


Figure 5.7: Advisory control explanation: Turning the next electrolyzers on using strategy 1

The total simulation is shown below in Figure 5.8. From Figure 5.8, it can be seen that electrolyzer 1 (shown in blue) is the first one to be turned on, followed by electrolyzer 2 (shown in yellow), then electrolyzer 3 (in green) and lastly electrolyzer 4 (in red). When the electrolyzers are turned off, they are shut down in the order of electrolyzer operating time. That is, the electrolyzer which has been operating the longest is the first one to shut down.

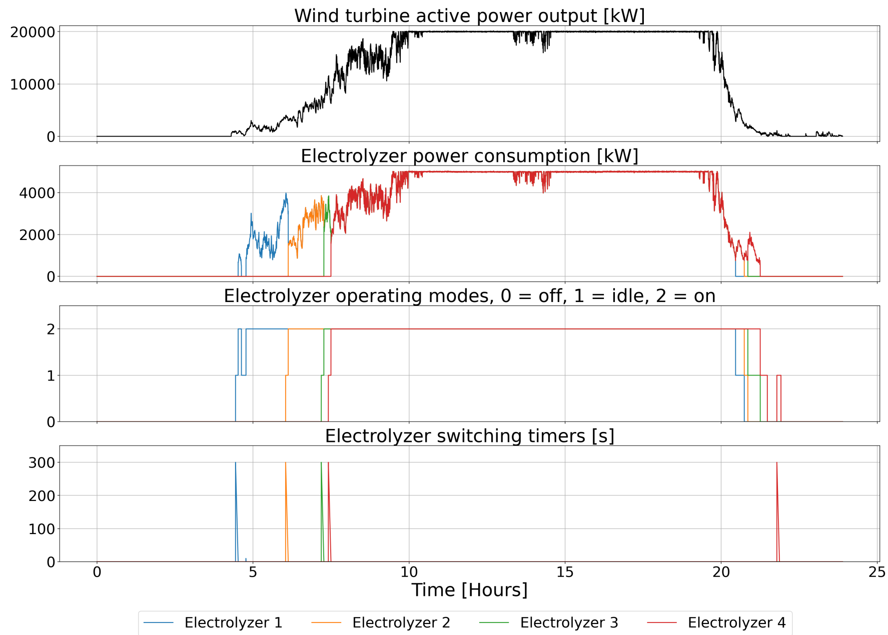


Figure 5.8: Advisory control explanation: Whole simulation

To further explain the shut down sequence, see Figure 5.9. As the wind speed is ramping down, one electrolyzer by one is set to idle. When an electrolyzer is set to idle and there is already an electrolyzer idling, the previously idling electrolyzer is fully turned off as it is inefficient to keep two electrolyzers idling. The red dashed line represents the turn-to-idle threshold of 15% when more than one electrolyzer is operating. The green dashed line represents the turn-to-idle threshold when only one electrolyzer is operating. The last electrolyzer is allowed to operate down to its minimum operating point of 10% before it is set to idle.

Figure 5.9, shows a common scenario in the time range of 21.5-22 hours. An electrolyzer is turned on, but when it becomes operational, there isn´t enough power to operate it, so it is set to idle. The wind turbine power output then ramps down further, causing the electrolyzer to be shut off.

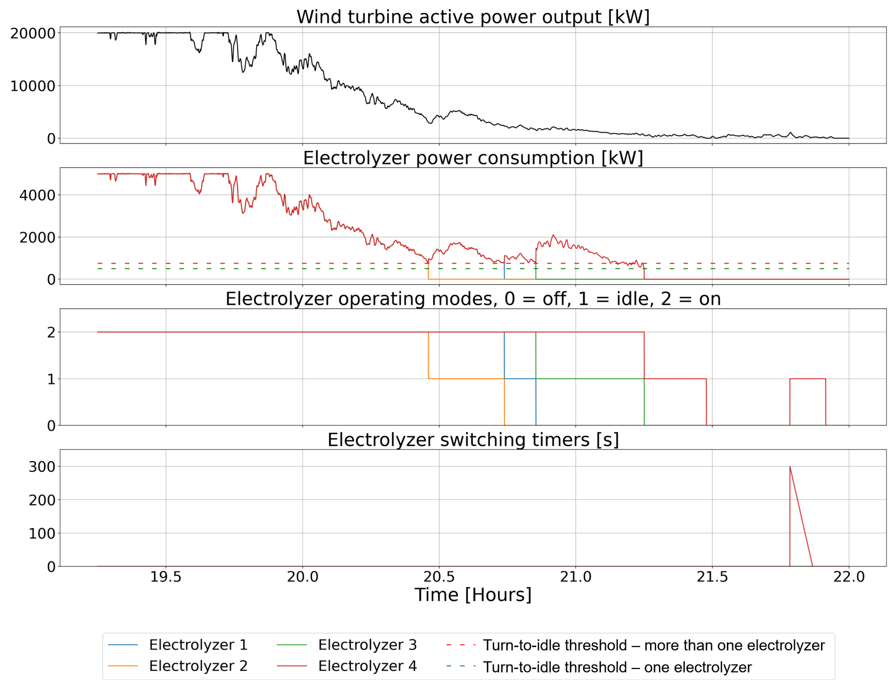


Figure 5.9: Advisory control explanation: Turning off sequence

In Figure 5.10, the entire system information is shown, with the wind turbine power output shown in subplot one, the electrolyzer power consumptions in subplot 2, the water tank volumetric level in subplot 3, and the battery SOC in subplot 4. It shows how the model captures the system dynamics.

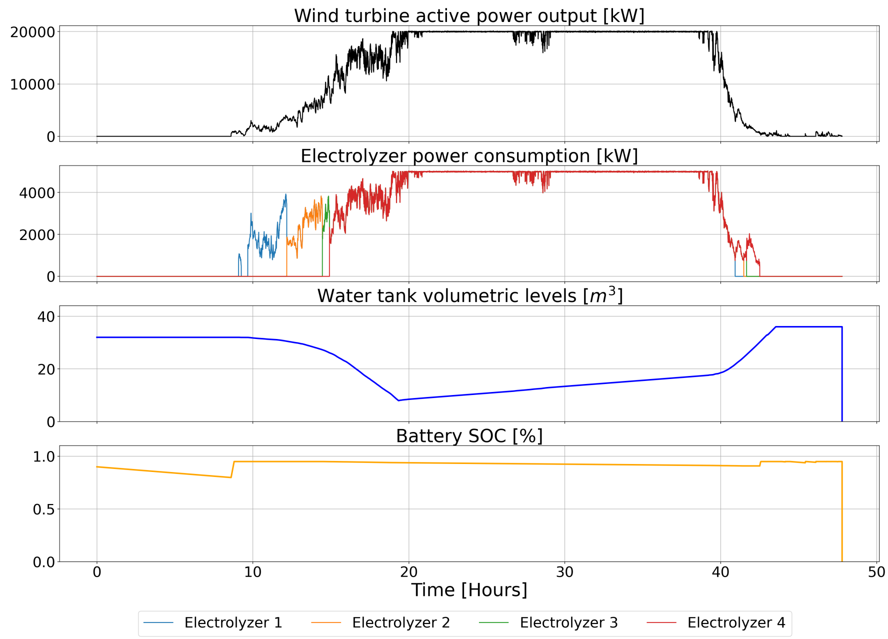


Figure 5.10: Entire system information: Wind turbine, electrolyzers, water tank and battery

The only difference from strategy 1, which was shown in the previous figures, to strategy 2, is that the turn-on and turn-to-idle thresholds are not constant but depend on how many electrolyzers are operational. The descriptions in this chapter are deemed enough to move on to the next chapter, where the results of these two strategies will be shown.

6

Advisory Control Simulation Results

This chapter will show the performance of the advisory control strategies explained in Chapter 5. The performance will be evaluated by simulating a one week fluctuating power output time-series. In Section 6.1 the simulation setup will be explained, describing the selected power output time-series and how the results will be displayed. Section 6.2 shows the results of the 4x5 MW configuration using strategies 1 and 2. Section 6.3 shows the results of the 2x10 MW configuration using strategy 1. A comparison between the results of the 4x5 MW and 2x10 MW is then shown in Section 6.4. Lastly, the main take-away's from this chapter are summarized in Section 6.5.

6.1. Simulation setup

To compare the advisory control strategies presented in Chapter 5, the response of the modeled system to a one week power output time series will be tested. Five key performance indicators (KPIs) will be used for the comparison. Those are:

- Hydrogen production
- Daily average number of turn-offs per electrolyzer (Daily turn-off rate)
- Daily average number of operating mode switches per electrolyzer (Daily switching)
- Daily idle time
- Curtailed energy

The hydrogen production is simply the total hydrogen production over the course of the 7 day simulation. The average number of turn-offs per day is the total number of turn-offs divided by the number of electrolyzers and divided by the number of simulated days. That metric will sometimes be called the daily turn-off rate to keep it short. The average daily switching of operating modes counts how often each electrolyzer is turned on, turned off, set to idle, and back on from idle. That metric will sometimes be referred to as the daily switching. Then there is the daily idle time, which sums up the entire time each electrolyzer was idling and divides that number by the total number of simulated days. Therefore, the idle time metric indicates how long all the electrolyzers were in idle operation per day. Lastly, there is curtailed energy, which is the energy that was not utilized.

The one week power output time series can be seen below in Figure 6.1. This week was selected due to its high variance in power output. High variance provides a nice simulation test case to understand the effectiveness of the two strategies with regard to the five key performance indicators mentioned above. This power output time series will be labelled as Case 1.

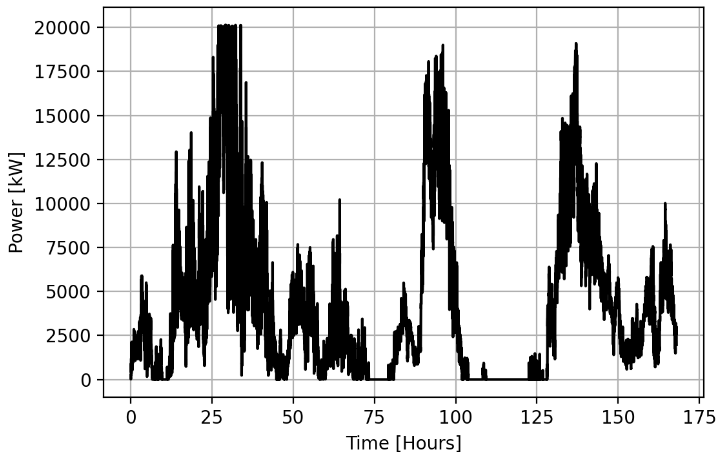


Figure 6.1: Case 1 - One week active power output time series

The two electrolyzer configurations that will be tested are 4x5 MW and 2x10 MW. The 4x5 MW configuration will firstly be tested using strategy 1, followed by 2. The solution space will be sampled and simulated to properly understand the effect of coupling different turn-on and turn-to-idle thresholds in strategy 1. The turn-on thresholds were selected from 60%-100%, with a step size of 1%, coupled with turn-to-idle thresholds of 10-20% with the same step size. Each combination was simulated, leading to a total of 41x11 = 451 simulations.

This can be clearly explained with an example. In Figure 6.2, a color map of hydrogen production can be seen, and this paragraph will explain how to read it. On the vertical axis, the turn-on thresholds can be seen, from 60% to 100%, with a step size of 1%. On the horizontal axis, the turn-to-idle thresholds can be seen, ranging from 10% to 20% with a step size of 1%. There are 451 boxes in this color map. Each box is a simulation result, connecting one turn-on threshold to one turn-to-idle threshold. For example, the bottom left corner connects the turn-on threshold of 60% to the turn-to-idle threshold of 10%, and the top right corner uses a turn-on threshold of 100% and turn-to-idle threshold of 20%. As a reminder, each simulation uses a turn-on-from-idle threshold of 50%.

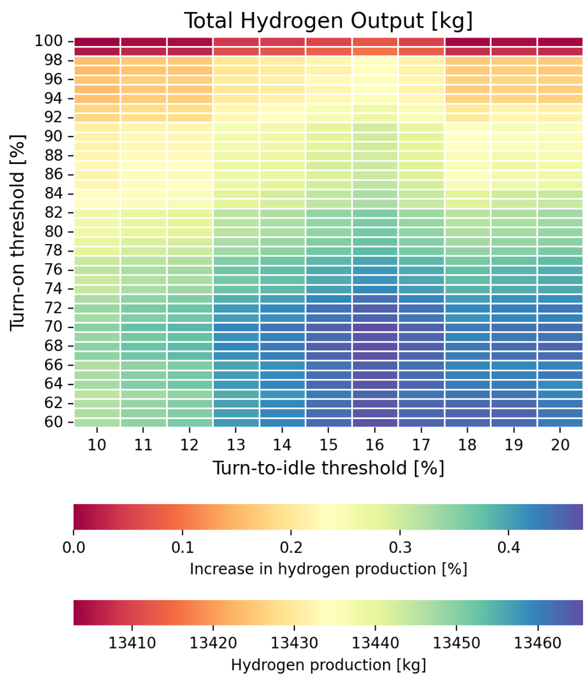


Figure 6.2: Explanatory colormap: Hydrogen production with different turn-on and turn-to-idle thresholds.

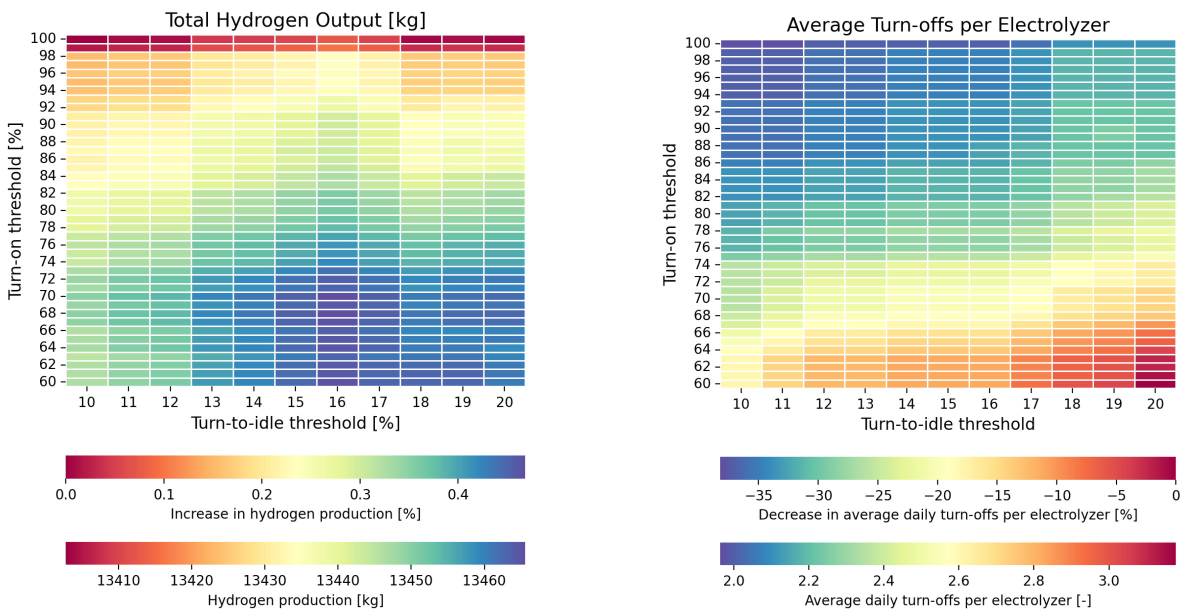
6.2. 4x5 MW Electrolyzer configuration

This section will describe the results of the 4x5 MW configuration, with the aim of understanding the system behaviour. Strategy 1 is presented first in Section 6.2.1, followed by strategy 2 in Section 6.2.2. In Section 6.2.2, the aim is to compare strategy 2 to strategy 1, to select either strategy 1 or 2 as a better performing strategy.

6.2.1. Strategy 1: Constant thresholds

In Figure 6.3a the color map for the hydrogen production when simulating case 1 with different versions of strategy 1 can be seen. From Figure 6.3a it can be seen that the hydrogen production is the largest in the bottom right corner, with the highest production achieved with a turn-on threshold of around 60-72% coupled with a turn-to-idle threshold of 15-17%. The worst performing versions have a high turn-on threshold, with dark yellow and red colors. That was to be expected, as those versions delay turning electrolyzers on, while versions with smaller thresholds are attempting to chase efficiency gains. The results also show that the turn-on threshold has a bigger impact than the turn-to-idle threshold, which is also due to the larger range (60-100% compared to 10-20%). Looking at the first color bar, which shows the relative increase in performance compared to the lowest hydrogen production, it can be seen that the highest hydrogen production only increases the production by roughly 0.5% compared to the worst. That shows that the different versions perform quite similarly with regard to hydrogen production. The reason for this small difference will be explained in steps throughout this section, with a deeper analysis at the end. But firstly, the color maps of the KPIs will be shown and discussed.

Figure 6.3b, shows the color map of the daily turn-off rate. Interestingly, the color map of the average turn-offs is almost the mirror image of the hydrogen production. The bottom right corner is the worst performer, meaning the highest daily turn-offs per electrolyzers, while the top left corner is the best. This could be expected, as versions chasing efficiency gains by having a low turn-on threshold turn electrolyzers on sooner. Furthermore, a high turn-to-idle threshold means the advisory control turns electrolyzers to idle sooner. By coupling those two (the bottom right corner), it can be expected that the electrolyzers are more frequently turned on and off. For a discussion on why a high turn-to-idle threshold leads to more turn-offs, see Section D.2.1. When looking at the relative decrease in turn-offs of the best performing version compared to the worst, the first color bar shows that the best performer (top left corner) has close to 40% fewer turn-offs than the worst performer (bottom right corner). That clearly shows that, even though the different versions might not be able to affect the hydrogen production largely, they can clearly affect the daily turn-offs. That is the main take-away from Figure 6.3.



(a) Hydrogen production colormap with different turn-on and turn-to-idle thresholds.

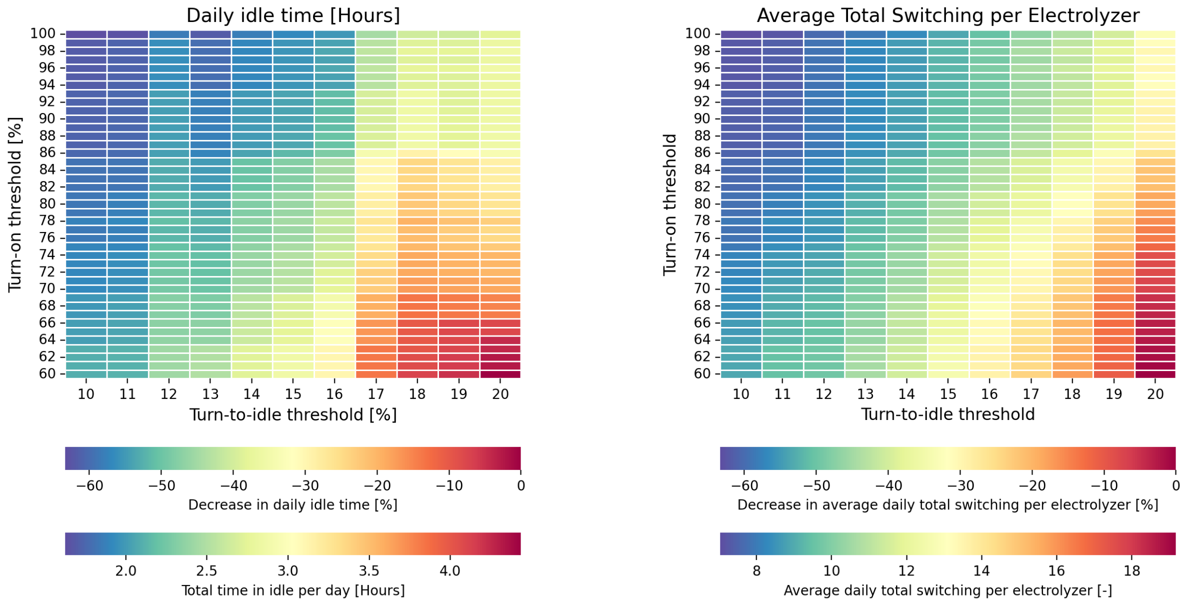
(b) Average daily turn-offs per electrolyzer colormap with different turn-on and turn-to-idle thresholds.

Figure 6.3: Total hydrogen production and average number of turn-offs with different turn-on and turn-to-idle thresholds for strategy 1. The percentage increase and decrease are always with regards to the lowest hydrogen production and highest average number of turn-offs respectively.

There are a few reasons why there is such a small difference in the hydrogen production. One of the reasons is that versions that attempt to maintain higher efficiencies are keeping electrolyzers longer in idle. In Figure 6.4a, the average daily idle time is depicted, showing a similar trend as the average number of turn-offs. The versions that keep electrolyzers longest in idle are the ones in the bottom right corner, which chase efficiency gains, as those versions turn electrolyzers on and to idle sooner. Looking at the daily idle time for the 1 week simulation, the lowest time was around 1.5 hours (top left corner), and the highest was 4.5 hours (bottom right corner). Considering that case 1 is a 7 day simulation, that is a range of 7 [days] x 3 [hours/day] = 21 hours. Keeping an electrolyzer idling is assumed to consume 2% of the electrolyzer rated capacity. Hence for a 5 MW electrolyzer that is equivalent to 2100 kWh of energy. Estimating that producing 1 kg of hydrogen consumes roughly 54 kWh, this additional time in idle operation decreases the hydrogen production by around 39 kg of hydrogen, or roughly 0.3%. That decrease in hydrogen is a negative effect that the gains from chasing higher efficiencies need to surpass over the course of a week. It is essentially a drag on the hydrogen production compared to versions that have lower idle time.

Then there is the negative effect of turning the electrolyzer frequently on and off. Every time an electrolyzer is turned on, it takes 5 minutes and consumes power of 2% of the rated electrolyzer power capacity. This is a lot smaller effect compared to the idle consumption but is still estimated to decrease the production by 5.2 kg of hydrogen over the week [1]. Although a smaller effect, it contributes to why versions attempting to chase high efficiencies by turning on and to idle sooner do not outperform more.

Furthermore, looking at the average daily switching per electrolyzer in Figure 6.4b, it can be seen that there is a large difference in the daily switching from the top left corner to the bottom right. The top left corner performs around seven switches of operating modes per day compared to around 19 for the bottom right corner. This has a marginal effect on hydrogen production. Still, it shows that a significant decrease in operating mode switches can be obtained by changing the turn-on and turn-to-idle thresholds.



(a) Daily time in idle colormap with different turn-on and turn-to-idle thresholds

(b) Average daily switching per electrolyzer colormap with different turn-on and turn-to-idle thresholds.

Figure 6.4: Total idle time per day and average number of switching per electrolyzer per day with different turn-on and turn-to-idle thresholds for strategy 1.

[1]Comparing the worst case (bottom right) of daily turn-offs in Figure 6.3b which is around 3.2 times per day, to the best case (top left) which has around two times per day there is a difference of 1.2 times per day. For a seven day simulation with 4x5 MW electrolyzer, that is equivalent to 34 turn offs (1.2 [times per electrolyzer per day] * 7 [days] * 4 [electrolyzers] = 34 times). 34 turn-offs mean there were also 34 turn-ons. If each turn-on takes 5 minutes, that adds up to around 2.8 hours. Turning electrolyzers on consumes 100 kW (2% of 5 MW), which for 2.8 hours consumes 280 kWh, which is equivalent to another 5 kg of hydrogen.

Before diving into why there is such a small difference in the hydrogen production, the curtailed energy will be described. It is interesting to analyse how well the electrolyzers managed to keep up with the fluctuating power output from the wind turbine. In the following paragraphs, when referring to curtailed energy, it is always the case that the battery attempts to capture any excess energy while the remaining is curtailed.

During the simulations in this thesis project, there were two main causes of curtailed energy. Firstly, when the wind turbine power output is below the minimum operating point of the first electrolyzer. This was found to be the most important cause of why energy was curtailed. As was explained in Section 4.3, the minimum operating point of the electrolyzers is 10%. Therefore, when the wind turbine produces power below that threshold, it needs to be curtailed. The second cause is when the wind turbine power output fluctuations exceed the dynamic capabilities of the electrolyzers. The dynamic capabilities of the electrolyzers can be split into two parts, the maximum ramp rate and the time it takes to turn an electrolyzer on. The simulations showed that electrolyzers with a maximum ramp up rate of 10% per second could very well keep up with the wind turbine power output fluctuations. However, the results showed that the 5-minute turn-on time was sometimes a bottleneck, causing periods where energy is curtailed while an electrolyzer is turning on.

The color map of the curtailed energy with different turn-on and turn-to-idle thresholds can be seen below in Figure 6.5. The main take-away is that the color map shows that all the versions curtail roughly 7000 kWh, which is 1% of the total energy in the power output time series. That curtailed energy was almost exclusively due to the wind turbine power output being below the minimum operating point and fluctuating below the 20% turn-on threshold of the first electrolyzer before it had been turned on. Figure 6.5 also shows that the curtailed energy increases with higher turn-to-idle thresholds. That was due to the modeling discretisation. Whenever an electrolyzer is set to idle, the other electrolyzers do not ramp up until the next simulation time step. That leaves excess power in the system, which is curtailed if the battery does not capture it. In the upper right corner, an instance of the second cause of curtailed energy can be seen. A situation where one version turned off an electrolyzer while another didn't. Then the wind turbine power output quickly ramped up, leaving the version which turned the electrolyzer off with too few operational electrolyzers. That led to a period where a lot of energy was curtailed while an electrolyzer was turning on. For a more detailed description of what is happening in the upper right corner and the discretisation impact, see Section D.3.

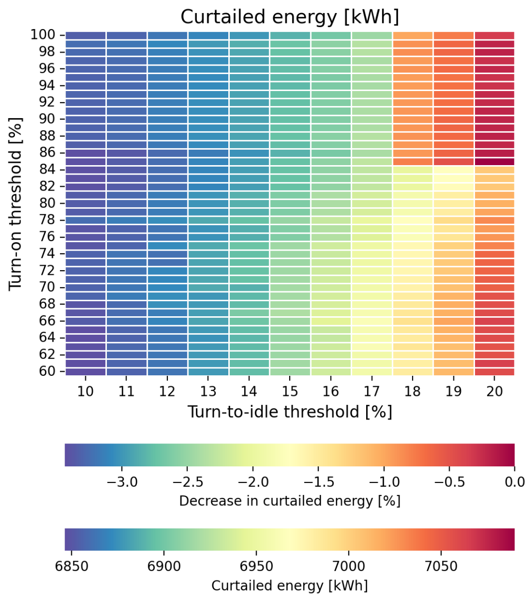


Figure 6.5: Curtailed energy with different turn-on and turn-to-idle thresholds for strategy 1.

The main reasoning for the small difference in hydrogen production will now be explained in detail.

The largest reason why the difference isn´t very large is that the gain of turning an additional electrolyzer isn´t very high on average. The jump in efficiency may be high on some occasions. For example, turning the second electrolyzer on when the first electrolyzer reaches rated capacity results in around 7% efficiency gain. But on average, the difference is very small. This can clearly be seen by plotting the system-level efficiency curves as a function of wind turbine power output when comparing the two extreme turn-on thresholds, namely 60% and 100%. The result can be seen in Figure 6.6, where the dashed line is with a turn-on threshold of 100%, and the solid line is with a turn-on threshold of 60%. When there is only a solid line, the versions are identical because they have the same number of operational electrolyzers. It is important to note that the curves do not consider the impact of the turn-to-idle threshold. For example, for a 100% turn-on threshold, the second electrolyzer would be turned on at 5 MW, but it would not be turned off if the power output decreases below 5 MW, as the figure shows. It is therefore showing the maximum potential difference in efficiency. The average difference in the efficiency of the two curves, from 0.5 MW - 20 MW, is only 1.8%. That shows that the average difference in efficiency is very small.

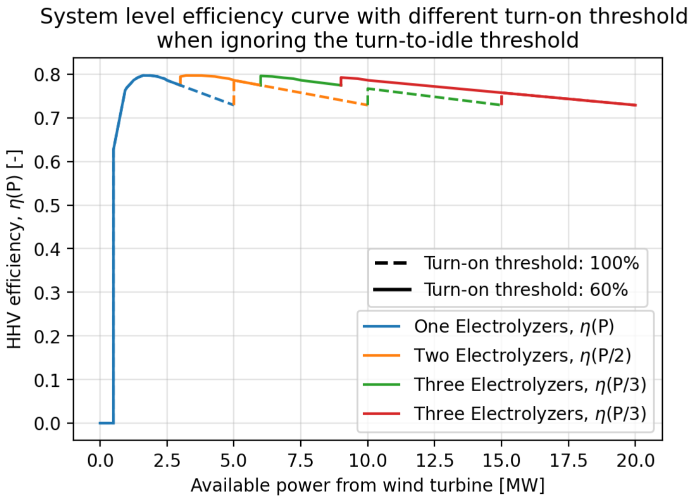


Figure 6.6: Difference in efficiency curves with a turn-on threshold of 60% compared to 100% when ignoring the turn-to-idle thresholds.

The 1.8% is the maximum average difference in efficiency. The reason why it is that maximum difference is because it ignores the impact of the turn-to-idle threshold. For example, versions chasing efficiency gains do not tolerate operating in sub-optimal efficiency regions and therefore keep turning electrolyzers on or to idle. But versions that delay turning electrolyzers on and to idle have a larger operating range before performing an action. For example, a version using 100% as a turn-on threshold and 10% as the turn-to-idle threshold gives the electrolyzers a 90% operating range to follow the power output from the wind turbine and often ends up operating in the partial load region with high efficiencies. The maximum average difference of 1.8% is therefore further reduced by this impact.

The other main reason why the difference is so small is that the versions only differ from 3 - 15 MW. This can be seen in Figure 6.6 showing only a solid line outside the range of 3 - 15 MW. In Figure 6.7 a wind speed probability histogram of the Aberdeen Bay Wind Farm can be seen alongside the power curve of the 20 MW wind turbine. The probability distribution was created using the 1-hour average wind speed ERA5 data at the Aberdeen Bay Wind Farm location from 2005-2021, extrapolated to hub height as described in Section 4.5. In between the black dashed vertical lines is the section of the power curve where the wind speed is between 3 - 15 MW. The wind turbine only produces power in the range of 3 - 15 MW, 36% of the time. That, combined with a maximum average difference in efficiency of 1.8%, is the main reason why the difference is so small.

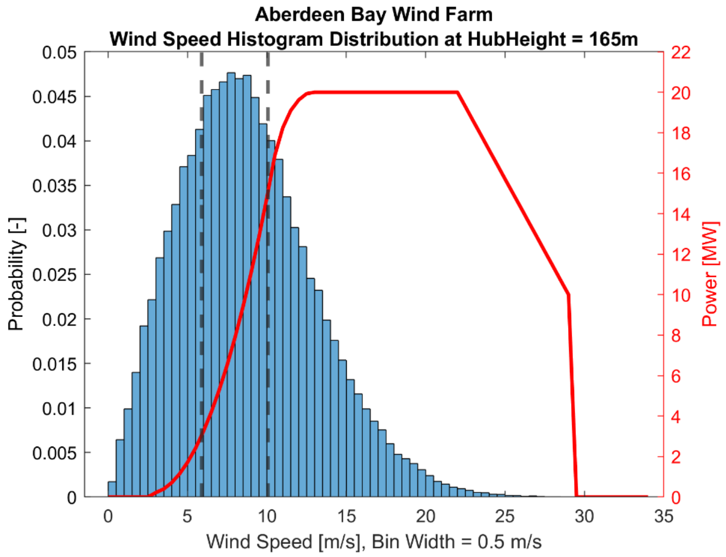


Figure 6.7: Wind speed probability distribution at the Aberdeen Bay Wind Farm, alongside the power curve of a 20 MW wind turbine. The black dashed lines are highlighting the wind turbine power output range between 3 - 15 MW.

To summarize, the reason why the difference in hydrogen production is so small is due to the following four reasons:

- The gain of turning an additional electrolyzer on is not large. The maximum average gain in efficiency is 1.8%.
- The versions are only different from 3 - 15 MW which is in the partial load region of the wind turbine power curve. The wind turbine only produces power within that range 36% of the time.
- Versions that chase efficiency gains are turning electrolyzers on more frequently and keep them idle longer compared to versions that do not chase efficiency gains, both of which consume power.
- Versions that do not chase efficiency gains, thereby having large operating ranges, often operate in high-efficiency regions due to the natural fluctuations in the wind turbine power output.

6.2.2. Strategy 2: Dynamic thresholds requiring a certain efficiency gain

This subsection will analyze the results of strategy 2 for the 4x5 MW configuration, with the main aim of showing whether strategy 2 is better than strategy 1.

The color maps for the 5 KPIs and the corresponding discussion can be seen in Section D.4, and only the main findings will be discussed here.

For strategy 2, for the same reasons as described for strategy 1, versions chasing efficiency gains do not outperform by much. The highest hydrogen production was achieved when requiring 2-3% efficiency gains for turning on and 2-3% for turning to idle. Those versions had the best balance between chasing efficiency gains and keeping electrolyzers idling and frequently turning them on and off. The difference between the highest and lowest production is again very small, only around 0.5%.

The main point is to see whether strategy 2 outperforms strategy 1. The overall system performance can be summarized in two parameters, hydrogen production and the average number of turn-offs. That is because the negative effects of daily idle time, curtailed energy and the power consumption for turning electrolyzers on (both from the off and idle state) are included in the hydrogen production. Therefore, it is possible to display the system's performance in a single graph as hydrogen production vs average number of turn-offs. This plot is shown in Figure 6.8, with the average number of turn-offs on the x-axis and hydrogen production on the y-axis, for the different versions of the two strategies. Every dot is a point from the color maps, with blue dots standing for simulations with strategy 1 (451 dots) and red dots from strategy 2 (81 dots).

Figure 6.8, shows that a higher hydrogen production comes at the expense of a higher number of turn-offs, until around 2.6 daily turn-offs per electrolyzer. After that, the hydrogen production starts to decrease again. Figure 6.8 clearly shows that strategy 1 is overall better, managing higher hydrogen production for similar average number of turn-offs. The only exception is that strategy 2 has a better production at the lowest obtained turn-off point of 1.96 times per electrolyzer per day.

The main conclusion from this picture is that strategy 1 mostly outperforms strategy 2 regarding both hydrogen production and daily average number of turn-offs, with strategy 2 only performing marginally better at the lowest daily average number of turn-off point. The reason for the underperformance was that the versions of strategy 2 attempting to chase efficiency gains (such as requiring <2%) had a really short operating range, causing them to frequently turn electrolyzers on and off, and keeping them idling. And as explained before, the average gain is very small. On the other hand, versions requiring higher efficiency gains managed to decrease their turn-off rate but produced less hydrogen than versions of strategy 1 for a given turn-off rate.

Therefore, it was decided to focus the following analysis on strategy 1.

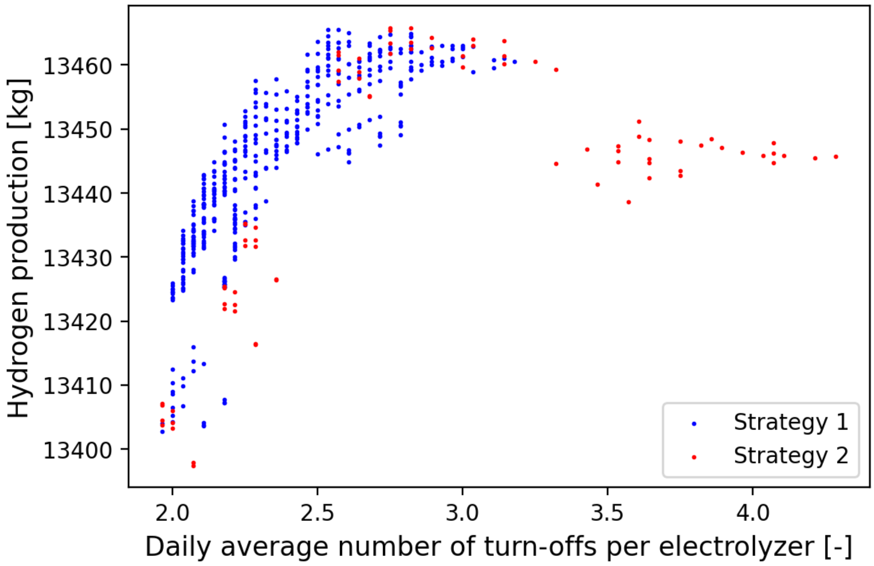


Figure 6.8: Hydrogen production vs Average number of turn-offs for both strategies 1 and 2 when simulating case 1 with 4x5 MW electrolyzer configuration

6.3. 2x10 MW Electrolyzer configuration

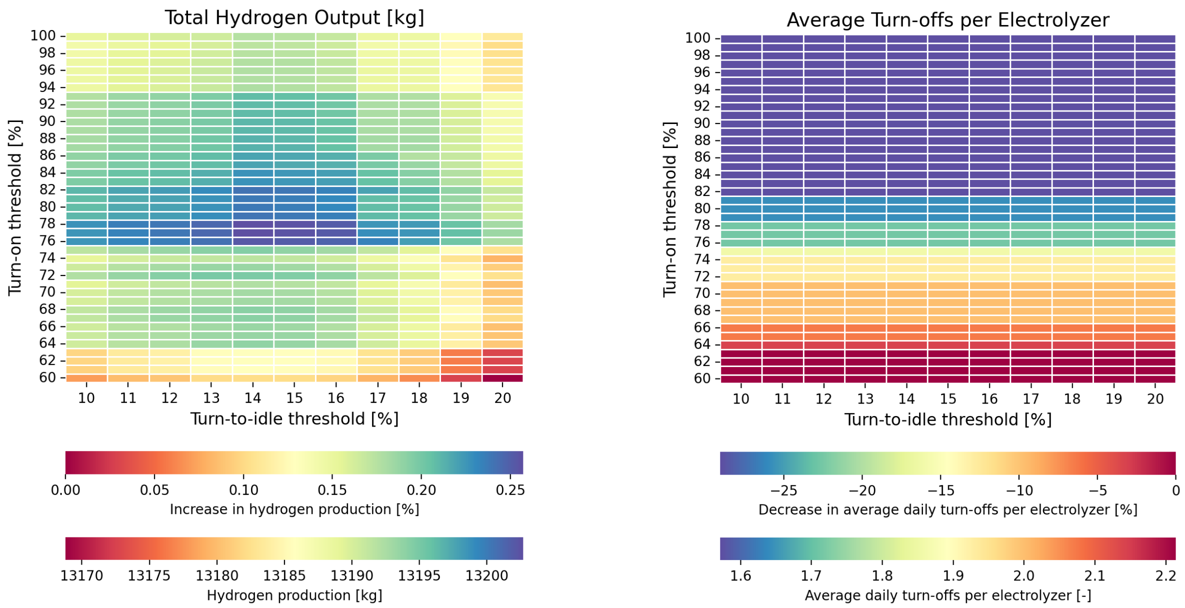
This section will describe the results of the 2x10 MW electrolyzer configuration.

There are two big changes when using the 2x10 MW configuration instead of the 4x5 MW. Firstly, the idle and starting up consumptions increase from 100 kW for the 5 MW electrolyzers to 200 kW with the 10 MW electrolyzers, as they are modeled as 2% of the electrolyzer rated capacity. Secondly, the minimum operating point increases. The effect of these changes can be seen in the color map of the hydrogen production in Figure 6.9a. For the 2x10 MW configuration, the highest hydrogen production is with a higher turn-on threshold, namely around 76-80%, while the 4x5 MW was around 60-70%. The first color bar shows that the absolute difference between the highest and lowest hydrogen-producing versions is only 0.25%, compared to 0.5% for the 4x5 MW. The same reasons for the small difference in hydrogen production apply to the 2x10 MW as the 4x5 MW, but there are three main reasons why the difference is even smaller for 2x10 MW.

- Firstly, the increased consumptions for starting up and idling further reduced the gap between the version chasing efficiency gains and those that delay turning electrolyzers on and to idle.

- The second reason is that the versions are now only different in the range of 6 - 10 MW when ignoring the turn-to-idle threshold and using a minimum of 60% and maximum of 100% as the turn-on thresholds. Furthermore, even when including the turn-to-idle threshold, the versions are always identical above 10 MW because the highest turn-on threshold of 100% causes the second electrolyzer to be turned on when the first electrolyzer reaches the rated capacity. For any greater power output, the versions are the same. For the 4x5 MW, that threshold is 15 MW.
- The third and last reason is that whenever there is only one operating electrolyzer, the advisory control operates that single electrolyzer the same way, independently of the version of strategy 1. That is, the first electrolyzer is turned on when the turn-on threshold of 20% is reached, and the electrolyzer is kept operating down to the minimum operating point of 10% before it is set to idle. The only difference between the versions is when the second electrolyzer should be turned on and set to idle. With only two electrolyzers, the fraction of time where there is only one electrolyzer operating is greater than with 4x5 MW electrolyzers hence making the simulations results more alike.

A noteworthy difference between the 2x10 MW to the 4x5 MW configuration can be seen when looking at the colormaps of the average number of turn-offs. Figure 6.9b shows that with a 2x10 MW configuration, the average number of turn-offs are independent of the turn-to-idle threshold. This is related to the thrid point mentioned above. The second electrolyzer is not turned off unless the first electrolyzer is set to idle. When only one electrolyzer is operating, there is no gain to be made by setting it to idle. Therefore the advisory control will keep the last operating electrolyzer on to produce hydrogen until the power consumption drops below the minimum operating point. Therefore, it does not matter when the second electrolyzer is set to idle, it will only be turned off if the first electrolyzer has reached the minimum operating point. That explains why the turn-on threshold is the only parameter that affects the daily turn-off rate.



(a) Hydrogen production colormap with different turn-on and turn-to-idle thresholds.

(b) Average daily turn-offs per electrolyzer colormap with different turn-on and turn-to-idle thresholds.

Figure 6.9: Total hydrogen production and average number of turn-offs with different turn-on and turn-to-idle thresholds for strategy 1, when using the 2x10 MW.

Looking at Figure 6.9b, it can be seen that after the turn-on threshold of 82%, increasing the turn-on threshold further did not decrease the turn-offs. That is related to the selected power output time-series of the 1 week. From Figure 6.1, it can be seen that every time the power output from the wind turbine surpasses 8,200 kW, it keeps ramping up above 10,000 kW as well. Therefore, simulating case 1 with a 10 MW electrolyzer using a turn-on threshold between 82% and 100%, all those thresholds get surpassed if the 82% is reached.

The idle time and daily switching trends were the same as for the 4x5 MW and are therefore shown in the appendix (Figure D.6). Most notably, the 2x10 MW has almost double the overall switching. That is directly related to the increased minimum operating point. The wind turbine power output frequently fluctuates around 1 MW, causing the first electrolyzer to switch from on to idle and back on frequently.

The lowest idle time is 2.3 hours shorter per day compared to the highest (a decrease of 60%). With a 10 MW electrolyzer and a 7 day simulation, that results in additional consumption of 3220 kWh, equivalent to roughly 60 kg of hydrogen. That shows the larger negative drag on the hydrogen production for versions attempting to chase efficiency gains for the 2x10 MW compared to the 4x5 MW configuration.

No noteworthy difference was observed in the trend of curtailed energy for the 2x10 MW compared to the 4x5 MW. The color map can be seen in Figure D.7. The main finding was that the curtailed energy, in absolute values, is twice as large compared to the 4x5 MW configuration due to the minimum operating point. With 2x10 MW, the first electrolyzer is turned on when the wind turbine power output exceeds 2 MW and is set to idle at 1 MW. Hence the amount of time that there is no operational electrolyzer is much greater than for the 4x5 MW configuration.

6.4. 2x10 MW compared to 4x5 MW

To properly visualise the difference in performance of the 2x10 MW electrolyzer configuration compared to the 4x5 MW, the hydrogen production vs daily average number of turn-offs will be used. In Figure 6.10 the hydrogen production vs average number for both the 4x5 MW and 2x10 MW configuration can be seen. The 4x5 MW configuration uses the colors blue and red for strategies 1 and 2, respectively, while the 2x10 MW results are shown in green.

Figure 6.10 shows that the 4x5 MW produces roughly 200-250 kg more of hydrogen throughout the 1 week simulation. An increase of 1.5-1.9%. On the other hand, the 2x10 MW configuration has lower average daily turn-offs per electrolyzer, reaching down to 1.57 compared to 1.96 for the 4x5 MW configuration, which is a decrease of 20%. The main difference between the 4x5 MW and 2x10 MW is that there is a clearer trade-off between hydrogen production and the daily turn-off rate for the 4x5 MW. For the 2x10 MW, the different versions mainly affect the turn-off rate.

The difference in hydrogen production between the two electrolyzer configurations is mainly caused by the difference in curtailed energy, which is related to the minimum operating point. The minimum operating point is 10% and is therefore 1 MW with a 10 MW electrolyzer compared to 0.5 MW for a 5 MW electrolyzer. When the wind turbine is producing power which is below the minimum operating point, the majority of the power is curtailed unless it is caught by the battery. However, the battery is not very large, with a storage capacity of 562 kWh and a maximum peak shave capability of 275 kW. Therefore it gets almost fully charged in about two hours. After that, the majority of the excess power is curtailed. Furthermore, the first electrolyzer is turned on at 2 MW for the 2x10 MW, compared to 1 MW for the 4x5 MW configuration. The difference in curtailed energy is equivalent to 194 kg of hydrogen production [2] That is almost the entire difference in the resulting hydrogen production between the 4x5 MW and the 2x10 MW configurations. This shows that the most significant factor is the increased minimum operating point. Other reasons that cause the decrease in hydrogen production is that the daily idle time is roughly the same for both configurations but consumes twice as much energy for the 2x10 MW configurations. Furthermore, every turn-on from off consumes twice as much energy as well.

[2] Using the lowest curtailed energy in the color maps from 4x5 and 2x10 MW, as an indicative estimate, the 4x5 MW, curtailed around 6850 kWh compared to 17350 kWh for the 2x10 MW configuration. Therefore, the 2x10 MW curtails additional 10500 kWh of energy, equivalent to around 194 kg of hydrogen.

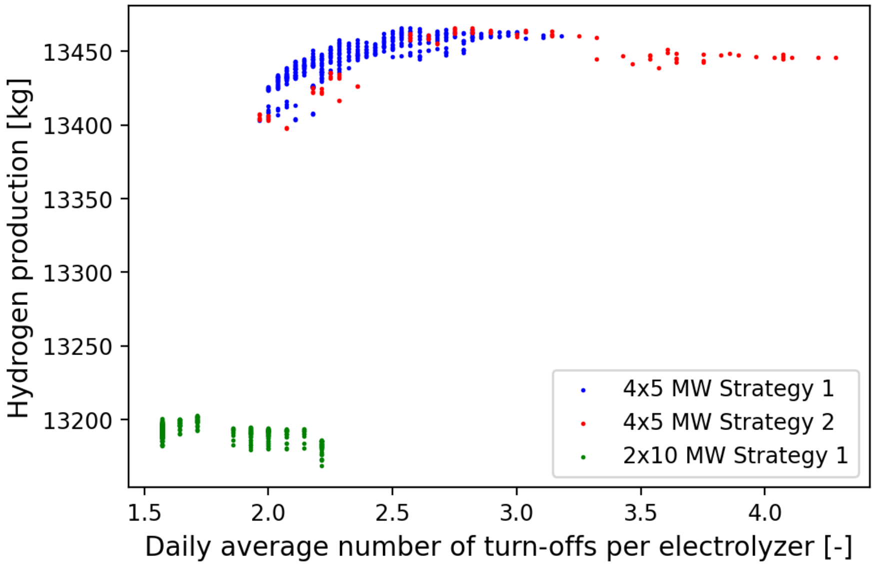


Figure 6.10: Comparing Hydrogen production vs Average number of turn-offs for the 4x5 MW and 2x10 MW electrolyzer configuration. Both strategies 1 and 2 are shown for simulating case 1.

6.5. Main take-aways from this chapter

The main finding of this chapter is that with a fluctuating power source, chasing efficiency gains using turn-on and turn-to-idle strategies does not manage to largely outperform in hydrogen production compared to versions that don´t chase efficiency gains. The results of the 4x5 MW configuration, showed that the different versions were mainly able to influence the daily turn-offs, while the difference between the highest and lowest produced hydrogen for strategy 1 was only around 0.5%. This small difference is due to four main reasons: (1) The average gain of turning an electrolyzer on is < 1.8%. (2) The different versions are only different in the partial load region of the power curve and were found to operate the same amount of electrolyzers the majority of the time. (3) Versions which have large operating ranges often end up operating in high-efficiency regions due to power output fluctuations, decreasing the expected benefit of versions chasing efficiency gains which use smaller operating ranges. (4) Versions attempting to chase efficiency gains have the negative effect that the keep electrolyzers longer in idle, and are more frequently turning them on and off both of which consume power. These reasons also explain why strategy 1 mostly outperformed strategy 2.

The 2x10 MW configuration showed an even smaller difference in hydrogen production between the different versions of strategy 1. That was because the starting-up and idle consumptions are twice as large, and with only two electrolyzers, the different versions become even more similar. The different versions could mainly influence the daily turn-off rate.

Both configurations had a similar daily idle time, but the 2x10 MW had a much higher overall switching rate due to the frequent fluctuations around the minimum operating point of the first electrolyzer. The increased minimum operating point and the higher required power output for turning the first electrolyzer on, were the key differences that caused the 2x10 MW to produce about 1.5-1.9% less hydrogen than the 4x5 MW configuration. But on the other hand, the 2x10 MW system obtained a lower turn-off rate.

There are a few possible ways to improve the system performance, which will be described in the next chapter.

7

Improvements To The Advisory Control Strategy And System Design

This chapter will analyze how the performance of the system can be improved. Firstly, changes to the advisory control strategy will be analyzed, followed by changes to the system design. Section 7.1 will introduce a moving average to smoothen the control signal, which the advisory control uses to turn electrolyzers on and to idle. Two versions will be selected from the results of Section 7.1, one for the 4x5 MW and one for the 2x10 MW, and those versions will be used for the remainder of the report. In Section 7.2, the effect of using a weather forecast on the two selected versions will be analysed. By having information about the expected power output from the wind turbine, the advisory control should be able to improve its decision-making regarding turning electrolyzers on. Next, Section 7.3 considers the impact of having an additional storage element capable of keeping the last electrolyzer idling. Lastly, in Section 7.4 the main take-aways from the chapter are summarized.

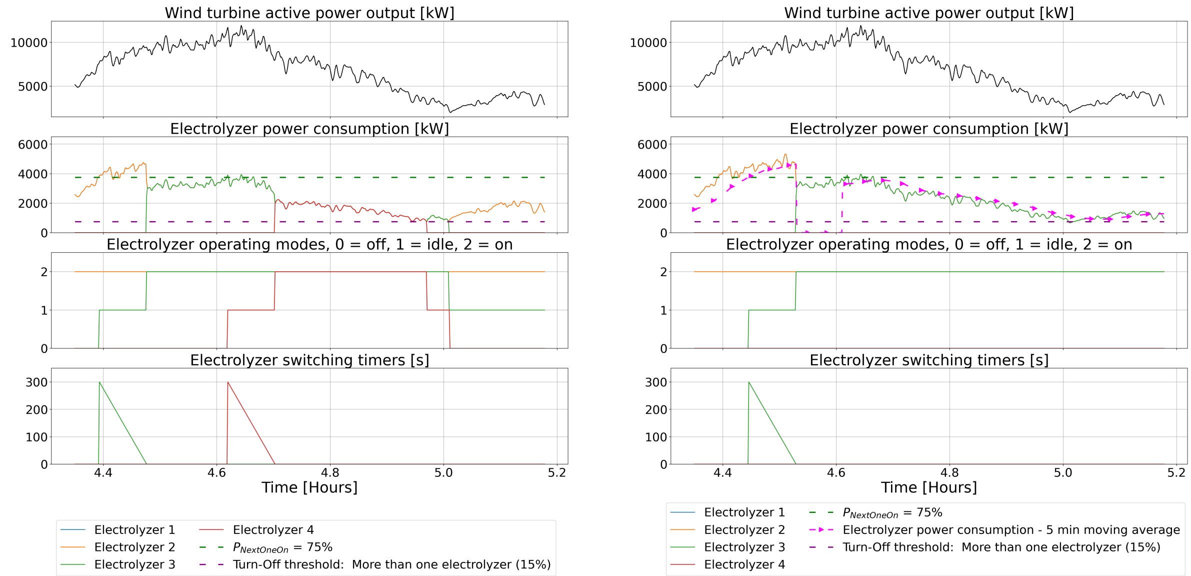
7.1. Moving average filtering of the control signal

This section will analyze how much of an impact a moving average filtering of the control signal can have on the system performance. By doing that, the advisory control will be less sensitive to instantaneous fluctuations in the control signal. As a reminder, the control signal is the wind turbine's power output when deciding whether to turn the first electrolyzer on and the electrolyzer power consumptions when deciding to turn additional electrolyzers on or to idle. Firstly, the reasoning for adding a moving average is explained in Section 7.1.1. Secondly, the changes to the advisory control along with the implementation are described in Section 7.1.2. In Section 7.1.3, the simulation setup is explained. This is followed by the simulation results using different moving average lengths in Section 7.1.4. In the results sections, the lengths of the moving averages that were tested were 2-minute, 5-minute and 10-minute moving averages. Their results were then compared to the results without a moving average. The main focus will be on how the 5 KPIs (mentioned at the beginning of Chapter 6) are affected, as well as the hydrogen vs turn-off graph. In Section 7.1.5, two versions will be selected from the results of the 4x5 MW and 2x10 MW to be analyzed further in the report. Lastly, the main take-aways from this section are described in Section 7.1.6.

7.1.1. Why it is beneficial to smoothen out the control signal

The reasoning for including a moving average is to smoothen out the control signal fluctuation, thereby preventing the advisory control from turning electrolyzers on and to idle, due to instantaneous fluctuations. By smoothening the control signal, the advisory control will rather make decisions to turn electrolyzers on or to idle, based on longer term trends.

To provide an example of a situation where including a moving average had a positive effect, see Figure 7.1a and Figure 7.1b. Both figures show a snapshot of the same time period from a simulation with the 4x5 MW configuration, but one uses a moving average while the other does not. Comparing



(a) Without moving average

(b) With 5 minute moving average

Figure 7.1: Simulation segment with and without using moving average to smoothen the control signal

the two figures, it can clearly be seen that by smoothening the control signal, the electrolyzers were not turned-on nor to idle, due to instantaneous fluctuations. The difference between these two scenarios shows how the advisory control becomes more robust with regard to instantaneous fluctuations in the wind turbine power output.

7.1.2. Additions to the designed advisory control strategy

The additions to the designed advisory control are split into three parts. Firstly, how to turn the electrolyzers on, and secondly, why the moving average is reset after each electrolyzer is turned on. Lastly, how to deal with idling electrolyzers is covered.

Turning the electrolyzers on

When there are no electrolyzers operating, the advisory control monitors the power output signal from the wind turbine when deciding if to turn the first electrolyzer on. The moving average of that control signal will not be long as no power is being captured for electrolysis when all electrolyzers are off. Therefore, a value of a 1-minute moving average was selected. Such a low moving average was chosen because the turn-on threshold for the first electrolyzer, of 20%, already provides a 10% margin above the minimum operating point, which is the turn-to-idle threshold when there is only one operating electrolyzer.

When the first electrolyzer has become operational, the advisory control starts measuring the moving average of the first electrolyzer's power consumption. That moving average signal is then used for the decision to turn the next electrolyzer on. For example, this can be seen in Figure 7.1b, that the electrolyzers get turned on when the moving average control signal (shown in the dashed purple line with triangles) crosses the turn-on threshold.

Resetting the moving average

Because the advisory control uses the moving average of the electrolyzers, but not the wind turbine, as the control signal, it is important to reset the moving average when a new electrolyzer becomes operational. An example of the signal being reset can be seen in Figure 7.1b by the signal dropping to zero when the third electrolyzer (in green) becomes operational. After the signal is reset, the advisory control starts measuring the moving average again but does not consider turning electrolyzers on or to idle until the moving average has reached the selected measurement length. For a 5-minute moving average, the measurement length is 5 minutes. Therefore, the advisory control does nothing while measuring the moving average, except if the electrolyzer's power consumption drops below the minimum operating point. In that case, the advisory control must turn an electrolyzer idle.

It is important to reset the moving average because when a new electrolyzer becomes operational, the advisory control splits the available power between the operational electrolyzers. By resetting the moving average when the newly turned on electrolyzers ramp up, each electrolyzer will have the same moving average value since the controller splits the available power evenly between the operational electrolyzers. There are other implementation reasons, for example because the advisory control always turns off the electrolyzer with the highest operating lifetime, which makes it necessary to reset the moving average. In case the reader is interested in a more detailed description and why it is required to reset the moving average, see Section E.1.

Idling electrolyzers

It was decided not to use the moving average of the signal when deciding to turn idling electrolyzers back on. The turn-on-from-idle threshold is kept at 50%. Therefore, whenever the instantaneous power consumption of the electrolyzers reach 50% of their rated capacity and there is an electrolyzer in idle, the advisory control will turn the idling electrolyzer back on. The reason for not using the moving average signal is the negative effect of having electrolyzers for long in idle operation, as was highlighted in Chapter 6. As was explained in Section 4.3, idle electrolyzers are also very quick to restart production, and it is assumed to not negatively impact their lifetime to frequently turn them, from on to idle and from idle back on.

7.1.3. Simulation setup

To simulate the effect of including a moving average, it was decided to increase the simulation length from 1 week to 1 month. A longer power output time series was required to properly visualize the impact on the hydrogen vs turn-off rate graph, as well as to better understand the changes in the 5 KPIs. The 1 month power output profile which was simulated can be seen below in Figure 7.2.

The results will be displayed in the same manner as in Chapter 6, with the only difference that now the curtailed energy and hydrogen production are shown in a ”per day” fashion. The overall hydrogen production and curtailed energy are therefore divided by the number of days of the simulation (31 days).

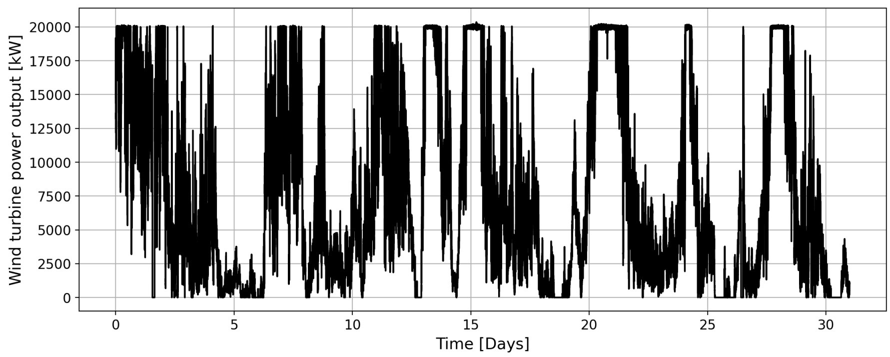


Figure 7.2: Case 2: One month power output profile

7.1.4. Results

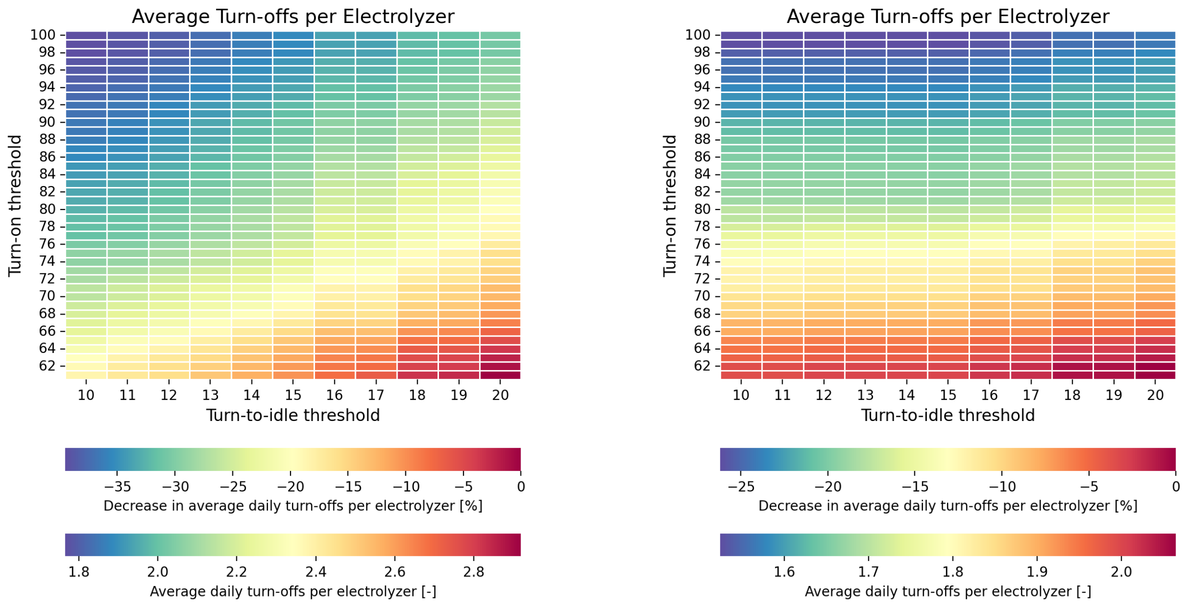
This section will analyse the impact of smoothening the control signal when using three moving average lengths, namely 2-minute, 5-minute, and 10-minute moving averages. This section starts with analysing if there are any observed changes in the color maps when using a moving average. The main focus of this section will then be to understand how the 5 KPIs are affected.

To graphically show the difference between the trends, the color maps of the results with and without the moving average will be shown side-by-side. It is important to know that their scales are not the same. The point of the figures is to identify the changes in the trends such that they can be understood. The results will be based on the 5-minute moving average as there were no large changes observed when using the 2-minute or 10-minute moving average. Furthermore, the results will be shown using the 4x5 MW configuration, as the same changes in trend were observed for the 2x10 MW configuration.

In Figure 7.3 the daily turn-off rate color map can be seen for the 4x5 MW configuration without and with moving average, in Figure 7.3a, and Figure 7.3b respectively. Looking at the changes in the trend, when comparing the figure to the right to the figure on the left, it can be seen that with a 5-minute moving average, the daily turn-off rate changes very little with different turn-to-idle thresholds. This can be seen by the colors staying mostly the same from left to right. Looking at Figure 7.3a, a clearer decrease in turn-offs can be seen when lowering the turn-to-idle threshold. This result can be explained that by smoothening the control signal, the turn-to-idle thresholds that are close to each other are, more often than not, all crossed in quick succession. When smoothening the control signal, the impact of instantaneous fluctuations is weakened, and the wind turbine power output trend becomes more important. When the 5-minute moving average of the electrolyzer's power consumption falls below 20%, for example, it means that the trend of the wind turbine power output has been declining and therefore is likely to also drop below 19%, and 18% and so forth. There is still an observed decrease in the turn-off rate from right to left, but the main point is that it is less than the results without a moving average. The same logic goes for the turn-on threshold, that the trend of the wind turbine power output becomes more important, causing versions with similar turn-on thresholds to have similar turn-offs.

For the other KPIs, similar changes were observed, that the versions started to only show a difference for different turn-on thresholds, and the turn-to-idle threshold started to have a lower impact. It is also due to the fact that for the moving average signal to drop below the turn-to-idle threshold, the power consumption of the electrolyzer is fluctuating close to the minimum operating point for some time and often drops below the minimum operating point, causing the electrolyzer to be set to idle.

The color maps of the other KPIs are shown with a 5-minute moving average, next to the results without a moving average, in Section E.2 for both the 4x5 MW and 2x10 MW.



(a) Without moving average

(b) 5 minute moving average

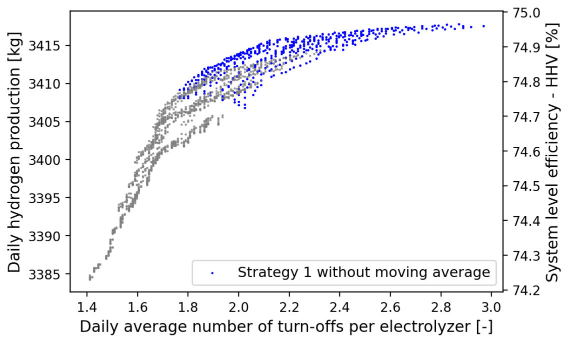
Figure 7.3: Average number of turn-offs with and without a 5-minute moving average (4x5 MW electrolyzer configuration)

The relationship between hydrogen production and turn-offs will be used to graphically show the effect of different lengths of the moving average. In Figure 7.4 the hydrogen production vs turn-offs for all 4 settings, namely without moving average (a), and with 2-minute (b), 5-minute (c) and 10-minute (d) moving average, can be seen. Each subfigure shows the results of their respective setting in color, while the other results are included in gray for comparison. Figure 7.4 clearly shows that decreasing the daily turn-off rate comes at the expense of lower hydrogen production. For clearer comparison, a secondary y-axis is included on the right of each subfigure, which shows the HHV system-level efficiency[1]. Looking

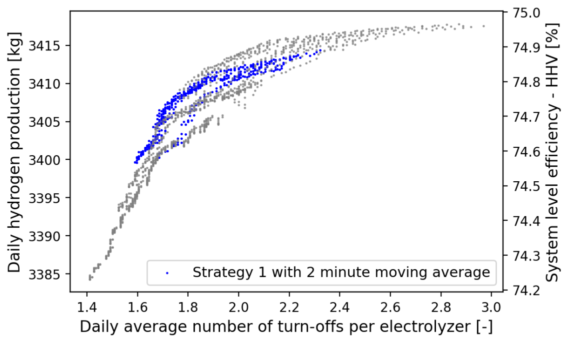
[1]The HHV system-level efficiency was obtained by dividing the HHV energy content of the produced hydrogen into the overall

at Figure 7.4a, it can be seen that without using a moving average, the highest hydrogen production is obtained at the top right corner, with around 3 daily turn-offs per electrolyzer. By smoothening the control signal, it was possible to decrease the daily turn-off rate down to 1.4, but that came at the expense of lowering the system level efficiency by about 0.8%. One of the main findings from Figure 7.4, is that depending on how the system is operated, it is possible to prioritise hydrogen production or the daily turn-off rate.

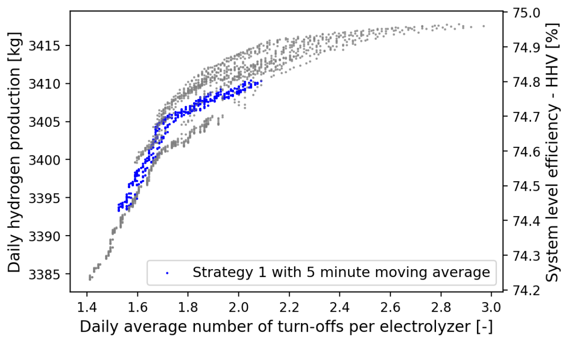
Figure 7.4 shows that by increasing the moving average length, the turn-off rate decreases. Furthermore, the results (the blue dots) start clustering up, while the results without the moving average have a larger spread. This is due to the same effect as explained with regard to the color maps earlier in this section. The difference in hydrogen production when using different versions but the same moving average length has decreased, with the versions having only around 0.2 - 0.3% differences. That shows that the selection of the moving average length also has a big impact.



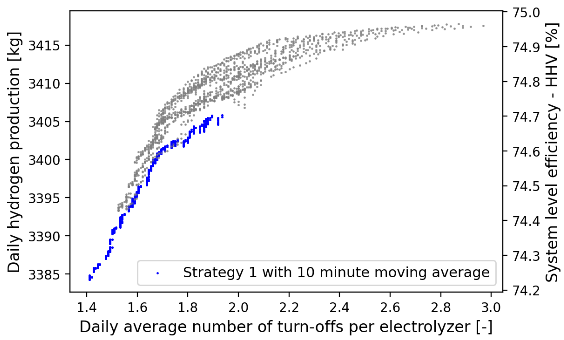
(a) Without moving average



(b) With 2 minute moving average



(c) With 5 minute moving average



(d) With 10 minute moving average

Figure 7.4: Comparison of hydrogen production vs turn-offs using different time lengths of moving average, with strategy 1. These results are based on simulating case 1 with a 4x5 MW electrolyzer configuration

In Table 7.1, the changes to the 5 KPIs for different moving average lengths can be seen. It was decided to show the result with a turn-on threshold of 60% coupled with a turn-on threshold of 20% (60/20) as that version showed the biggest impact as expected. Table 7.1 shows that the daily turn-off rate, overall switching rate, and idle time sequentially improve when increasing the moving average length. On the other hand, the curtailed energy increases when increasing the moving average length, and that is reflected in the decreasing hydrogen production. The result for the 100/10 version can be seen in the appendix, in Table E.1. To summarize the findings, versions not chasing efficiency gains had lower decreases in the turn-off rate, switching, and idle as expected. Most notably, the increased curtailed energy was roughly twice as large compared to 60/20. That is because having a higher turn-on threshold, it occurs more frequently that the wind turbine power output exceeds the maximum operating point of the electrolyzers while the next electrolyzer is turning on, causing periods where energy needs to be curtailed.

energy output from the wind turbine

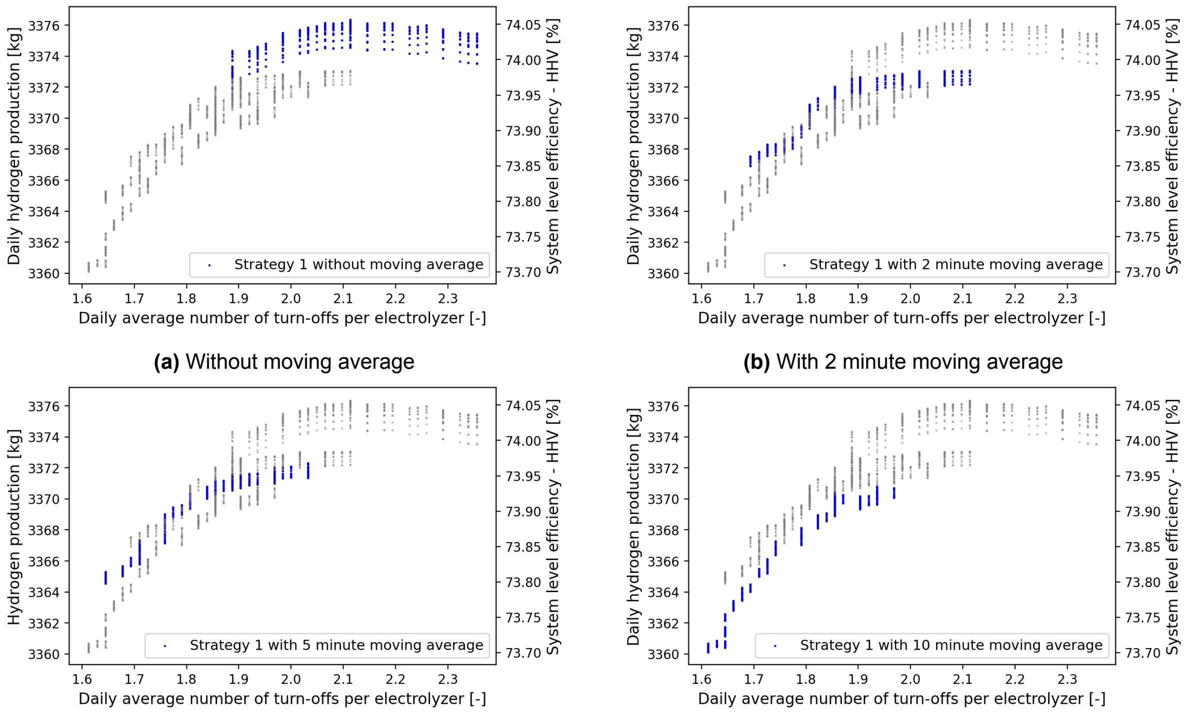
These results mainly show that the use of a moving average has a more profound impact on versions attempting to chase efficiency gains. The results from Chapter 6 showed that versions attempting to chase efficiency gains had much higher turn-off rates than other versions without a large benefit in hydrogen production. Including a moving average is making versions attempting to chase efficiency gains more competitive with regards to the turn-off rate.

Table 7.1: Results of the 5 KPIs when simulating case 2 with the 4x5 MW configuration, with and without a moving average.

Simulation setting	Daily hydrogen production	Daily turn-off rate per electrolyzer	Daily switching rate per electrolyzer	Daily idle time	Daily curtailed energy
	Turn-on threshold: 60% Turn-to-idle threshold: 20%				
Base case:	3,417.5 kg	2.97	19.1	3.53 hours	1,204 kWh
2 minute average	-0.1%	-21.7%	-34.4%	-17.7%	+7.7%
5 minute average	-0.2%	-29.6%	-46.0%	-20.6%	+15.4%
10 minute average	-0.3%	-34.8%	-52.8%	-29.9%	+25.1%

The same analysis will be shown for the 2x10 MW, but to not be repetitive, the aim is to observe the differences when using the 2x10 MW instead of 4x5 MW.

In Figure 7.5, the hydrogen vs turn-off graph is shown for the four different settings. A similar trend is observed that by smoothening the control signal, the turn-off rate is decreased, and by increasing the moving average signal, a further reduction is possible. The secondary y-axis shows that the difference between the lowest and highest average system-level efficiency is only around 0.35%.



(a) Without moving average

(b) With 2 minute moving average

(c) With 5 minute moving average

(d) With 10 minute moving average

Figure 7.5: Comparison of hydrogen production vs turn-offs using different time lengths of moving average, with strategy 1. These results are based on simulating case 1 with a 2x10 MW electrolyzer configuration

The results of the 5 KPIs for 60/20 and 100/10 versions, with and without a moving average, can be seen in Table E.2. The findings will be summarized here. The same effect was observed: turn-offs, switching, and idle time decreased. The magnitude of the decreases was greater with the 4x5 MW, leading to the result that the 4x5 MW managed to get a lower daily turn-off rate than the 2x10 MW. The lowest observed daily turn-off rate of the 2x10 MW is 1.61 with a 10-minute moving average compared to 1.41 for the 4x5 MW configuration with the same moving average length.

To get an understanding of how good of a result this is, a for loop went through the earlier power output time series, case 2, and counted the number of turn-offs, under the below assumptions:

- The first electrolyzer is turned on when the power output from the wind turbine exceeds 20% the electrolyzer rated power
- The next electrolyzer is turned on when the power output from the wind turbine exceeds 120% of the operating electrolyzer´s power capacity
- All turned on electrolyzers are turned off when the power output drops below the idling consumption of a single electrolyzer (2%; 100 kW for the 4x5 MW and 200 kW for the 2x10 MW)

The result of this back-of-the-envelope analysis was that the estimated lowest possible number of daily turn-offs per electrolyzer was 1.31 for the 4x5 MW and 1.45 for the 2x10 MW. That shows how close to the theoretical lowest possible number of turn-offs the operational strategy got. Furthermore, this shows the effect of increasing the size of the electrolyzers.

The hydrogen production decreased for the 2x10 MW just like for the 4x5 MW, but by a lower magnitude because the increase in curtailed energy was less with the 2x10 MW. That can be explained by the fact that for a 5 MW electrolyzer to ramp up from 100% to 120%, the wind turbine's power output needs to increase by 1 MW, but for the 2x10 MW configuration, the power output needs to increase by 2 MW. Hence, it is less likely that a 2x10 MW configuration exceeds the maximum operating point while turning the next electrolyzer on.

7.1.5. Selection of two versions to use as base cases for further improvements, for the 4x5 MW and 2x10 MW

To select two versions, the length of the moving average needs to selected first. The results in this section showed a trade-off between hydrogen production and the daily turn-off rate. The following sections of this chapter will analyse the two selected versions with the aim of decreasing the turn-off rate further. Therefore the two versions will be selected such that they have high hydrogen production. It was decided to select the versions such that they were as close to the upper left corner as possible from figures 7.4 and 7.5. For the 4x5 MW, that is a turn-off rate of around 1.7, while for the 2x10 MW, a turn-off rate of around 1.8. For both configurations, that was using a 2-minute moving average, and the selected versions are summarized below in Table 7.2.

Table 7.2: Selected versions of the 4x5 MW and 2x10 MW electrolyzer configurations to use as base cases for further analysis

Electrolyzer configuration	Turn-to idle threshold	Turn-on threshold	Length of moving average	Daily hydrogen production [kg]	Daily turn-off rate per electrolyzer
4x5 MW	15%	85%	2 minute	3,407.6	1.71
2x10 MW	17%	87%	2 minute	3,370.9	1.81

7.1.6. Main take-away´s

The main finding of smoothening the control signal using a moving average was that there was an apparent improvement in the system performance. The daily turn-off rate, overall switching, and idle time all decreased considerably. The hydrogen production only decreased slightly, primarily due to increased curtailed energy.

The choice of the version and the moving average length are design choices, both of which can be selected to prioritise either the hydrogen production or the daily turn-off rate. However, further knowledge of the importance of decreasing the turn-off rate is required to make a more enlightened decision on which to prioritise.

7.2. Inclusion of a weather forecast

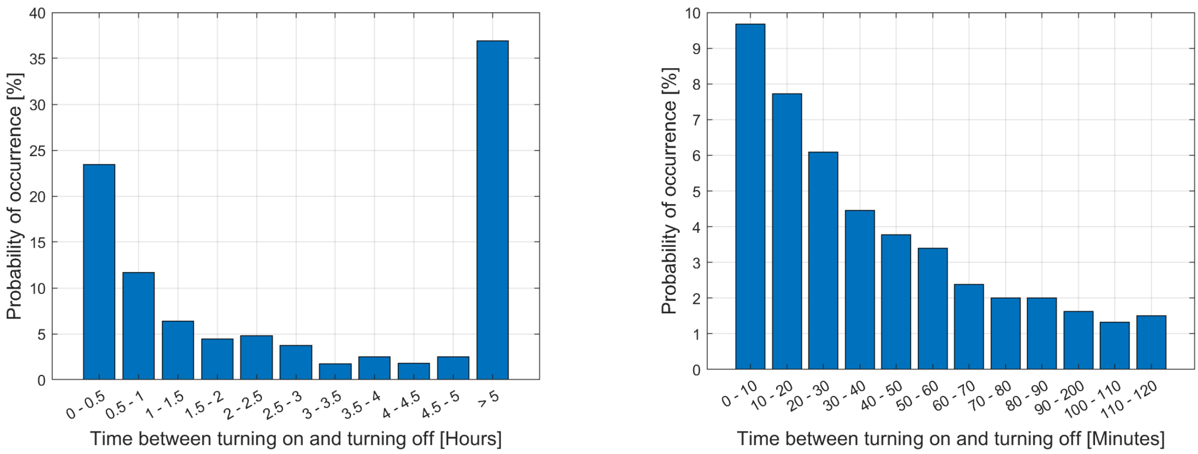
This section will analyze how much impact a weather forecast can have on the system performance. This analysis will be focused on the 4x5 MW electrolyzer configuration, while the results of the 2x10 MW will be shown in the appendix and mainly summarized in this chapter.

Firstly, the reasoning for adding a weather forecast is explained in Section 7.2.1. Secondly, a top-level description of the weather forecast implementation is given in Section 7.2.2. How the advisory control will use the forecast is detailed in Section 7.2.3, where the term minimum acceptable forecasted power will be described. An analysis of the minimum acceptable forecasted power is done in Section 7.2.4. This is followed by the results, which are split into two parts, firstly with a perfect forecast in Section 7.2.5 and then with an imperfect forecast in Section 7.2.6. The perfect forecast will show the maximum achievable gain with a forecast, while the imperfect forecast will quantify how a more realistic forecast manages to perform compared to the perfect forecast.

7.2.1. Why include a weather forecast

With the current designed advisory control strategy, an electrolyzer is turned on when the operating electrolyzers reach a power consumption above the turn-on threshold. However, these decisions are made with no information about the expected wind turbine power output over the next hour(s). Therefore, the advisory control may turn an electrolyzer on, only to turn it off a few minutes later if the wind ramps down.

To visualize the expected benefit of having a weather forecast, a simulation was run where the operating time of each electrolyzer between turn-on and turn-off was counted and stored. To get a long-term representative result, a 9 month, 5-second resolution power output time series was simulated. The 9 month power output profile can be seen in Figure F.1. A simulation of 9 months was selected as it was the longest consecutive period in the 1.5 year data set, where there were no large gaps in the data collection. The 9 month period is from 26th September 2020 - 1st July 2021. A histogram distribution of the result for the 4x5 MW can be seen below in Figure 7.6, where Figure 7.6a shows a big picture overview and Figure 7.6b zooms in on the first two hours and increases the resolution by having more bins. Figure 7.6a shows that around 23% of the turn-offs occur in the first half hour after turning an electrolyzer on. This is followed by around 12% for the next half hour. These results show that a large portion of the turn-offs occur in the first 1 hour after an electrolyzer is turned on. In Figure 7.6b, each bar represents a 10 minute interval and goes up to 2 hours. Figure 7.6b is shown to better understand the distribution within the first two hours. From Figure 7.6b, it can be seen that the first 10 minutes represent roughly 10% of the total turn-offs and the next 10 minutes close to 8%.



(a) Big picture overview

(b) Zoomed in on the first two hours

Figure 7.6: Histogram of the time between turning any electrolyzer on and turning any electrolyzer off for the 4x5 MW

These results were based on a first-in-first-out (FIFO) operational strategy to get a correct distribution. Hence whenever an electrolyzer needed to be turned off, it was the most recently turned on electrolyzer. This shows the potential of including a weather forecast. By estimating the future power output, it should be possible to prevent unnecessarily turning electrolyzers on.

7.2.2. Forecast description

Usually, when referring to a weather forecast, the advisory control would receive a forecasted wind speed over a certain time horizon and translate that wind speed to an estimated power output. However, for this thesis project, it was not possible to obtain a real weather forecast data that could correspond to the power output time-series used for the simulations. To solve that problem, the conversion step from a weather forecast to power forecast was skipped, and the power forecast was created from the power output time-series data.

A perfect forecast is when the advisory control will know exactly what will happen over the selected time horizon. To simulate that, the advisory control will need to know the exact control signal (the moving averaged control signal) and the instantaneous power fluctuations. It is important to know the instantaneous power fluctuations as the moving average control signal might not drop below the turn-to-idle threshold, but the instantaneous power might drop below the minimum operating point, causing the advisory control to set an electrolyzer to idle.

Knowing the exact control signal and instantaneous power output from the wind turbine would be very difficult to obtain in practice, however. The imperfect forecast will attempt a more realistic approach. As explained before, the generic process is to convert the expected average wind speed over the horizon to an average power output. Skipping the conversion step from wind speed to power output, the exact time-series of the power output is used to calculate the average power output over the selected time horizon. That average power output is then used as the power forecast. Although the estimated average power over the horizon will be 100% accurate, this forecast will be referenced as the imperfect forecast as it still leaves out a lot of information.

7.2.3. Additions to the designed advisory control strategy

This section will describe how the advisory control will use the perfect and imperfect forecasts in the decision process of turning electrolyzers on. The perfect forecast will firstly be described, followed by the imperfect forecast.

Usage of the perfect forecast

The main aim of the weather forecast is to prevent unnecessarily turning electrolyzers on. Two methods were identified to prevent unnecessarily turning electrolyzers on. Firstly by knowing beforehand whether an electrolyzer will be turned off, and secondly, by knowing whether it is sub-optimal to turn an electrolyzer on from a production perspective.

The advisory control turns an electrolyzer on when the control signal surpasses the turn-on threshold. With a perfect forecast, the advisory control will add another conditional statement that it will only turn on the next electrolyzer if it is not turned off over the time horizon. The moving average control signal of the wind turbine power output will be used such that the advisory control can estimate beforehand if the signal will drop below a point where the electrolyzer will be turned off. The wind turbine power output moving average could be converted to an electrolyzer power consumption moving average, hence replicating the control signal that would occur if an electrolyzer would be turned on. Furthermore, the advisory control will know if the instantaneous power output of the wind turbine will drop below a point where the electrolyzer will be turned off.

The advisory control will also base the decision on whether to turn an additional electrolyzer on, depending on whether it is more efficient to do so or not. A way to estimate whether or not it is beneficial to turn an electrolyzer on is to check whether the average power over the horizon leads to a higher hydrogen production with an additional electrolyzer. The advisory control will add another conditional statement that the average power over the horizon needs to be greater than a selected Minimum Acceptable Forecasted Power (MAFP). Therefore, the MAFP is a design variable that should be selected such that the advisory control only turns the next electrolyzer on if it is more efficient. The next sub chapter will describe how the MAFP was selected. The perfect forecast will then not turn an electrolyzer on unless all of three conditional statements are true:

- Moving average control signal has surpassed the turn-on threshold.
- It is beneficial from a production perspective to turn the electrolyzer on. That is, the average power over the horizon is greater than the minimum acceptable forecasted power.
- The electrolyzer will not be turned off with the horizon.

Usage of the imperfect forecast
With the imperfect forecast, the advisory control will not know the exact control signal nor the instantaneous power output from the wind turbine over the time horizon but only the average power output over the time horizon. Therefore, only the first two conditional statements from the bulleted list above will be used.

7.2.4. Selecting the minimum acceptable forecasted power

The production efficiency curve for four 5 MW electrolyzers with a 20 MW wind turbine can be seen below in Figure 7.7. The dashed lines show the threshold where turning the next electrolyzer on becomes equally efficient as not turning it on. For example, when deciding to turn the second electrolyzer on, the advisory control should not turn it on unless the average power over the horizon is at least equal to the threshold of 2.5 MW. However, having the MAFP threshold at the exact point where the efficiency curves cross is sub-optimal. This is because the power forecast only indicates the average power over the time-horizon, while the actual fluctuations will fluctuate around the average. The MAFP should therefore be increased to indicate that turning the next electrolyzer on is truly more efficient.

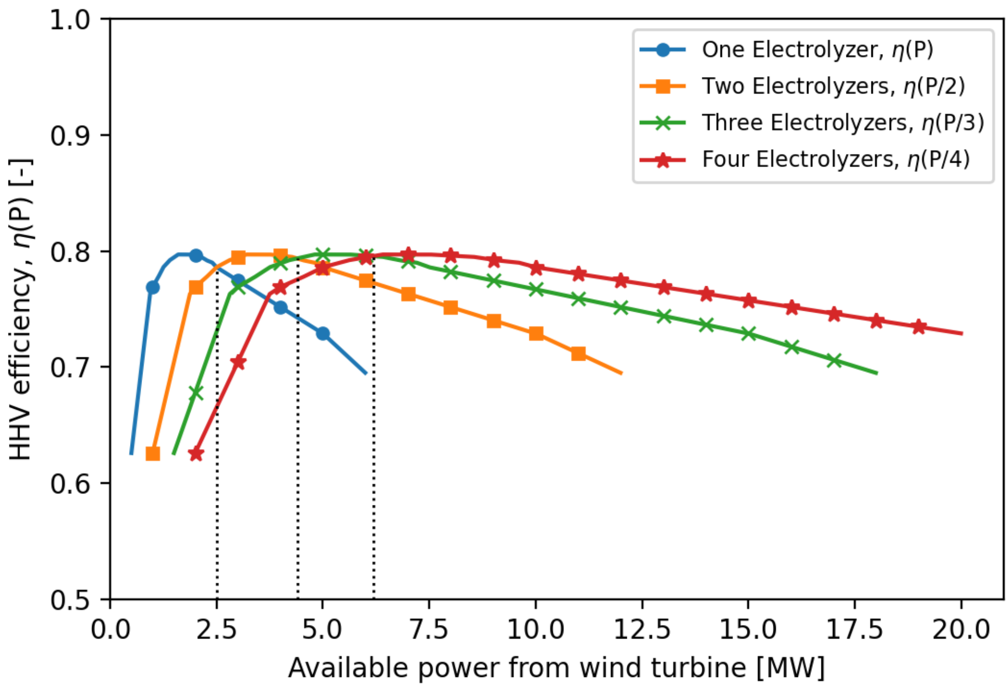


Figure 7.7: Production efficiency with different number of operational 5 MW electrolyzers.

As the impact of frequent turn-offs on degradation and long-term hydrogen production is unknown, it is hard to define the ”optimal” MAFP. To find a ”good” MAFP, multiple different thresholds were tested to evaluate the impact on the hydrogen production and the turn-off rate. The MAFP thresholds were tested by adding a percentage change to the exact cross-over points in Figure 7.7. The percentage changes were from 0% to 100%, with a 5% step size, and were simulated with 60/90/120/150-minute horizons. The imperfect forecast was used. Hence it knew the correct average power over the horizons but not the exact control signals. The result can be seen below in Figure 7.8, where the color bar shows the results with a MAFP using a certain percentage increase to the cross-over points. Figure 7.8 shows the usual trade-off between hydrogen production and the turn-off rate. Therefore, the selection of the MAFP is a design choice that can either prioritize hydrogen production or the turn-off rate.

An acceptable decrease in hydrogen production was deemed to be 0.1%, and in Figure 7.8, a dashed horizontal line is plotted at the decrease of 0.1% in each subfigure. Focusing on where the dashed line crosses the scatter trends, it can be seen that where the MAFP increase surpasses a decrease of 0.1% in hydrogen production, changes depending on the horizon. The information at the cross-over points are summarized below in Table 7.3, to more clearly show this. Table 7.3 shows how that the required percentage increase decreases for longer horizons. At this point, the optimal time horizon is not known, and this analysis has shown that there will be an optimal time horizon for each MAFP setting.

It was decided to select a 35% increase, as that is roughly the average of the percentage increases for the different horizons in Table 7.3. With the selected MAFP increase at 35%, the MAFP thresholds are summarized below in Table 7.4.

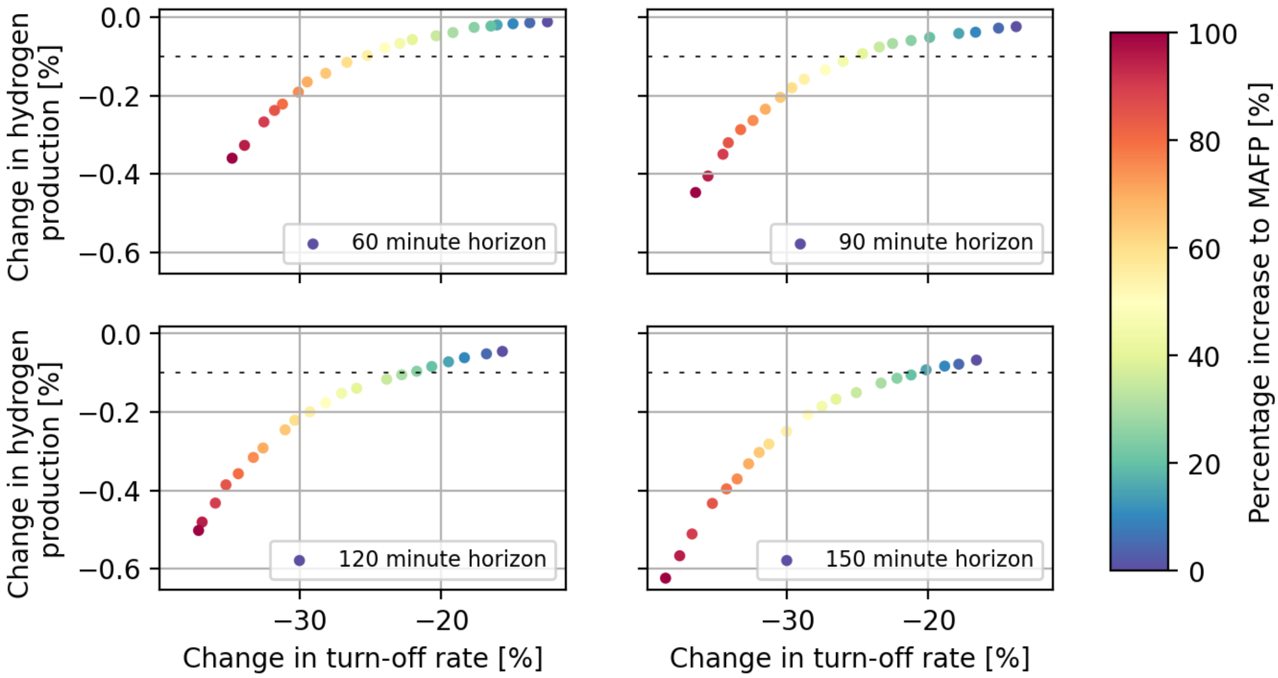


Figure 7.8: H2 vs average number of turn-offs with different MAFP.

Table 7.3: Cross-over points where the decrease in hydrogen production is around 0.1%.

Time horizon minutes>minutes	Decrease in hydrogen production [%]	Decrease in the turn-off rate [%]	Percentage increase to the MAFP [%]
60	-0.098%	-25.2%	55%
90	-0.093%	-24.6%	40%
120	-0.096%	-21.7%	25%
150	-0.106%	-21.2%	20%

Table 7.4: Summary of the minimum acceptable forecasted power with different number of operational electrolyzers, and using an increase of 35% on top of the cross-over points.

Number of operational electrolyzers	Cross-over point	MAFP General	MAFP 5 MW electrolyzers [MW]
0	N/A (minimum operating point = 10%)	1 x 10 x 1.35 [%]	0.675
1	50%	1 x 50 x 1.35 [%]	3.375
2	43.9%	2 x 43.9 x 1.35 [%]	5.93
3	41.2%	3 x 41.2 x 1.35 [%]	8.34

The same analysis was done for the 2x10 MW and can be seen in Section F.2.1. The results were very similar, and an increase of 35% was also selected for the 2x10 MW configuration.

7.2.5. Simulation results with a perfect forecast

This section will simulate the 9 month power output time-series with the 4x5 MW configuration, based on the selected versions from Section 7.1.5. By using a perfect forecast, the maximum potential decrease in the turn-off rate will be quantified. To get a good understanding of the effect of using different time horizon settings, the time horizons were tested in the range of 15 minutes to 5 hours with 15-minute increments.

In Figure 7.9 a bar chart is depicted, which shows how the effect on hydrogen production and daily turn-off rate changes with different time horizons on the x-axis. The percentage changes are using the results of the selected version without a forecast as the reference. Figure 7.9 shows that with an increasing time horizon, the daily turn-off rate decreases, as expected. With a horizon of 30 minutes, the turn-off rate decreases by almost 30%, while the decrease in production is largely negligible, or 0.2%. As the horizon increases, hydrogen production starts decreasing more because the advisory control does not turn any electrolyzer on if it will be turned off within the horizon. Interestingly, the hydrogen production does not decrease as much as expected. With a 5 hour horizon (300 minutes), the hydrogen production only decreases by around 3%. The reason for this is that if the advisory control knows that the electrolyzer will be turned off within the horizon, that is also an indication that the power output over the horizon will not be very high. However, with longer horizons, a single turn-off can cause the advisory control to skip turning an electrolyzer on, even though it would be very beneficial to turn the electrolyzer on most of the time.

The main point of Figure 7.9 is to provide a benchmark to which the imperfect forecast will be compared in the next section.

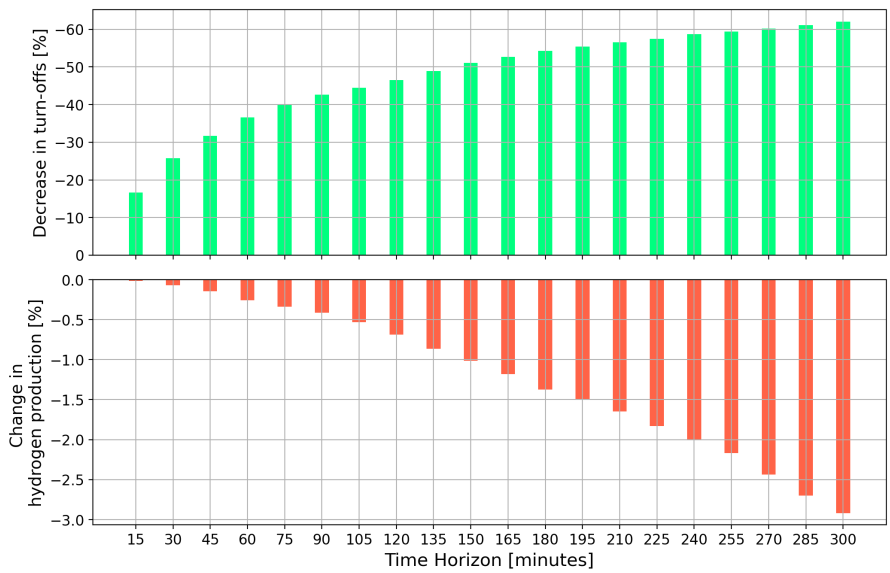


Figure 7.9: Change in hydrogen production and daily turn-off rate with different horizons of a perfect forecast

7.2.6. Simulation results with an imperfect forecast

Now the results with the imperfect forecast will be shown and compared to the perfect forecast. In Figure 7.10, the results of both the imperfect forecast and perfect forecast can be seen. The imperfect forecast, manages to perform relatively well, obtaining around 50-60% of the maximum achievable turn-off rate reduction, up to the horizon of 2 hours, after which the spreads start to increase. Interestingly, with an imperfect forecast, the reduction in turn-off rate starts tapering off after a horizon of around 90 - 120 minutes. Hence a longer horizon does not bring noticeable further reductions in the turn-off rate. Another big difference is that the imperfect forecast has a smaller reduction in hydrogen production. That is because, with the imperfect forecast, electrolyzers are turned on even though they might be turned off within the time horizon of the forecast.

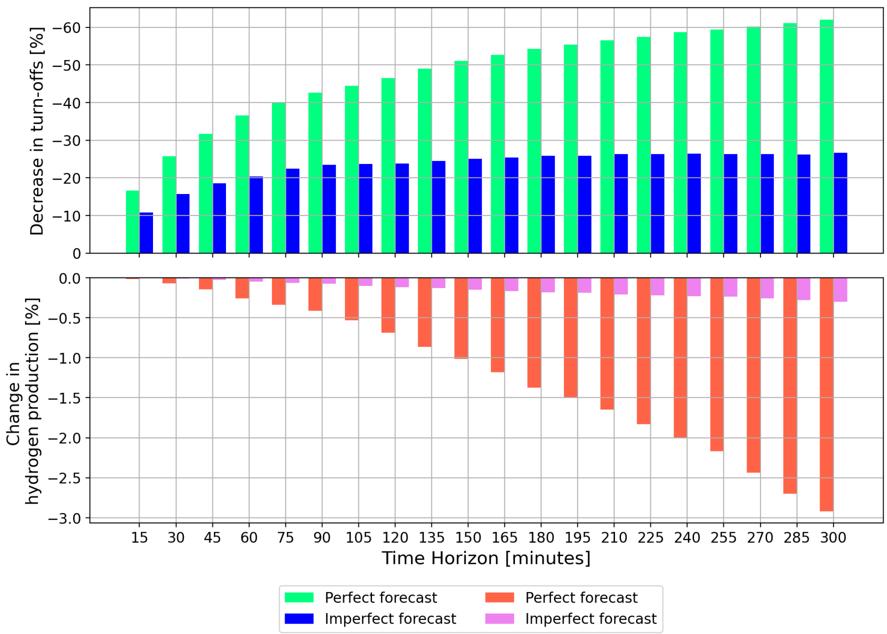


Figure 7.10: Perfect vs imperfect forecast: Change in hydrogen production and daily turn-off rate with different time horizons

To further understand the impact of having a weather forecast, the 5 KPIs are summarized below in Table 7.5 for a few selected time horizons, namely 30/60/90/120 minutes. Table 7.5 shows that the turn-off rate, switching rate, and idle time decrease, which positively impacts the hydrogen production. The curtailed energy increases, which has a negative impact on the hydrogen production, however. Curtailed energy increases because the advisory control system switches electrolyzers on less frequently compared to the base case, which doesn't include a weather forecast. These four KPIs all tie back to the hydrogen production, which shows that the lost hydrogen production of the increased curtailed energy, is cancelled out by the decreased consumption of the turn-ons, switching, and idle time. That shows that overall, the main impact of the forecast is a decrease in the turn-off rate while having a negligible impact on the hydrogen production. This makes the inclusion of a weather forecast a very attractive addition to the advisory control.

Table 7.5: Changes in the 5 KPIs with an imperfect forecast with 4 selected time horizons.

Weather forecast settings	Electrolyzer system configuration	Change in Hydrogen production [%]	Change in the daily turn-off rate per electrolyzer [%]	Change in the daily switching rate per electrolyzer [%]	Change in the daily idle time [%]	Change in curtailed energy [%]
Base case No Horizon	4x5 MW	3652 kg/day	1.55 daily turn-offs per elec	6.67 daily switching per elec	1.4 hours/day	1152 kWh/day
30 min forecast Imperfect	4x5 MW	-0.01	-15.7	-10.4	-9.8	+2.1
60 min forecast Imperfect	4x5 MW	-0.05	-20.3	-14.7	-15.1	+6.4
90 min forecast Imperfect	4x5 MW	-0.08	-22.46	-17.6	-20.1	+9.8
120 min forecast Imperfect	4x5 MW	-0.12	-23.8	-18.4	-21.1	+15.6

The same analysis was done for the 2x10 MW, and can be seen in Section F.3. A time horizon of 60 minutes was also chosen for the 2x10 MW. The only difference between the results for the 2x10 MW is that the decrease in hydrogen production is a bit larger. For example, a time horizon of 60 minutes has a -0.05% reduction in hydrogen production for the 4x5 MW but -0.15% for the 2x10 MW configuration. The reason for this difference is largely because the increase in curtailed energy is much higher for the 2x10 MW when using a weather forecast than the 4x5 MW.

For both system configurations, a 1 hour time horizon seemed to be a good balance between decreasing the turn-off rate while not negatively affecting the hydrogen production too much. Therefore, it was decided to select 1 hour as the best time horizon.

7.3. The effect of having an additional storage element capable of keeping electrolyzers in idle operation

In the current system design, there is one battery whose role is to maintain the system integrity when the wind turbine stops producing enough power. That battery is used only to keep all the necessary auxiliary equipment operating but not to maintain electrolyzers in idle operation. If the power output from the wind turbine becomes insufficient to keep the last electrolyzer idling, the electrolyzer is fully shut off. This section will analyze the effect of having an additional storage element (ASE) capable of keeping the last electrolyzer in idle operation.

There are two cases where the ASE comes into play. Firstly, when the wind turbine power output drops below the idling consumption, and there is an electrolyzer in idle. Secondly, if the power output drops below the starting up power consumption and there is an electrolyzer starting up. For the first case, the ASE will keep the idling electrolyzer in idle, and for the latter case, the ASE will continue the turning-on sequence of the newly turned-on electrolyzer, and when the turn-on sequence finishes, the ASE will set the electrolyzer to idle, and keep it there. When the power output from the wind turbine increases above the idle- and starting up consumptions, the wind turbine power output takes over from the ASE. The modeling implementation of the ASE was described in Section 3.5. In this sub-chapter, when referring to the ASE being able to operate an electrolyzer, that stands for the above description.

As was described in Section 3.5, the storage capacity of the ASE is given in time. By selecting the storage capacity of the ASE in minutes, it is possible to quantify the impact of having an ASE capable of operating the electrolyzers for a certain time. As the system is not connected to the grid, the energy that the ASE uses needs to come from the wind turbine and, therefore should negatively affect the hydrogen production. To take that into account, the required energy consumption to keep the electrolyzer in idle was summed up over the periods when the ASE kept an electrolyzer idling/starting up. After the simulation, the energy which was consumed was converted into equivalent hydrogen production, and that number was withdrawn from the total hydrogen production[2].

To investigate the effect of the ASE, the 9 month power output time-series was simulated with an ASE capable of operating the last electrolyzer for 10, 30, 60, 90, and 120 minutes. The analysis was done for both the 4x5 MW and 2x10 MW using their selected versions, with a 2-minute moving average and a 1-hour imperfect weather forecast. The results will be compared to the results with a 1-hour imperfect forecast and without an ASE.

The results for the 4x5 MW can be seen below in Table 7.6. The results show that the turn-off rate decreased drastically with an ASE capable of keeping the last electrolyzer idling. With a storage capacity capable of operating the electrolyzer for only 10 minutes, the turn-off rate decreased by further 25% and even increased the hydrogen production. That shows that the positive impact of having the electrolyzer ready to ramp up outweighs the hydrogen equivalent of the used energy in the ASE. The overall switching increases, which can be explained by the last electrolyzer frequently switching from on to idle and back on, whereas without the ASE it would have been turned off.

Table 7.6: Resulting change in performance in 4 KPIs with an additional storage element for the 4x5 MW using 85% turn-on threshold, 15% turn-to-idle threshold, 2-minute moving average and 60 minute power forecast.

Storage capacity [minutes]	Change in the hydrogen production after subtracting the hydrogen equivalent of the ASE energy usage [%]	Change in the turn off rate [%]	Change in the overall switching rate [%]	Change in the total idle time [%]
10	+0.12	-24.4	+12.5	+47.7
30	+0.15	-28.7	+16.2	+88.5
60	+0.15	-31.2	+17.9	+128.4
90	+0.14	-32.6	+18.5	+156.4
120	+0.14	-33.4	+19.1	+181.9

[2]Assuming 1 kg of hydrogen production consumes roughly 54 kWh

In Table 7.7, the results are shown for the 2x10 MW configuration. The hydrogen production increases similarly to the 4x5 MW, but the turn-off rate decreases more. An ASE with a storage capability of 10 minutes decreased the turn-off rate by 32%, compared to 24% for the 4x5 MW. This is because the idle consumption of a 10 MW electrolyzer is assumed to be twice as large as of a 5 MW electrolyzer. That increases the probability that the wind turbine power output drops below the required idle consumption. The results for both the 4x5 MW and 2x10 MW showed that the largest portion of the decrease in the turn-off rate is observed with a storage capacity up to 30 minutes. Any increase on top of the 30 minutes does not lead to drastic reductions in the turn-off rate.

Table 7.7: Resulting change in performance in 4 KPIs with an additional storage element for the 2x10 MW when simulating with a 87% turn-on threshold, 17% turn-to-idle threshold, 2 minute moving average and 60 minute power forecast.

Storage capacity [minutes]	Change in the hydrogen production after extracting the hydrogen equivalent of the ASE energy usage [%]	Change in the turn off rate [%]	Change in the overall switching rate [%]	Change in the total idle time [%]
10	+0.19	-31.9	+11.4	+54.3
30	+0.24	-38.8	+14.8	+94.8
60	+0.27	-42.6	+17.1	+129.7
90	+0.29	-45.0	+17.5	+154.8
120	+0.31	-47.3	+18.2	+177.8

To better visualize the impact of the ASE, Figure 7.11 shows the results with an imperfect forecast and an ASE with 10-minute storage capacity, and compares that to the results of the perfect forecast. The percentage changes are based on the selected version without a forecast and no ASE. Therefore, they are not the same percentage changes as shown in Table 7.6 which are based on a comparison with a forecast but no ASE. Nevertheless, the results show that the inclusion of an ASE, even just a small one capable of keeping a single electrolyzer idling for 10 minutes, provides substantial benefit to the system. The reduction in the turn-offs is substantial, making the system much better equipped to deal with the wind turbine power output fluctuations.

Including an ASE capable of keeping one electrolyzer in idle for 10 minutes only requires a storage capacity of 16.7 kWh for the 4x5 MW system [0.167 [hours]*5000 kW *2%] and 33 kWh for the 2x10 MW.

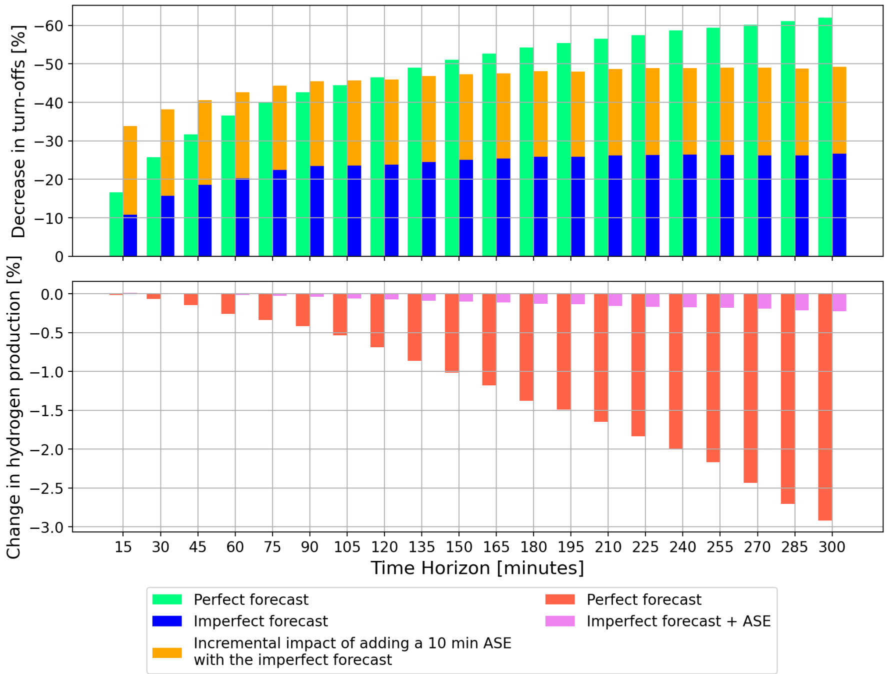


Figure 7.11: Perfect vs imperfect forecast with the ASE: Change in hydrogen production and daily turn-off rate with different time horizons

The inclusion of the ASE had one more important benefit, only improving the 2x10 MW configuration. The first electrolyzer is turned on at 20%, because having that threshold lower was found to result in a steep increase in the turn-off rate. The inclusion of the ASE, made it possible to decrease the turn-on threshold of the first electrolyzer without negatively impacting the turn-off rate by much. The analysis can be seen in Section F.4, but the results showed that for the 2x10 MW, by decreasing the turn-on threshold from 20% to 15%, the hydrogen production increased by 0.3%, while the turn-off rate increased by only 0.2%. Most of the results in this thesis have shown the relationship, that to increase the hydrogen production by x%, the negative impact to the turn-off rate is an order of magnitude higher. Hence, such an equal impact can be considered a very good result. For the 4x5 MW, it was not found to be beneficial to decrease the turn-on threshold, because the hydrogen production did not increase. The gain in hydrogen production was equally met by the increased consumption of the ASE.

The results in this sub-chapter have indicated that having an additional storage element capable of keeping electrolyzers in idle could bring substantial benefits to the system performance. When there is no ASE, the wind turbine is the only power source in the system that can operate the electrolyzers, and if the power production falls below the idling- and starting up consumption, the electrolyzers have to be shut down. Most interestingly, the results showed that having an additional storage element will not decrease the hydrogen production, under the assumption that keeping an idling electrolyzer consumes 2% of the electrolyzer rated power. The gain in having the electrolyzer ready to ramp up evens out the lost hydrogen production when directing energy to the ASE instead of to the electrolyzers.

The ASE had the additional benefit that for larger systems such as the 2x10 MW configuration compared to the 4x5 MW, it made it possible to decrease the turn-on threshold, which closed the performance gaps between the two systems slightly. The increase in performance can be seen in Section 7.4.

Increasing the idle consumption would result in an ASE with a larger energy capacity, but it would also make the inclusion of the ASE even more important. For example, if the idle consumption is increased to 10% of the electrolyzer rated power, the last idling electrolyzer would need to be fully shut down when the power production falls below 500 kW and 1 MW for the 4x5 MW and 2x10 MW configurations, respectively. Those numbers are far above the power production at the cut-in wind speed, as can be seen in Figure 4.1.

7.4. Main take-aways from this chapter

In this chapter, three additions to the system have been explored. Firstly the impact of smoothening the control signal with a moving average was analyzed. This was followed by the addition of a forecast estimating the power output over a given time horizon. Lastly, the effect of having an additional storage element capable of keeping the last electrolyzer idling was explored. All of these additions brought considerable improvements in the system's performance.

To visualize the impact of each of the above-mentioned additions, the results using the selected version for the 4x5 MW and 2x10 MW, when simulating the 9 month power output profile, will be displayed with the following settings:

- No moving average (from Chapter 6)
- With a 2-minute moving average
- With a 2-minute moving average and a 1-hour imperfect forecast
- With a 2-minute moving average, 1-hour forecast, and an additional storage element with a storage capacity of 10 minutes.

The resulting hydrogen production vs daily turn-off rate can be seen below in Figure 7.12.

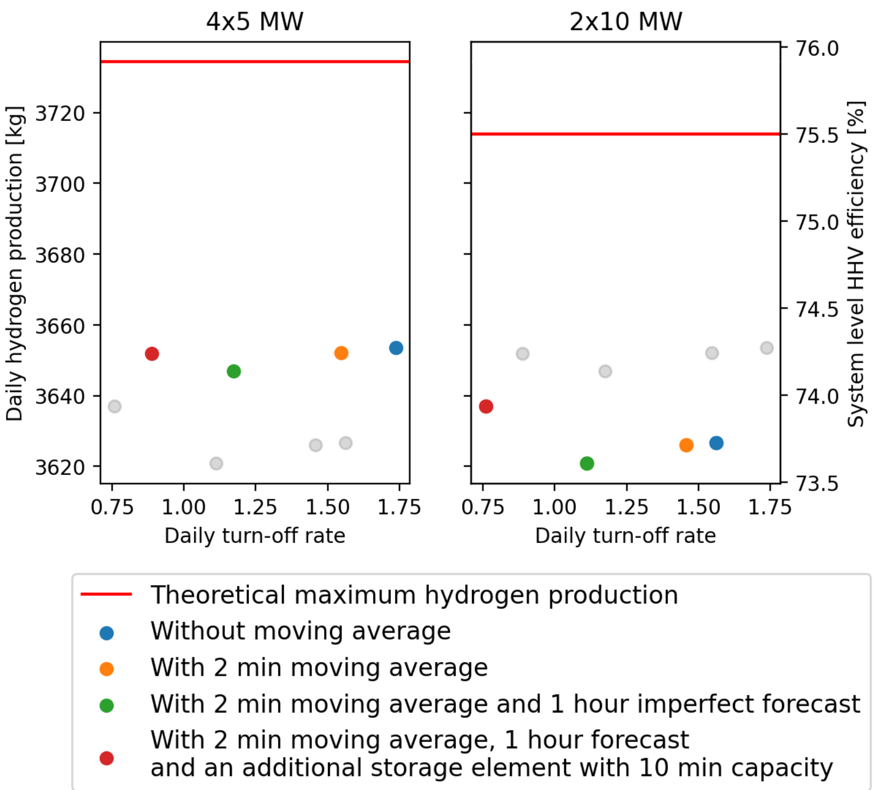


Figure 7.12: Hydrogen production vs turn-off rate, showing the incremental impact of each advisory control and system design improvement.

The red lines show the theoretical maximum hydrogen production of the two configurations for the 9 month power output time series. They were obtained not by simulation but by processing the power output time series such that at all times, there were the optimal number of operational electrolyzers, as shown in Figure 5.3. Furthermore, the auxiliary power consumption and desalination power consumptions were taken into account [3]. However, the idle- and starting up consumptions are not included, nor

[3]The auxiliary power consumption of 5.8 kW was withdrawn from the power output time series. Then depending on the estimated hydrogen production, the hydrogen equivalent of the desalination energy consumption of 0.045 kWh per kg of produced hydrogen was withdrawn from the obtained hydrogen production, assuming 1 kg of hydrogen consumes 54 kWh.

is the time it takes to turn the electrolyzers on. Hence, the red line is shown as the maximum theoretical hydrogen production, but is impossible to reach under the assumptions of the simulated system, outlined in Section 4.3.

Figure 7.12, clearly shows that the additions to the advisory control operation and system design can mainly influence the daily turn-off rate. Each incremental addition to the system managed a similar hydrogen production but decreased the turn-off rate, with large benefits when including a forecast and the ASE. For the 2x10 MW, a jump in hydrogen can be seen when including the ASE due to the possibility of decreasing the turn-on threshold, see Section 7.3. The 2x10 MW has a smaller theoretical maximum hydrogen production because it has a higher minimum operating point.

There are two main points that Figure 7.12 conveys. Firstly, that the different system designs and advisory control changes can mainly influence the daily turn-off rate. Secondly, any attempt to further improve the system efficiency based on operational strategies is constrained by a maximum gain of 2.5% for the 4x5 MW and 2.1% for the 2x10 MW, which were obtained under the unrealistic assumption that the advisory control would manage to, at all times, have the optimal number of operational electrolyzers, ignoring start-up and idling consumptions as well as the time it takes to turn electrolyzers on. That shows that the current operational strategies are performing really well under the assumption that each electrolyzer has the same efficiency curve.

Before moving on to the next chapter, the difference in the system-level efficiency for the electrolyzer configurations needs to be calculated. They were calculated by dividing the HHV energy content of the produced hydrogen into the overall energy produced from the wind turbine. The red dots in Figure 7.12, show the results of optimally obtained system designs. They are summarized below in Table 7.8, which shows that the 4x5 MW is 0.4% more efficient than the 2x10 MW[4]. The main reasons causing this difference in performance of the two configurations is the increased minimum operating point and higher idle and starting up consumptions for the 2x10 MW compared to the 4x5 MW.

The rated system level consumption was assumed to be 54 kWh per kg of produced hydrogen, when defining the case study. The obtained result show that the average system level consumption was around 53 kWh per kg for both configurations. This includes the curtailed energy as well, which was roughly 0.5-1%. This shows the impact of the increase in efficiency when operating in the partial load region.

Table 7.8: Results of the two electrolyzer configurations with the best obtained system designs

Electrolyzer configuration	Daily hydrogen production [kg]	Daily turn-off rate per electrolyzer	Obtained system level efficiency, HHV [%]	Obtained system level consumption [kWh/kg]
4x5 MW	3651.8	0.89	74.24%	53.06
2x10 MW	3637.9	0.76	73.94%	53.27

This information, along with a maximum potential efficiency increase of roughly 2.5% for the two configurations due to more efficient operational strategies, will be used in the next chapter.

[4] 74.24/73.94 = 1.004

8

Economic Assessment

This chapter will analyse the levelized cost of hydrogen for the two different electrolyzer configurations. The electrolyzer configurations have different efficiency, availability, investment, and operating costs, all of which will impact the LCOH. An analysis will also be performed to quantify how much the LCOH can be decreased by even more efficient operational strategies.

8.1. Methodology

There are multiple different methods available for performing an economic analysis. The most complete version is to include all direct and indirect costs, taxes, and externalities for each year over the project lifetime [56]. However, the purpose and scope of the analysis will determine which method to use. The objective of this analysis is to use the findings of this thesis, such as the obtained system-level efficiency of the two electrolyzer configurations, along with some additional assumptions, to get a gross estimate of the LCOH, what the main drivers of the LCOH are, and how the LCOH differs between the two different electrolyzer configurations. Since the analysis is focused on the expected difference in the LCOH but not focused on being as accurate as possible, a simple analysis will suffice. The two electrolyzer configurations will differ on three main aspects:

- System efficiency
- Availability
- Investment and operating costs

The results of this thesis have shown that the 4x5 MW is 0.4% more efficient due to reaching lower operating points and having lower idling and starting up consumption. Furthermore, having four 5 MW electrolyzers will have higher redundancy than with two 10 MW electrolyzers. That is because if one electrolyzer needs maintenance, that will have a larger negative impact on 2x10 MW as 50% of the system will be unavailable for hydrogen production, compared to only 25% for the 4x5 MW. The CAPEX and OPEX costs will also differ for the two electrolyzer configurations, as larger electrolyzer modules have the benefit of economies of scale [4, p. 72].

The analysis will be performed based on guidelines on economic evaluations of renewable energy technologies, published by NREL [56], which have also been used in recent papers for investigating LCOH [57, 58]. The methodology, also summarized by NREL in [59], is a simple method for estimating the levelized cost of energy (LCOE), which can then be tailored to calculate the LCOH. This method can be used when presenting the system output as a constant over time and having a constant operation and maintenance cost [56, p. 49]. This method calculates the LCOE as

$$\text{LCOE}\left[\frac{€}{\text{kWh}}\right] = \frac{\text{crf}_{\text{WT}} * \text{CAPEX}_{\text{WT}}\left[\frac{€}{\text{kW}}\right] + \text{OPEX}_{\text{WT}}\left[\frac{€}{\text{kW}}\right]}{\text{FLH}_{\text{WT}}} \tag{8.1}$$

where CAPEX is the initial investment cost in [€/kW], OPEX is the annual operating costs in [€/kW], and FLH_{WT} is the full load hours of the wind turbine. crf_{WT} is the capital recovery factor for the entire wind turbine system and is calculated as

$$\text{crf} = \frac{\text{WACC}(1+\text{WACC})^n}{(1+\text{WACC})^n - 1} \tag{8.2}$$

where WACC is the weighted average cost of capital, and in this methodology, the WACC is used as the discount rate. For utilities, such as energy projects, it is common practice to use the WACC as the discount rate [56, p. 8]. The capital recovery factor (or fixed charge rate) determines the amount of revenue, in present value, that must be collected annually to cover the investment costs [56]. In Equation 8.2, n is the number of years that the investment cost is repaid in.

This methodology can be tailored to the case of hydrogen, as done in [57], and then the LCOH is calculated as

$$\text{LCOH}\left[\frac{€}{\text{kg}}\right] = \left(\text{LCOE}\left[\frac{€}{\text{kWh}}\right] + \frac{\sum\left(\text{crf}_{\text{Elec}} * \text{CAPEX}_{\text{Elec}}\left[\frac{€}{\text{kW}}\right]\right) + \text{OPEX}_{\text{Elec}}\left[\frac{€}{\text{kW}}\right]}{\text{FLH}_{\text{Elec}}}\right) * C\left[\frac{kWh}{\text{kg}}\right] \tag{8.3}$$

where LCOE is for the wind turbine, and C is the energy consumption parameter of the entire stand-alone hydrogen-only wind turbine. The energy consumption parameter will consider the average efficiency over the lifetime including the effect of degradation.

NREL specifically mentioned that this methodology does not include future replacement and degradation costs [59]. That will be taken into account by including an additional CAPEX and crf values for the stack replacement as

$$\begin{aligned}\text{LCOH}\left[\frac{€}{\text{kg}}\right] &= \text{LCOE}\left[\frac{€}{\text{kWh}}\right] * C\left[\frac{kWh}{\text{kg}}\right] \\ &+ \left(\frac{\text{crf}_{\text{Elec}} * \text{CAPEX}_{\text{Elec}}\left[\frac{€}{\text{kW}}\right] + \text{crf}_{\text{Elec,SR}} * \text{CAPEX}_{\text{Elec,SR}}\left[\frac{€}{\text{kW}}\right] + \text{OPEX}_{\text{Elec}}\left[\frac{€}{\text{kW}}\right]}{\text{FLH}_{\text{Elec}}}\right) * C\left[\frac{kWh}{\text{kg}}\right]\end{aligned} \tag{8.4}$$

where $CAPEX_{Elec,SR}$ is the CAPEX of the stack replacement, and $crf_{Elec,SR}$ is the corresponding crf value. The stack replacement cost will depend on which year the stacks will be replaced due to the decreasing trend in costs. The selection of which year will depend mainly on the stack lifetime but also considers the degradation of the electrolyzer efficiency and the lifetime of the project. This will be explained in Section 8.2.2.

A few important assumptions will be made. Firstly, the desalination system, critical battery system, and the ASE will be roughly identical for the two systems and, therefore will not impact the difference in the LCOH. Consequently, they will be left out of this analysis. Secondly, the crf value for the wind turbine and electrolyzer system will be the same as both systems are assumed to have a lifetime of 30 years. Only the stacks have a shorter lifetime and therefore have their own CAPEX, lifetime, and crf value.

This analysis will be based on cost and performance estimates for 2030, as future SAHO wind turbines are mainly expected to become operational around that time. The following section will go over the setup and assumptions to use the methodology discussed in this section.

8.2. Setup

This section will discuss and summarize the setup, such as the inputs and assumptions used to calculate the LCOH. The emphasis will only be on the wind turbine, overall project information, and the electrolyzers.

8.2.1. Wind turbine LCOE and project information

The first input in Equation 8.3, is the LCOE for the offshore wind turbine. The simplest and most straightforward approach to estimating the LCOE, is to select the LCOE based on future estimates. The LCOE for the offshore wind turbine will be the same for the 4x5 MW and 2x10 MW. Hence it suffices to select a realistic value. However, the methodology presented above was also tested as an exercise to see whether the estimated LCOE is in the same range as future estimates. The exercise can be seen in Section G.2.

In 2019, IRENA projected that in 2030 the LCOE for offshore wind would be in the range of 0.05 - 0.09 $[\text{USD}_{2018}/\text{kWh}]$ [11], or 0.054 - 0.097 $[\text{USD}_{2021}/\text{kWh}]$ [1]. That report might already be a bit outdated, however, as the 2021 Renewable Power Generation Cost publication by IRENA [6] showed that the weighted average LCOE for offshore wind in Europe was 0.065 $[\text{USD}_{2021}/\text{kWh}]$ in 2021, showing a 13% decrease from 2020. It is important to note that these estimates are based on grid-connected offshore wind farms but not off-grid individual offshore wind turbines, which exclude the offshore substations and export cables. Janssen et. al estimated the LCOH for off-grid renewable hydrogen production [57] for 2030. In that publication, the LCOE for off-grid offshore wind production in 2030 was also estimated. Their results found that the LCOE for off-grid offshore wind would be in the range of 0.035 - 0.05 €/kWh. It was decided to use a value of 0.05 $[€/\text{kWh}]$, which was also close to the estimated value of 0.057 $[€/\text{kWh}]$, obtained in Section G.2.

The full load hours of the wind turbine will need to be determined as it will be used for the electrolyzers. The 17-year-long ERA5 data, from 2005 - 2021, with 1-hour average wind speeds was used, using the synthetic 20 MW power curve (see Figure 4.1), to convert those average wind speeds to power output. The resulting power output and corresponding full load hours for each year can be seen in Table G.1. The average FLH over the 17 years was 4405 hours, and that value will be taken as the representative FLH.

Vattenfall provided information that an estimated availability of the 20 MW wind turbine is around 97% and that a reference plant lifetime is around 30 years. Hence a value of 30 years will be used as the project lifetime. Considering a 97% availability, the FLH value is decreased accordingly. The only remaining input from the wind turbine and the overall project is the WACC. The WACC used for renewable energy generation projects, based on country-specific data in Europe, was summarized for offshore wind and other renewable energies as part of a study in [57]. For offshore wind, it was clear that most countries use 6-8%. A value of 7% will be used. All of the above described numbers are summarized below in Table 8.1.

Table 8.1: Levelized cost of energy for the 20 MW wind turbine

Parameters	Value
Wind turbine LCOE $\left[\frac{€}{\text{kWh}}\right]$	0.05
Wind turbine full load hours assuming 100% availability [Hours/Year]	4405
Wind turbine full load hours assuming 97% availability [Hours/Year]	4273
Project lifetime [Years]	30
WACC [%]	7
crf_{WT}	0.0806

[1] 1 USD in 2018 was worth 1.08 USD at the end of 2021 [60]

8.2.2. Electrolyzers

To estimate the LCOH, the values that need to be determined are the CAPEX, OPEX, and FLH, which will depend on the availability of the electrolyzers. Furthermore, the stack lifetime is important as it will determine how many stack replacements are necessary. Next, the corresponding CAPEX for stack replacement needs to be estimated, and lastly, the consideration of degradation per year such that an average system efficiency can be obtained. The values are summarized below in Table 8.2, and the following paragraphs will explain how those values were obtained.

The lifetime of stacks is estimated to be around 50,000 hours in 2025 [31], and will be greater than 80,000 hours in 2030 [17]. That leads to a stack lifetime of roughly 19 years when assuming that the wind turbine has around 4300 FLH. Considering that the project lifetime will be 30 years, a stack lifetime of 15 years will be used, after which (in the year 2045) there is a stack replacement. The reason for not waiting until year 19 is to utilize the increased efficiency after the stack replacement for the remaining 15 years of the plant lifetime.

The system level consumption will be assumed to be 50 kWh/kg in 2030 [17, p. 53] for the 2x10 MW system. The 4x5 MW will then be 0.4% more efficient than the 2x10 MW due to reaching lower operating points and having lower idling and starting-up consumption, as discussed in Section 7.4. After the stack replacement in 2045, an upgraded system level consumption will be obtained. IRENA stated for PEM electrolyzers, the target electrical efficiency of the system is ≤ 45 kWh/kg. A value of 46 kWh/kg will be used for the replaced stacks in the 2x10 MW configuration, with the 4x5 MW again being 0.4% more efficient than the 2x10 MW.

Every year, the stacks will degrade. Hence a yearly degradation factor needs to be estimated. To obtain the degradation factor, data sheets of commercial electrolyzer were analyzed. Most electrolyzer suppliers assume around 1% degradation for one year operation at full load [26]. Hence for around 4300 hours of full load operation, a 0.5% degradation will be assumed [2]. Therefore, every year, the system level consumption will increase by 0.5%. See Table G.4 to see the yearly system level consumption of the 4x5 MW and 2x10 MW system. At the bottom, in Table 8.2, the average system level consumption over the project lifetime is shown.

The CAPEX costs of electrolyzers have decreased drastically in recent years, and in 2020, it was estimated that the capex of a 10 MW PEM electrolyzer is around 720 €/kW [4]. DNV stated in the 2022 hydrogen outlook that they expect a 25% reduction in average electrolyzer costs by 2030[17]. That results in a CAPEX of 540 €/kW for a 10 MW electrolyzer. The relationship between electrolyzer module size and the CAPEX cost was summarized in [4, p. 72], and there IRENA estimated that a 5 MW electrolyzer would be roughly 12% more expensive per MW than a 10 MW electrolyzer. A similar relationship was observed in quotes that Vattenfall received for an electrolyzer project. Two quotes were received from the same electrolyzer supplier, one quote with a large electrolyzer module size, and the CAPEX was 14.4% cheaper than the quote with an electrolyzer module of half the size but double the quantity. A value of 14.4% will be used. Hence a CAPEX of 540 €/kW is used for the 10 MW electrolyzer and 631 €/kW for the 5 MW electrolyzer.

In 2018, IRENA estimated that the stack replacement CAPEX would be 30% of initial system CAPEX [3] [31]. This relationship will be used so that the stack replacement cost will be 30% of the electrolyzer CAPEX cost in 2045. DNV estimates that by 2050, the CAPEX costs will reduce by 50% compared to 2020 values which are 360 €/kW. Assuming a linear trend between the 540 €/kW in 2030 and 360 €/kW in 2050, a value of 405 €/kW is obtained as the electrolyzer CAPEX in 2045.

The OPEX for electrolysis is estimated to be 3% of CAPEX in [61], and 2% of CAPEX in [31]. A value of 2.5% will be assumed.

Limited information could be obtained on the availability of electrolyzers, but a report on the design of a 1 GW electrolyzer facility, estimates that the availability of 1 GW electrolyzer facility is 94% [41, p. 13]. With 4x5 MW, if one electrolyzer becomes unavailable, there are still three operational electrolyzers that together can reach 18 MW at 120% of their rated capacity. If one electrolyzer needs maintenance for

[2] 4300 hours is 49% of the 8670 hours in every year. Hence half of 1% is used

[3] IRENA estimated that in 2025, the total system CAPEX would be 700 €/kWh and that the stack replacement would cost 210 €/kW

the 2x10 MW, the single remaining electrolyzer can reach 12 MW. Using the ERA5 data, the probability distribution of the wind turbine power output could be obtained. Using that distribution, the probability of the wind turbine producing more than 18 MW was 24.24% compared to 35.4% for 12 MW. The availability will then be adjusted as

$$\text{Availability} = 94\% + (100\% - 94\%) * (1 - P) \tag{8.5}$$

where the P is the probability of exceedance, and is 24.24% for the 4x5 MW and 35.4% for the 2x10 MW. See Figure G.1 to see the wind speed probability distribution at the site alongside the power curve and for further explanation of this analysis. All the parameters and numbers described in this section are summarized below in Table 8.2, and the next section will show the results.

Table 8.2: Electrolyzer information

Parameters	4x5 MW	2x10 MW
CAPEX [€/kW]	631	540
Total CAPEX [Million €]	12.3	10.8
crf_{Elec}	0.0806	0.0806
Annual OPEX [€/kW]	16.2	13.5
Availability [%]	98.5	97.9
Full load hours [Hours/Year]	4209	4183
Plant lifetime [Years]	30	30
Degradation per year [%]	0.5	0.5
Stack lifetime [Years]	15	15
Number of stack replacements [-]	1	1
CAPEX for stack replacement [% of CAPEX]	30	30
$crf_{Elec,SR}$	0.11	0.11
Average system consumption [kWh/kg]	49	49.2

8.3. Results

Based on the LCOE of 0.05 [€/kWh], a project lifetime of 30 years, and the values in Table 8.2, the levelized cost of hydrogen could be calculated for the two electrolyzer configurations. The results can be seen in Table 8.3.

Table 8.3: Levelized cost of hydrogen for the two electrolyzer configurations

LCOH breakdown	4x5 MW	2x10 MW
crf*CAPEX [€/kg]	0.59	0.51
crf*CAPEX (stack replacement) [€/kg]	0.18	0.16
OPEX [€/kg]	0.18	0.16
Offshore wind generation cost [€/kg]	2.45	2.46
LCOH [€/kg]	3.41	3.29

Table 8.3. shows that the offshore wind generation cost is the dominant factor or roughly 72-75% of the LCOH. The small increase in efficiency and availability of the 4x5 MW configuration are less important factors than the economies of scale, which caused the CAPEX and OPEX of the 2x10 MW to be smaller.

In Section 7.4, it was shown that the designed advisory control strategy could theoretically be 2.1 - 2.5%, more efficient by managing to always have the optimal number of electrolyzers turned on. Although that would be impossible to achieve from an operational strategy perspective, it is interesting to understand how much of an impact that would have on the LCOH.

The same analysis was done, with the only change, that the average system consumption parameter, C, was decreased by 2.5%. The results are shown in Table 8.4. As could be expected, based on Equation 8.3, if the energy consumption parameter decreases by 2.5%, then the LCOH will decrease by 2.5%.

Table 8.4: Maximum potential gain of having a better operational strategy

Electrolyzer configuration	Base case simulated results	Max potential gain due to better operational strategies	Delta
4x5 MW	3.41	3.32	-0.09 (-2.5%)
2x10 MW	3.29	3.21	-0.08 (-2.5%)

Based on the results of this chapter, a recommended electrolyzer configuration would be the 2x10, as it has a lower LCOH and also a lower turn-off rate than the 4x5 MW. The negative effect of turn-offs on degradation was ignored in this analysis, as further knowledge is required to be able to model the affect of frequent turn-offs on efficiency degradation. If that would be included however, it would have a greater negative impact on the 4x5 MW.

9 Conclusion

The purpose of this report was to analyse how the system design and the advisory control strategy can impact the performance of an offshore stand-alone hydrogen-only offshore wind turbine regarding hydrogen production and the number of turn-offs. The focus was on three areas, namely how to operate the electrolyzers, the impact of adding a weather forecast, and lastly, whether an additional storage element capable of keeping an electrolyzer in idle should be included in the system. The two system designs that were tested were 4x5 MW electrolyzers and 2x10 MW, both coupled to a 20 MW wind turbine.

It was found that the power should always be evenly split between the operational electrolyzers, as it is beneficial to operate them in the partial load region where the system level efficiency is highest (see Section 5.3). Using constant turn-on and turn-to-idle thresholds was a simple but effective operational strategy as it managed to have high hydrogen production and low turn-offs. The selection of those thresholds made it possible to test different versions and governed whether the strategy chases efficiency gains with the aim of increasing the hydrogen production or prioritises decreasing the number of electrolyzer turn-offs.

An alternative strategy was also designed, turning electrolyzers on and to idle, depending on the obtained efficiency gain. However, the results showed that strategies chasing efficiency gains by frequently turning electrolyzers on and off in an attempt to operate at the highest efficiency points were sub-optimal because the gain in hydrogen production was very small, $< 0.5\%$, while the increase in the turn-off rate could go as high as 40%. There are four main reasons why versions that chase efficiency gained so little in hydrogen production:

- The largest reason is that the average gain in efficiency of different versions over the range of wind turbine power output is less than 2%.
- The versions are only different in the partial load region of the wind turbine power curve and were found to operate with the same number of electrolyzers the majority of the time.
- Versions which minimize turn-offs used high turn-on thresholds and low turn-to-idle thresholds. That gives the electrolyzers large operating ranges before turning electrolyzers on and off. Due to the fluctuations in power output, those versions often end up operating nevertheless at high-efficiency regions, which caused the difference to be further reduced.
- Lastly, the remaining benefit of versions chasing efficiency, was reduced even further because those versions are more frequently turning electrolyzers on and keeping electrolyzers in idle, both of which consume power that could have been used for hydrogen production

Three additions to the operational strategy and system design were tested; Smoothening the control signal, using a weather forecast and including an additional storage element. All three additions were beneficial and also showed that there is a design choice between prioritising hydrogen production and decreasing the turn-off rate.

Section 7.1 showed that smoothening the control signal using a moving average made the advisory control much more robust with regard to instantaneous fluctuations in the power output and caused a clear improvement in the system performance. The daily turn-off rate, idle time, and overall switching could be decreased by roughly 20-40% depending on the length of the moving average. However, the curtailed energy increased, which caused a decrease in the overall hydrogen production up to 0.3-0.5%. To choose a best moving average length, hydrogen production and the daily turn-off rate were given an equal weight, resulting in a 2-minute moving average being the best, obtaining a 20% decrease in the turn-off rate and 0.1% decrease in hydrogen production.

The weather forecast results, in Section 7.2, showed that by turning the electrolyzers on, depending on the average power output over the horizon, the advisory control could make much more strategic decisions. The turn-off rate decreased by roughly 20%, while the hydrogen production stayed more or less the same. The hydrogen production stayed the same because the increased operating efficiency and decreased consumption for turning electrolyzer on and keeping them idle was equally met by an increase in curtailed energy. The optimal time horizon was found to be 1 hour but will depend on the selected version.

The most significant impact was obtained with the inclusion of an additional storage element (ASE) capable of keeping one electrolyzer idling, analyzed in Section 7.3. By having a system with a 1-hour forecast and an ASE capable of keeping one electrolyzer idling for just 10 minutes, the turn-off rate was decreased by 30% compared to a system with only the forecast. That shows the importance of having an additional storage element when operating electrolyzers with a fluctuating power source. Furthermore, the hydrogen production was even increased by 0.1%, because when keeping the last electrolyzer idling, it was ready to ramp up when the wind turbine power output increased, which outweighed the required energy to operate that additional storage element.

Section 7.4, showed that from a hydrogen production perspective, the designed operational strategy managed a system level efficiency that reached close to 98% of the maximum theoretical efficiency that is obtained under the unrealistic assumption that the system would manage to, at all times, have the optimal number of electrolyzers turned on, and ignoring start-up times as well as the idling- and starting up consumption. Reaching 98% of that efficiency is a very promising result.

This thesis tested two different electrolyzer configurations. Few large electrolyzers, and multiple small electrolyzers in the form of 2x10 MW and 4x5 MW, respectively. The results showed that having multiple small electrolyzers has two main benefits. Firstly, smaller electrolyzers have a lower minimum operating point making it possible to produce hydrogen at lower wind turbine power output. Secondly, they have a lower idle and starting-up consumption than larger electrolyzers. This led to the finding that the 4x5 MW was 0.4% more efficient than the 2x10 MW. On the other hand, the 2x10 MW had a roughly 15% lower turn-off rate per electrolyzer.

The differences in the system performance of the two analysed configurations were then analyzed from an economic perspective in Chapter 8. The 4x5 MW configuration is slightly more efficient and has a higher availability than the 2x10 MW configuration. However, the 2x10 MW has lower investment and operating costs. These factors resulted in the 2x10 MW having a 3.5% lower LCOH compared to the 4x5 MW. The levelized cost of energy of the offshore wind turbine was the dominant factor in the levelized cost of hydrogen, comprising 75% of the LCOH. Few large electrolyzers look more promising than multiple small electrolyzers, as the 2x10 MW system had both a lower turn-off rate and lower LCOH than the 4x5 MW.

The main conclusion of this project is that for an offshore stand-alone hydrogen-only wind turbine, the system design and advisory control strategy can substantially decrease the daily turn-off rate of electrolyzers. It was found to be harder to influence the hydrogen production, but that also resulted in the hydrogen production being very close to the theoretical limit.

10 Recommendations for future work

This thesis project made a few simplifications and assumptions which will require further analysis.

Firstly, the results of this thesis are highly related to the assumption that all electrolyzer units have the same efficiency curve, irrespective of the number of operational electrolyzers. That might not be the case. For example, if the auxiliary consumption will have a smaller impact with each additional electrolyzer. That would result in different efficiency curves as more electrolyzers are turned on. However, no information was found indicating that.

The desalination system was considered as an off/off component. It might be the case that frequent turn-on/off behavior of the desalination system accelerates component degradation, thereby reducing the desalination system lifetime. Would that be the case, the designed advisory control strategy should be updated to attempt to decrease the number of desalination system turn-offs. For example, by running the desalination system at partial load in an attempt to fill the water tank as slowly as possible to delay the need to turn the desalination system off. The size of the water tank which stores the desalinated water will, therefore, also have a direct impact on the operational strategy of the desalination system.

The sizing of the water tank was not selected based on a detailed analysis. The water tank sizing will be governed by weight limitations that the offshore support structure can withstand as well as costs. The weight of the other components and the load limit of the support structure also needs to be considered. This was not included in the scope of this thesis.

This thesis project only considered electrolyzers of equal sizing. It might bring some improvements in the system performance by including a smaller electrolyzer that could operate at low wind speeds. This becomes more interesting for systems with few large electrolyzers, such as 2x10 MW. The 2x10 MW had the problem that the wind turbine power output often fluctuated around 1-2 MW, thereby frequently turning the first electrolyzer on and idle and back on. A small electrolyzer such as a 1-5 MW PEM electrolyzer could help minimize that problem. The downside is that the small electrolyzer would only capture low power outputs and will therefore not greatly impact the overall hydrogen production. Hence, the trade-off between the increase in hydrogen production and the additional cost of the small electrolyzer would need to be considered.

The electrolyzers were also sized such that their rated capacity should be equal to the size of the wind turbine. Oversizing the wind turbine is also an option and was analyzed by Mehta et al. [38]. The decrease in the required CAPEX was found to outweigh the decrease in hydrogen production, thereby resulting in a lower levelized cost of hydrogen [38]. Further work could analyse how the advisory control would change with such a system design. However, it is expected that the advisory control strategy would be the same regarding when to turn electrolyzers on and idle. When the wind turbine produces power above the rated capacity of the electrolyzer system, the extra power could be used to desalinate water, store power in the ASE and the battery for the critical auxiliary consumption. If none of those would be possible, the wind turbine would reduce its power output to the rated capacity of the electrolyzers.

The battery was sized based on the critical auxiliary power consumption of the system components. Multiple assumptions were made when estimating the total critical auxiliary power consumption. Further analysis is required to get more accurate numbers on those consumptions.

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A

Calculating hydrogen output

A.1. Translating power consumption to hydrogen output

In Figure A.1 depicted below, an estimate of the efficiency curve of the HyLYZER500 is shown. The setup of this example is shown below in Table A.1

Table A.1: Setup of the example

	HyLYZER500
Rated Capacity [MW]	5
Input Power [MW]	3
Corresponding operating point	3/5 = 0.6

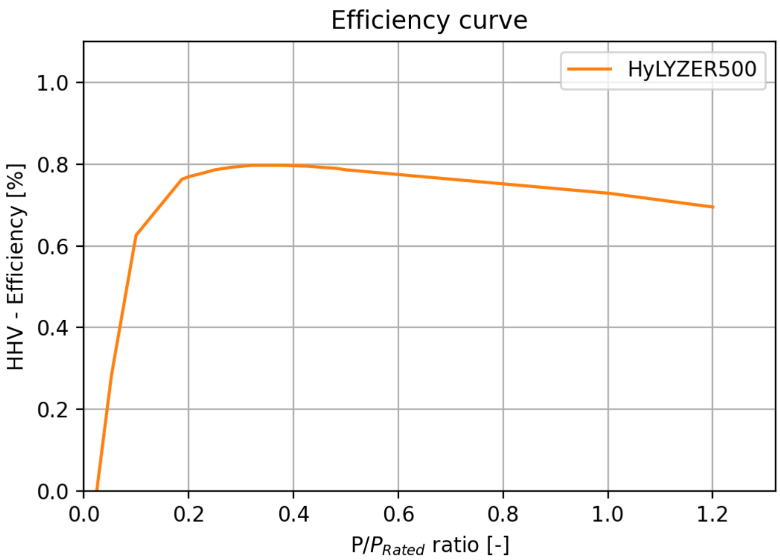


Figure A.1: Efficiency curve of the HyLYZER500

For an operating point of 0.6, it can be seen that the efficiency is roughly 77%. For a 3 MW input power, and efficiency of 77%, only 2.31 MW of power are leaving the system. Operating at 2.31 MW for 1 hour is equivalent to 2.31 MWh of energy. Using the higher heating value of hydrogen of 39.39 kWh/kg, the amount of hydrogen that is produced in 1 hour is equal to 58.64 kg. The mass flow per second is then 0.016 kg/s.

B

Control logic implementation

B.1. Turning electrolyzers on

As was explained briefly in Section 5.4 the advisory control will turn the first electrolyzer on when the wind turbine power output has become greater than 20% of the rated power of the first electrolyzer. In case the moving average is being used, then it will wait until the moving average of the wind turbine power output has become greater than those 20%. When the first electrolyzer has become operational, the controller will monitor the power consumption of the operational electrolyzer to decide when to turn the next electrolyzer on, as is shown below in Figure B.1.

The only reason why that was chosen instead of monitoring the signal from the wind turbine was to make the code independent of the electrolyzer power capacity. And the author believed that was simplest to do by using the operating points along the power curves as an indicator of when to turn electrolyzers on and off.

Figure B.1 shows that if the power consumption of electrolyzer 1, $P_{Elec,1}$ is greater than the turn-on threshold the next electrolyzer should be turned on.

$\forall i$

If $P_{Elec,i}$ > $P_{NextOneOn,i}$
&&
$Elec_{i+1}$ is off

Then turn $Elec_{i+1}$
on

Figure B.1: Advisory control monitors the power consumption of the electrolyzers to decide when to turn the following electrolyzer on

In the python implementation the electrolyzer objects are put into a matrix. Each electrolyzer object has its own characteristics as summarized in Table 3.1. When the power consumption of the first electrolyzer is greater than the corresponding turn-on threshold and the next electrolyzer is off or in idle, the next electrolyzer is turned on. This is shown graphically below in Figure B.2. In Figure B.2, the configuration of 4 electrolyzers is shown. The circles in the upper left corner are green if the electrolyzer is on but red if they are idle or off. The arrows incrementing from left to right indicate the for loop that the controller checks in each simulation step. Therefore, there are two conditional statements that need to be true before turning the next electrolyzer on. Firstly, the power consumption of the prior electrolyzer (in the python matrix) is greater than the corresponding turn-on threshold (off or idle), and the next electrolyzer in the matrix is off or in idle. If that is true, turn the next electrolyzer on.

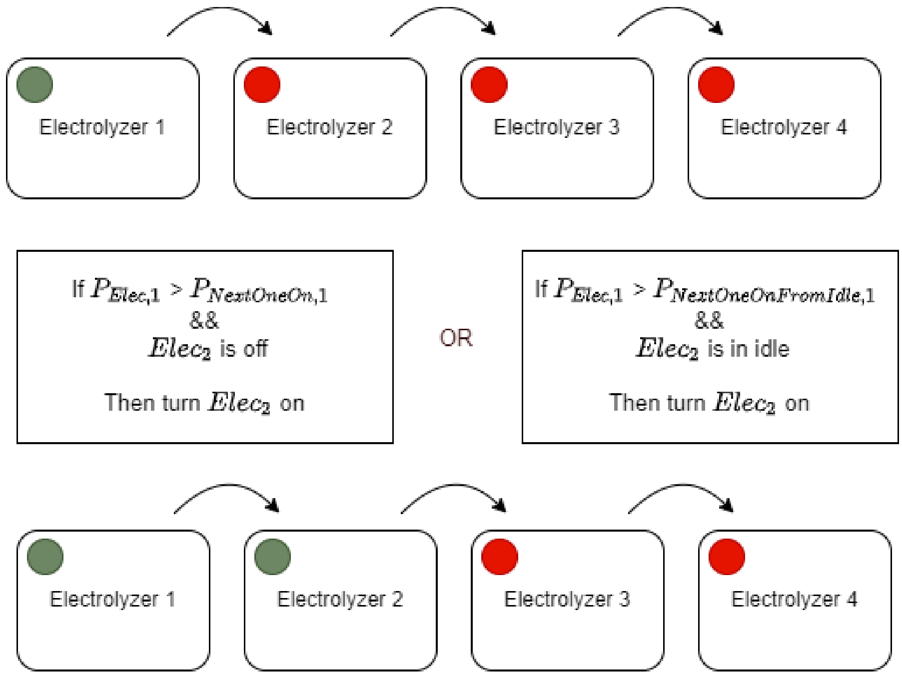


Figure B.2: Turning electrolyzers on

B.2. Turning electrolyzers to idle

The same methodology applies to turning electrolyzers to idle. If the power from the wind turbine has ramped down, the operational electrolyzers need to decrease their power consumption. The advisory control measures how much mismatch is between the available power and the sum of the electrolyzer power consumption. Then the advisory control withdraws an equal amount of power from all operational electrolyzers, starting with the electrolyzer furthest to the right in the matrix. The reason why that is done is that it allows the advisory control to sort the electrolyzers depending on what electrolyzer is preferred to be turned off, as will be explained later in this appendix. The code is designed to make the last operational electrolyzer in the matrix the one to be turned off. Therefore, a for loop is done, starting from the far right in the matrix, and if withdrawing the mismatch from the furthest to the right operational electrolyzer causes its power consumption to go below the turn-to-idle threshold, it is turned to idle. If there is still a mismatch after the electrolyzer is turned to idle, the advisory control will go to the next electrolyzer, to the left in the matrix.

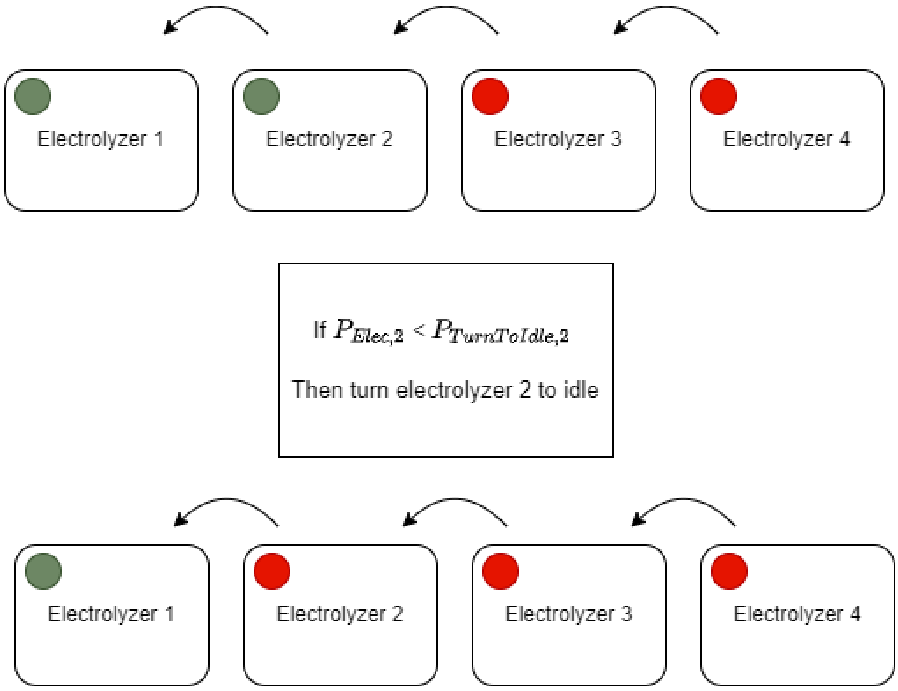


Figure B.3: Turning electrolyzers to idle

B.3. Strategy 2 - Turning electrolyzers to idle, and back on from idle

In Section 5.3.4 it was discussed that whenever an electrolyzer is set to idle, not only does it stop producing hydrogen but it also consumes power that could be used for hydrogen production. Strategy 2 attempts to utilize the negative impact in the selection process of the turn-to-idle thresholds and turn-on-from-idle thresholds.

This effect is shown below in Figure B.4. In Figure B.4, the more transparent versions of the curves show the efficiency gain when neglecting the effect of having an electrolyzer in idle. When this effect is not neglected, the efficiency gain for turning an electrolyzer to idle is decreased. A negative efficiency gain on the y-axis in Figure B.4 indicates that there is a gain in efficiency by turning an electrolyzer to idle and allowing the other electrolyzers to ramp up. The results for efficiency gains from 0-4% are shown in Table 5.5

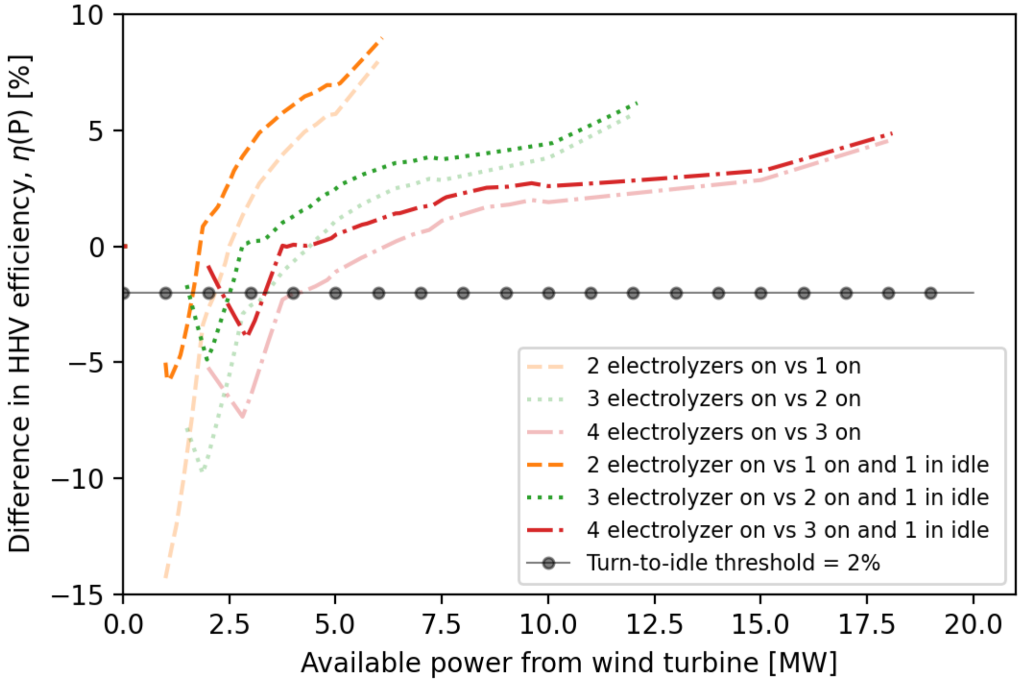


Figure B.4: Efficiency gain comparison with different number of operational electrolyzers, considering the effect of having an electrolyzer in idle. Example of requiring 2% efficiency gain for turning to idle. Each electrolyzer has a rated capacity of 5 MW but can be operated up to 120%

The same approach was used to select the threshold to turn idle electrolyzers back on. Since idle electrolyzers are consuming power which could otherwise be used for hydrogen production, Figure B.4 can be used when looking at positive efficiency gains. A positive efficiency gain indicates that there is an efficiency gain to be made by turning an idle electrolyzer back on. The corresponding thresholds can be seen for different required efficiency gains in Table 5.6.

B.4. Sorting electrolyzers

The advisory control sorts the electrolyzers in the electrolyzer matrix such that it positions the electrolyzer, which would be preferred to be turned off, in the far right location (only considering operational electrolyzers). For example, in Figure B.5, electrolyzer 2 has just been turned on. If there is not enough power in the system to keep 2 electrolyzers operational, it would be preferred that electrolyzer 1 is turned off since electrolyzer 2 just became operational. Therefore, electrolyzer 2 goes to the first location in the matrix and electrolyzer 1 to the far right of the operational electrolyzers.

The second case is that when the electrolyzers have been operational, it would be preferred to turn off the electrolyzer unit which has been operating the longest over its lifetime. Therefore, the electrolyzer sorts the electrolyzer objects depending on operational time. In Figure B.6, it is shown that electrolyzer 2 which has the shortest operational time of the operational electrolyzers is put in the first location in the matrix. Therefore, if an electrolyzer will be turned off, the advisory control will turn off unit 3 instead of unit 2. Electrolyzer 1, in Figure B.6, has an operating time of 5 hours and has already been turned off (shown as an example).

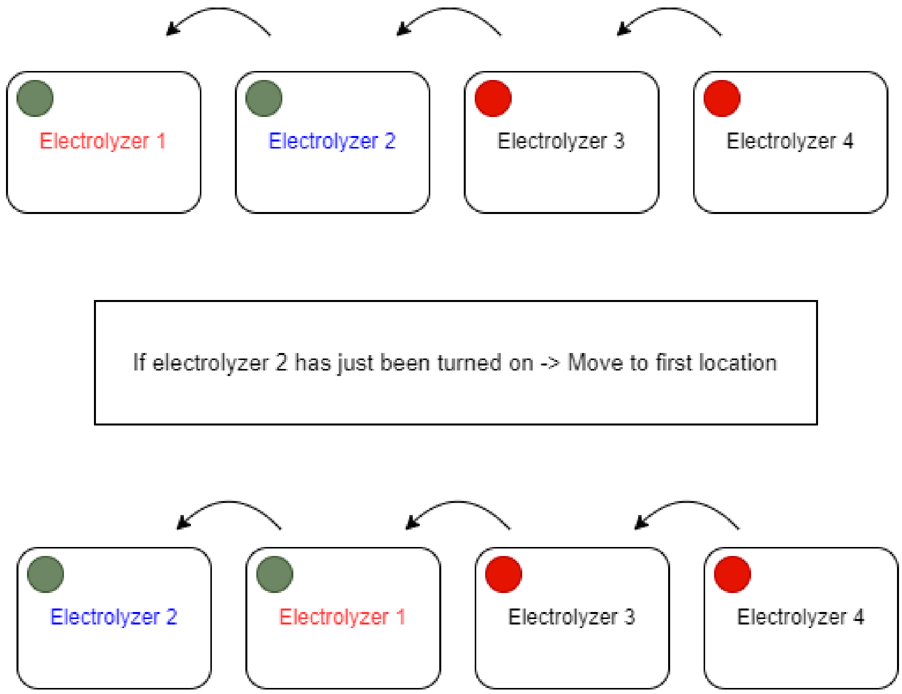


Figure B.5: Sorting electrolyzers - 1

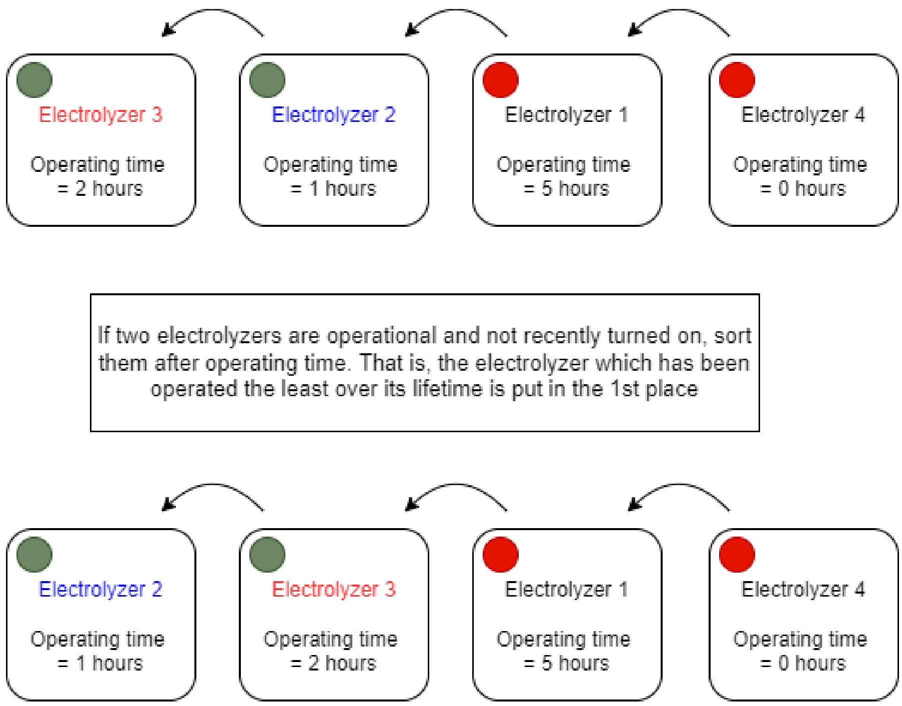


Figure B.6: Sorting electrolyzers 2

B.5. Advisory control flow charts

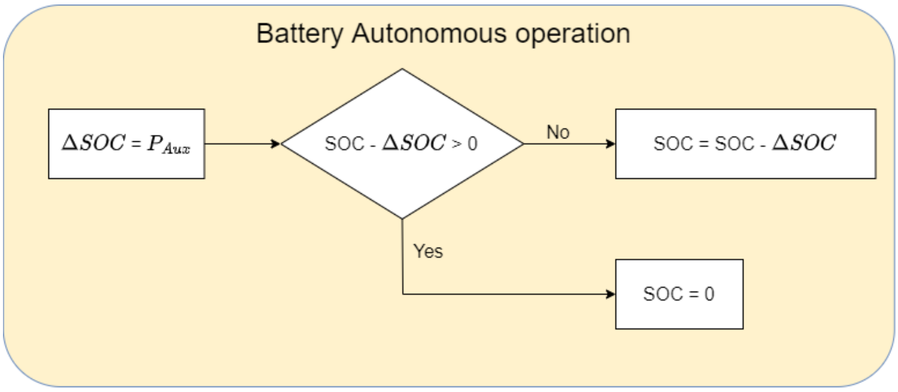


Figure B.7: Battery Autonomous Operation Control Flowchart

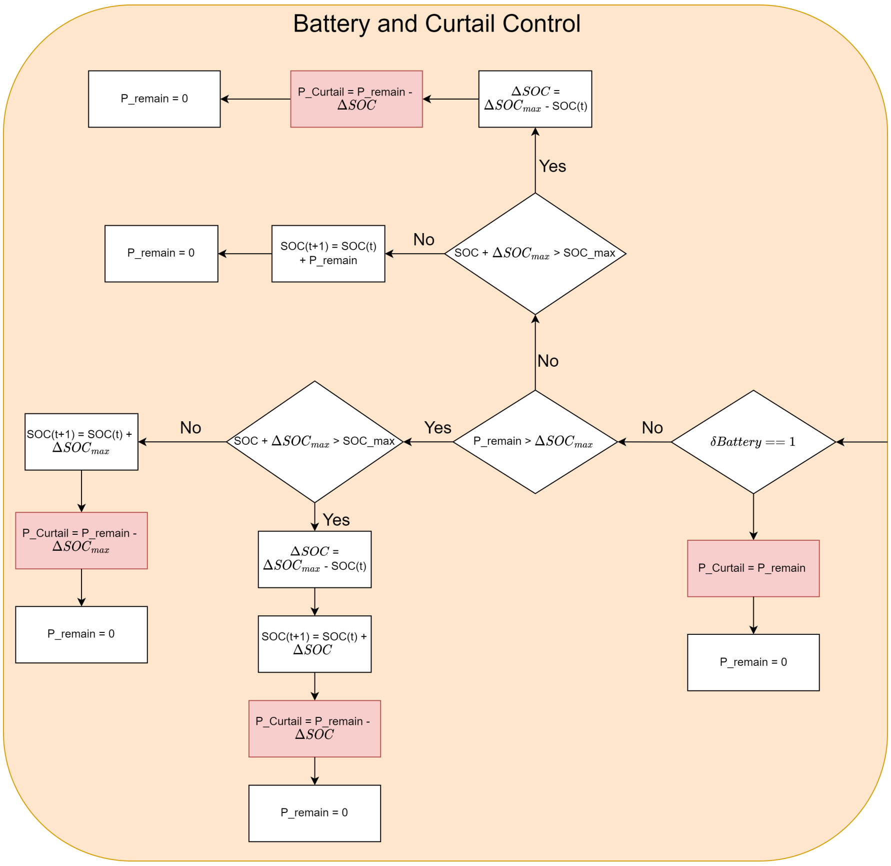


Figure B.8: Battery and Curtail Control Flowchart

C

Aberdeen Bay Wind Farm Weather Analysis

C.1. 30 year extreme wind speed analysis

This section will describe how the 30 year extreme consecutive idle time in Section 4.5.2 was obtained.

In Section 4.5.2, the ERA5 data, showing the 1 hour average wind speed from 2005-2021 was analysed, such that the maximum consecutive idle time for each month was stored. The result was shown in Figure 4.3a. This data was then sorted from low to high, as can be seen below in Figure C.1a. Using this data, the probability of exceedance was calculated as

$$P = \frac{m}{n+1} \tag{C.1}$$

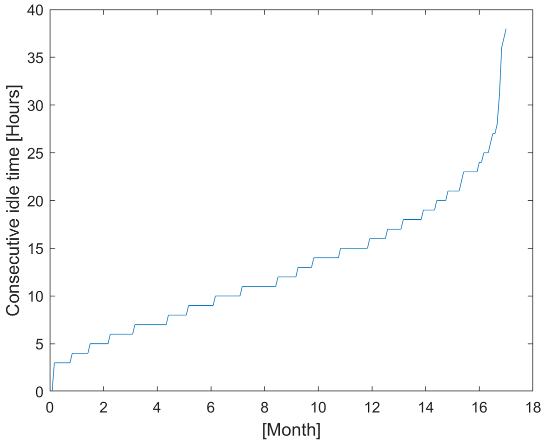
where P is the probability that a given consecutive idle time is equaled or exceeded. m is the rank of the consecutive idle time measurement, and n is the total number of stored monthly maxima. Using the probability of exceedance, the recurrence rate is calculated as

$$\text{Recurrence} = \frac{1}{1-P} \tag{C.2}$$

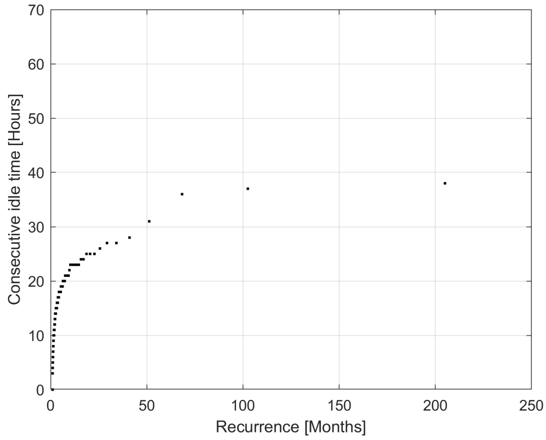
where P is the probability of exceedance. The results of the recurrence rates, displayed in months, can be seen below in Figure C.1b. To explain better what Figure C.1b stands for, it can for example be seen that a value of 38 hours was equalled or exceeded once in the 204 measured months. Therefore, it has a recurrence rate of 204 months. A value of 37 hours was equalled or exceeded twice (by itself and the 38 hour measurement). Therefore the value of 37 hours has a recurrence rate of 102 months. Plotting the recurrence rates in Figure C.1b with the x-axis as logarithmic, a roughly linear trend is observed as can be seen in Figure C.1c. A Matlab code from TU Delft then fitted a straight line to the recurrence trend such that the squared error is minimized. The result can be seen in Figure C.1d in the green dashed line. This green dashed line takes the form of

$$CET = 5.929 + 16.0671 * log_{10}(T) \tag{C.3}$$

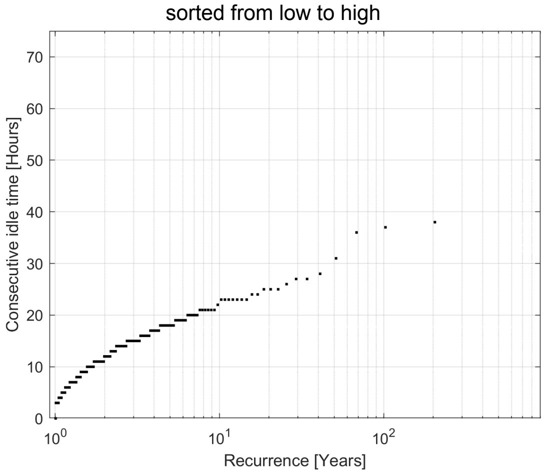
where CET is the consecutive idle time, and T is the recurrence rate in months. For a value of 30 years, or 360 months, a CET value of 47 hours is obtained.



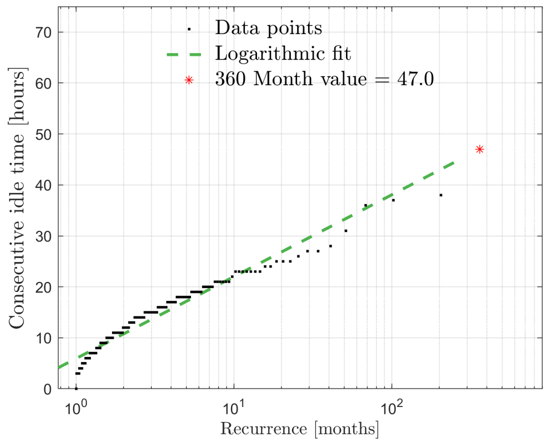
(a) Monthly maximum consecutive idle time; sorted from low to high



(b) From the monthly maximum consecutive idle time, estimate the recurrence rate



(c) Plotting the recurrence rate with a logarithmic x-axis



(d) Fitting a straight line with a least squares method for extrapolation

Figure C.1: Obtaining the 30-year extreme consecutive idle time.

D

Simulation results without moving average

D.1. Simulation figure of 2x10 MW

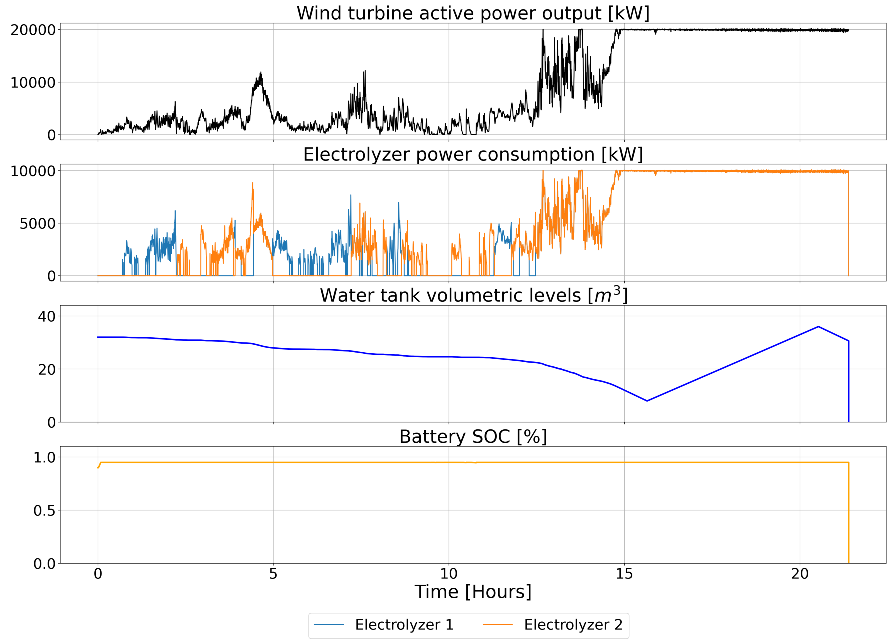


Figure D.1: Electrolyzer, battery and water tank time-series simulation for - Case 1 - 2x10 MW

D.2. Turn-to-idle thresholds

D.2.1. Why a higher turn-to-idle threshold leads to more turn-offs compared to a lower turn-to-idle threshold for 4x5 MW electrolyzer configuration

This section will explain why more electrolyzers are being turned off when the advisory control uses a high turn-to-idle threshold compared to a lower turn-to-idle threshold. This is best explained with an example.

Imagine the wind turbine has an active power output of 5 MW, and there are four operational 5 MW electrolyzers, each consuming 1.25 MW. If the advisory control has a turn-to-idle threshold of 20%, it means that the fourth electrolyzer will be set to idle if its consumption drops below 1 MW. If the active power output from the wind turbine drops below 4 MW, say 3.99 MW as an example, the fourth electrolyzer is set to idle. Then there are 3.89 MW of available power as the idling electrolyzer consumes 0.1 MW to keep it idling. The 3 operational electrolyzers will split the 3.89 MW, evenly, meaning each consumes 1.297 MW. If the active power output from the wind turbine decreases down to 3.1 MW, the 3 operational electrolyzers are all consuming 1 MW and the third electrolyzer is set to idle. The previously idling electrolyzer is shut down. In this example the active wind turbine power output needed to drop from 5 MW to 3.1 MW to cause one electrolyzer to be shut down.

If we now decrease the turn-to-idle threshold to 10%, the fourth electrolyzer is not set to idle unless the active power output from the wind turbine drops down to 2 MW. Then all four electrolyzers are consuming 0.5 MW (10% of their rated power), and the fourth is set to idle. The idling electrolyzer consumes 0.1 MW, leaving 1.9 MW left to be split by the 3 operational electrolyzers. They will then all consume 0.63 MW. If the wind turbine active power output drops down to 1.6 MW, the idling electrolyzer consumes 0.1 MW, and the 3 operational electrolyzers consume 0.5 MW and the third electrolyzer is set to idle, causing the already idling electrolyzer to be fully shut down. In this example, the active power output from the wind turbine needed to drop from 5 MW to 1.6 MW.

This example has clearly shown that by lowering the turn-to-idle threshold, the wind turbine power output will need to ramp down more to turn an electrolyzer to idle. Using a 20% turn-to-idle threshold, the example above required a decrease of 1.9 MW, compared to 3.4 MW for a 10% turn-to-idle threshold.

D.3. Curtailed Energy discussion

It is not obvious why there should be an increasing curtailed energy trend with increasing turn-to-idle thresholds. This section will describe why that is due to modeling discretisation. Furthermore, more details will be given about the jump in curtailed energy in the results of strategy 1.

D.3.1. 4x5 MW - Strategy 1

Every version of strategy 1 is the same with regards to turning the first electrolyzer on as well as when to turn it off. That is, the first electrolyzer is turned on when the power output from the wind turbine has surpassed 20% of the electrolyzer rated power (1 MW for the 5 MW electrolyzer), and it turned to idle when it drops below 10% of the electrolyzer rated power. Therefore they all have the same curtailed energy due to the power output from the wind turbine being lower than the minimum operating point. That amount of curtailed energy is the base curtailed energy of 6850 kWh in the far left in Figure D.2.

After an analysis of why the curtailed energy increases from left to right, it was evident that the discretization of the simulation is the cause of why there is an increase in curtailed energy when increasing the turn-to-idle threshold. Figure 6.5 shows a difference of around 250 kWh from the top left to the bottom right, equivalent to around 5 kg of hydrogen.

To quantify this effect, looking at Figure 6.4b, the average daily switches per electrolyzer is in the worst case, around 18 times per day. That number includes going from idle to on and turning on, which, do not cause energy curtailment. It is only when electrolyzers are set to idle or shut down. Therefore assuming only half of those switches are turning electrolyzers to idle, there are only 9 actions per electrolyzer per day. For a week simulation with four electrolyzers there are 9*4*7 = 252 actions. Taking the bottom right corner as an example, which means a 20% turn-to-idle threshold, there is a jump of 1 MW meaning each idle action curtails approximately 1.4 kWh. Those 252 actions therefore lead to an increase in curtailed energy of about 352 kWh.

For the top left corner, there are around 7.5 switching actions per day. Assuming half of those are turning an electrolyzer to idle, an estimate of 105 actions are obtained With 4 electrolyzers over a 7 day simulation. With a 10% turn-to-idle threshold, each idle action leaves a mismatch of 0.5 MW for 5 seconds. That is equivalent to 2.5 MJ, or 0.7 kWh. With 105 idle actions, that curtails around 74 kWh. Therefore, an estimate of the increase in curtailed energy is due to implementation reasons are around 352 - 74 - 278 kWh. That factor alone accounts for almost the entire curtailed energy range shown in Figure D.2. The conclusion is therefore that there is no large difference in curtailed power energy the different versions of strategy 1.

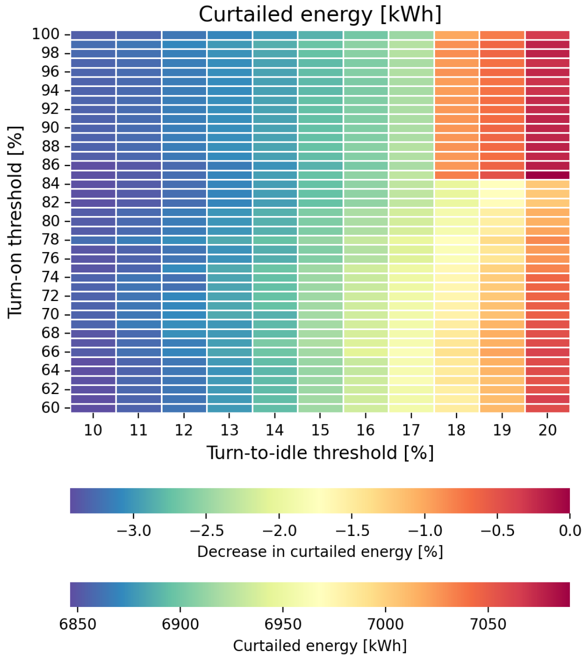


Figure D.2: Curtailed energy color map with different turn-on and turn-to-idle thresholds for strategy 1. These results are based on simulating Case 1 with a 4x5 MW electrolyzer configuration

The top right corner, in Figure 6.5, shows a sudden jump when using a turn-on threshold of 85% instead of 84%, coupled with turn-to-idle threshold of 18-20%, and also with turn-on thresholds from 85-100% when using 18% turn-to-idle threshold instead of 17%. There is a logical explanation for this jump. This jump in curtailed energy is because of the idiosyncrasy of the selected 1-week power output time-series. The power output from the wind turbine reached 84% of the electrolyzer rated power but not 85%, and then ramped down again. A few minutes later, the wind turbine's active power output quickly ramped up, and the simulation with the 84% turn-on threshold had a newly turned-on electrolyzer ready to capture the ramp up, while the simulation with the 85% threshold, only crossed the turn-to during the rapid ramp up. Since it takes 5 minutes to turn another electrolyzer on, there was a period of a few minutes where the version with 85% turn-on threshold did not manage to capture all the energy.

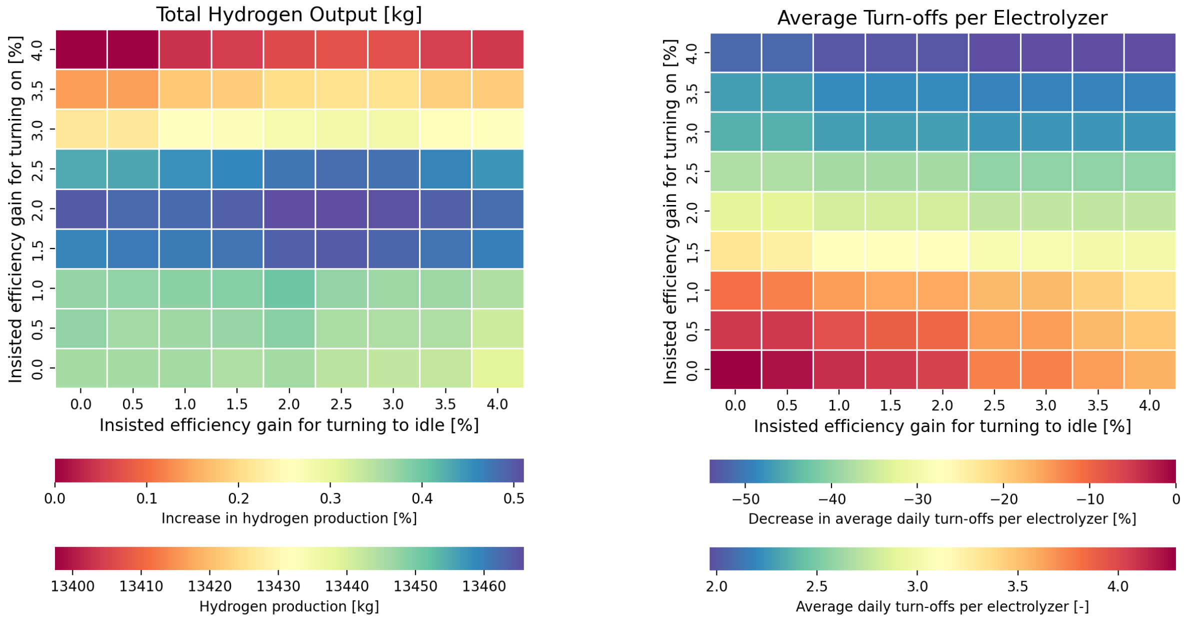
A similar scenario happened with a turn-to-idle threshold of 18% instead of 17%. An electrolyzer was turned to idle and then fully off with a turn-to-idle threshold of 18%, but that did not happen with 17%. Then there was a sudden increase in wind turbine active power output resulting in a period of time where the 18% version did not have enough operational electrolyzers to capture all the power from the wind turbine, as an electrolyzer was still being turned on. For the 17%, an electrolyzer was not turned off, but in idle and could therefore quickly be ramped up. It can be expected that the color map of curtailed energy should have jumps here and there due to random events such as those.

D.4. Heatmap results of 4x5 MW - strategy 2

This section will discuss the results of strategy 2 in detail.

For strategy 2, the color map of the hydrogen production and average number of turn-offs, for different combinations of required efficiency gains for turning-on and turning-to-idle, can be seen in Figure D.3a. Figure D.3a shows that the highest hydrogen production is obtained in the middle to the right when requiring a 2% efficiency gain for turning on, and 2-3% for turning-to-idle.

Looking at the daily turn-off rate in Figure D.3b, strategies which chase efficiency gains have a very high turn-off rate, which can clearly be seen by the bottom left corner having a daily turn-off rate of 4.5 times per electrolyzer. The same trends are observed with the idle time and total switching color maps, shown in Figure D.4a and Figure D.4b respectively. The version in the bottom left corner is always attempting to have the optimal number of electrolyzers operational, equivalent to jumping from one efficiency curve to the next, in Figure 5.3, as soon as it becomes more efficient to do so. The four color maps in Figure D.3 and Figure D.4 show clearly that versions attempting to chase efficiency gains, such as the bottom left corner, have the highest idle time, most turn-on's and overall switching which negatively impact the hydrogen production. These results are mainly echoing the conclusions that were obtained from strategy 1.

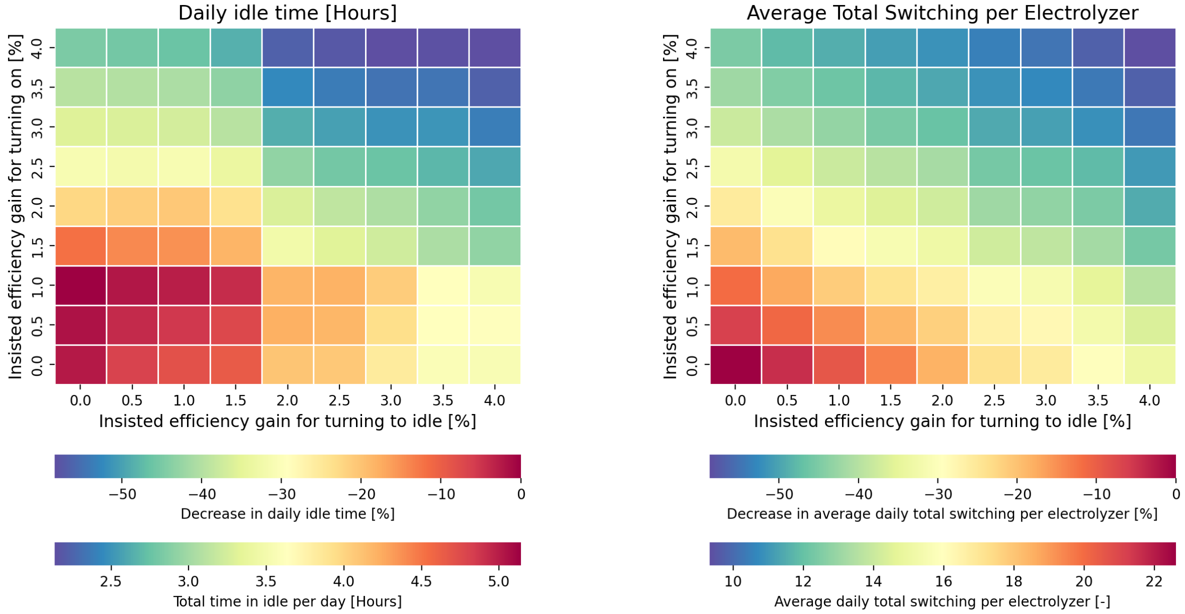


(a) Hydrogen production colormap with different turn-on and turn-to-idle thresholds.

(b) Average daily turn-offs per electrolyzer colormap with different turn-on and turn-to-idle thresholds.

Figure D.3: Hydrogen production and average number of turn-offs color map with different required efficiency gains for turning on and to idle. These results are based on simulating Case 1 with a 4x5 MW electrolyzer configuration

In Figure D.5, the difference in curtailed energy can be seen. Figure D.5 shows similarly to the results from strategy 1, that the magnitude of the curtailed energy is around 7000 kWh for all versions. Furthermore, the color map has a very similar trend as the daily average total switching, except for an idiosyncratic event which caused less energy to be curtailed with 2% turn-on and 0% turn-to-idle threshold. This overall trend is again related to the discretisation that each action of turning an electrolyzer to idle, causes certain energy to be curtailed.



(a) Daily time in idle colormap with different turn-on and turn-to-idle thresholds

(b) Average daily switching per electrolyzer colormap with different turn-on and turn-to-idle thresholds.

Figure D.4: Idle time and average number of daily switches color map with different required efficiency gains for turning on and to idle. These results are based on simulating Case 1 with a 4x5 MW electrolyzer configuration

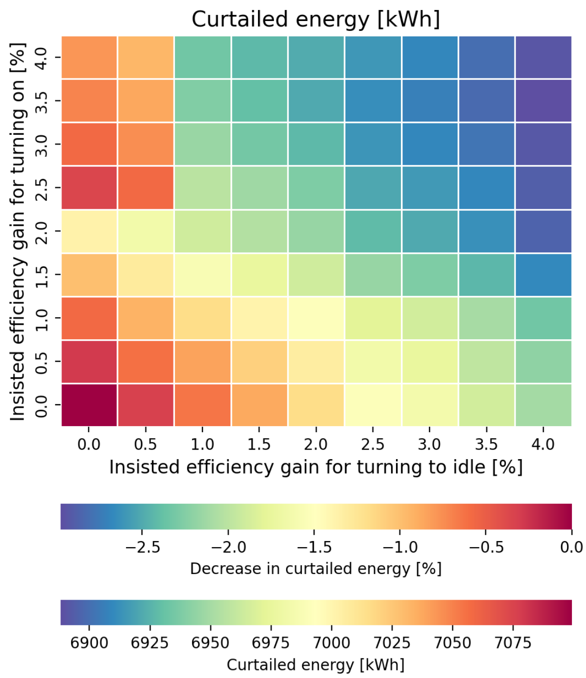
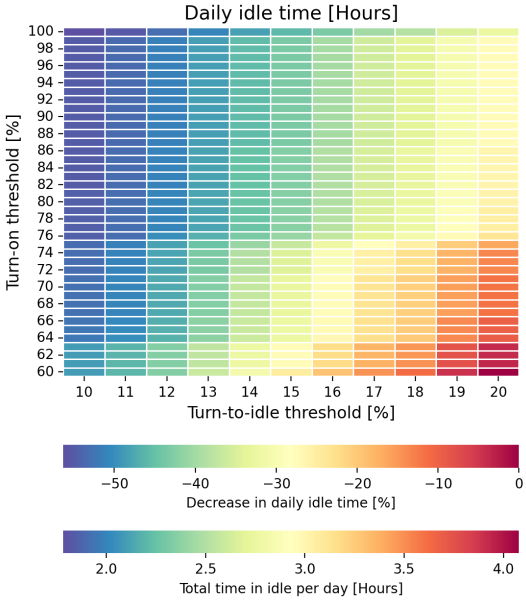
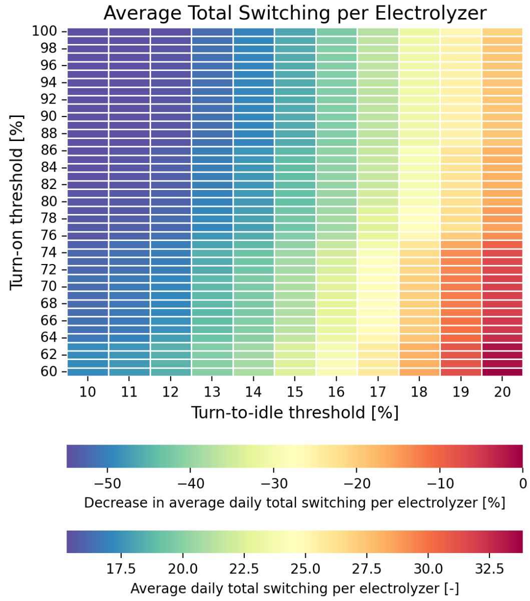


Figure D.5: Curtailed energy color map with different required efficiency gains for turning on and to idle. These results are based on simulating Case 1 with a 4x5 MW electrolyzer configuration

D.5. Color map results of 2x10 MW - Strategy 1



(a) Daily time in idle colormap with different turn-on and turn-to-idle thresholds



(b) Average daily switching per electrolyzer colormap with different turn-on and turn-to-idle thresholds.

Figure D.6: Colormaps of the average total idle time per day and average number of switching per electrolyzer per day with different turn-on and turn-to-idle thresholds for strategy 1. The percentage decreases and always with regards to the highest idle time and highest average number of switches respectively. These results are based on simulating Case 1 with a 2x10 MW electrolyzer configuration

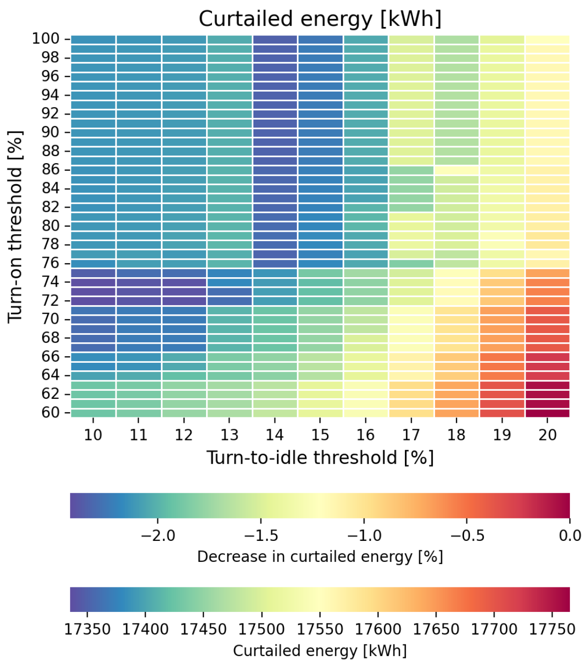


Figure D.7: Colormap of the curtailed energy with different turn-on and turn-to-idle thresholds for strategy 1. The percentage decrease is with regards to the highest curtailed energy. These results are based on simulating Case 1 with a 2x10 MW electrolyzer configuration

E

Moving Average

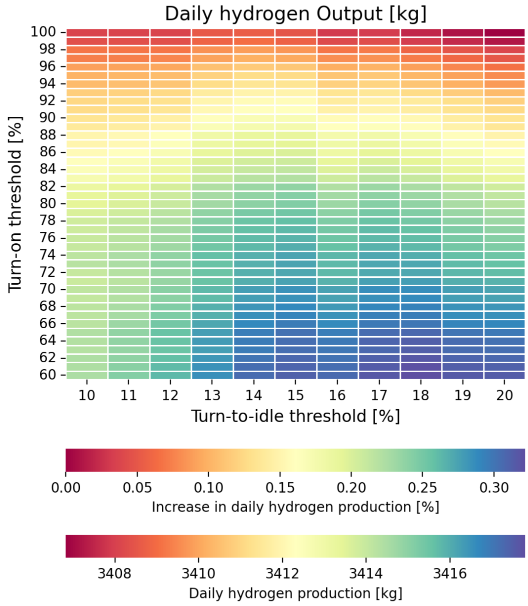
E.1. Resetting the moving average signal after turning an electrolyser on: Reasoning

As was briefly explained in Section 7.1, the moving average signal is reset after an electrolyzer is turned on. The reason why that is done is best explained with an example. Imagine the case where one electrolyzer is operational, and its moving average has become greater than the turn-on threshold. The advisory control will turn the next electrolyzer on. When the newly turned on electrolyzer becomes operational, the controller will reset all electrolyzer moving average signals. If the controller would not do that, the moving average of the first electrolyzer might still be above the turn-on threshold when the second electrolyzer becomes operational. The controller never allows more than one electrolyzer to be turned on at a time. But when the second electrolyzer becomes operational, the moving average of the first electrolyzer might still be above the turn-on threshold, causing the controller to turn the third one on right away. As the second electrolyzer becomes operational, the advisory control will split the available power between them, causing their moving averages to drop considerably. Therefore, the controller will reset their moving averages, and start monitoring their power consumptions from the point when the newly turned electrolyzer becomes operational. That allows the controller to make the decision when to turn the third electrolyzer on, based on the information available since the newly turned electrolyzer became operational.

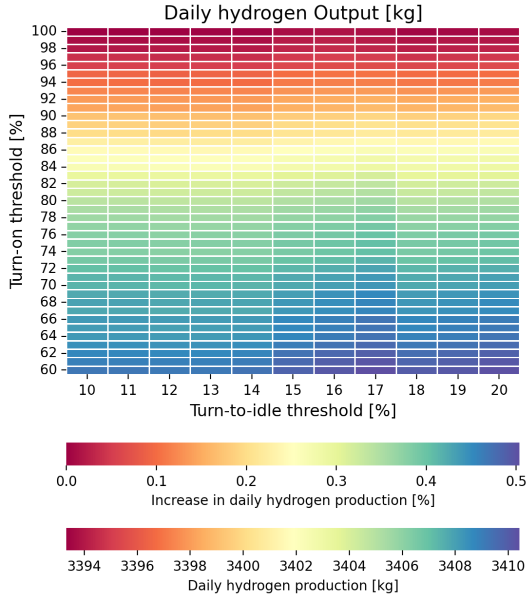
This is very important as the advisory control also sorts the electrolyzer every time a new electrolyzer is turned on, as was explained in B.4. Therefore the newly turned on electrolyzer mostly goes to the first position in the electrolyzer matrix, and the already operational electrolyzer goes later on in the matrix. If the moving average of that electrolyzer is not reset, its moving average is likely still above the turn-on threshold, causing the controller to turn the third electrolyzer on.

E.2. Color maps - 1 month power output

E.2.1. 4x5 MW - Strategy 1

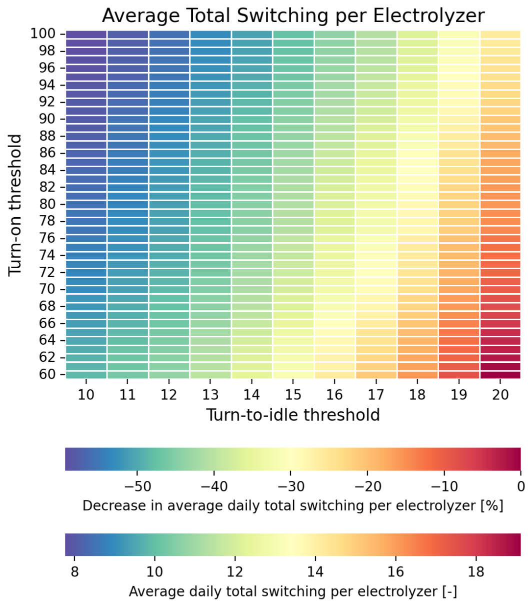


(a) Without moving average

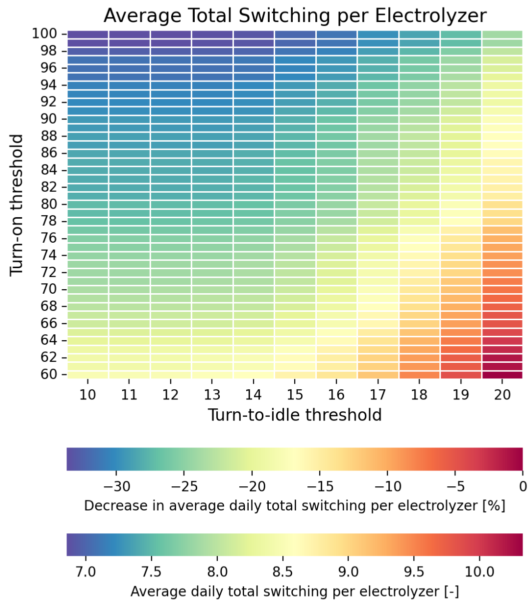


(b) 5 minute moving average

Figure E.1: Hydrogen production of different versions with and without a 5-minute moving average

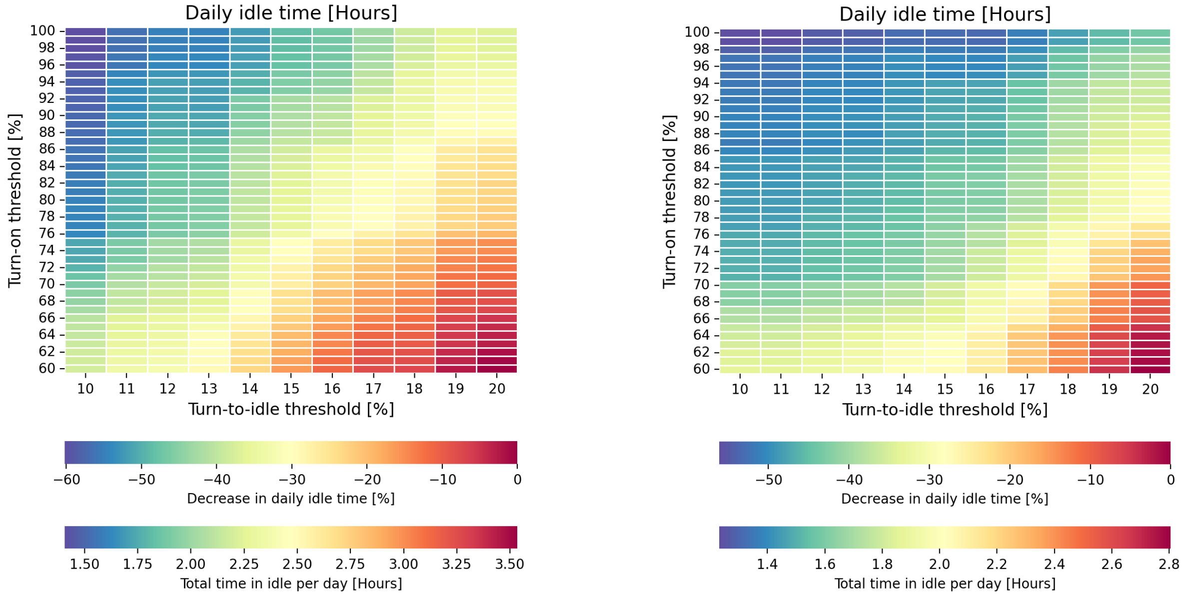


(a) Without moving average



(b) 5 minute moving average

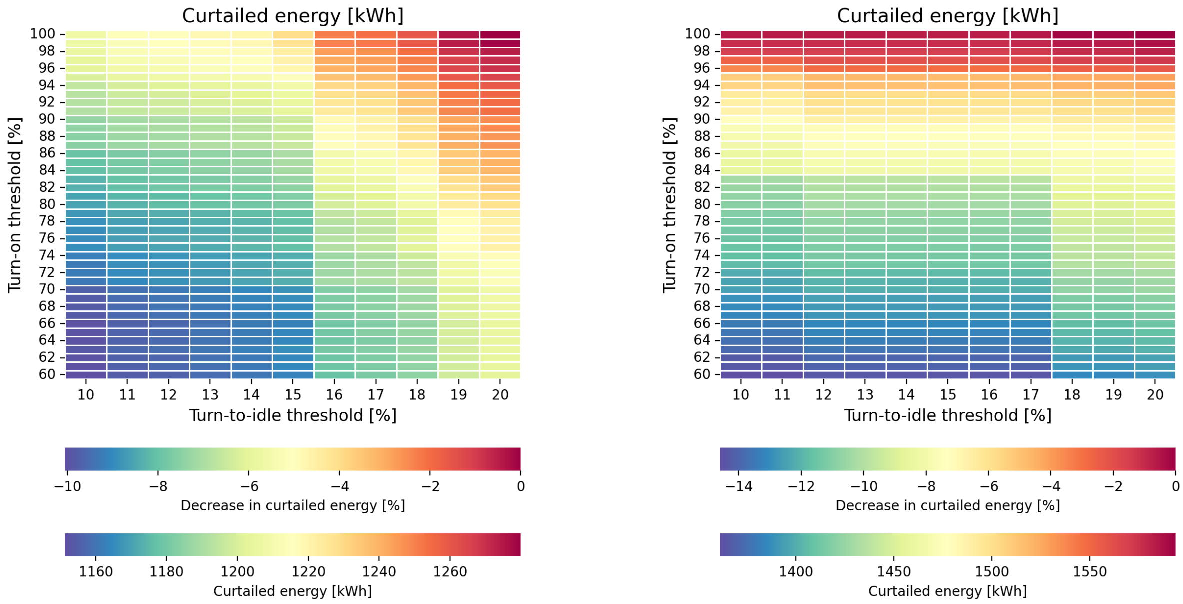
Figure E.2: Average daily switching per electrolyzer of different versions with and without a 5-minute moving average



(a) Without moving average

(b) 5 minute moving average

Figure E.3: Average daily idle time of different versions with and without a 5-minute moving average

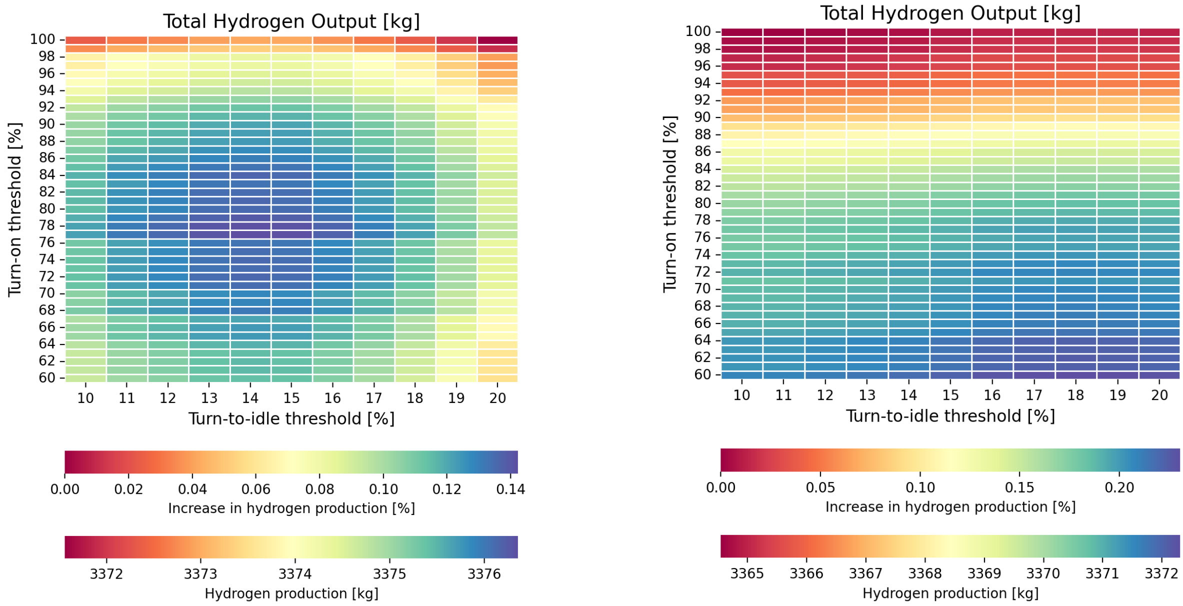


(a) Without moving average

(b) 5 minute moving average

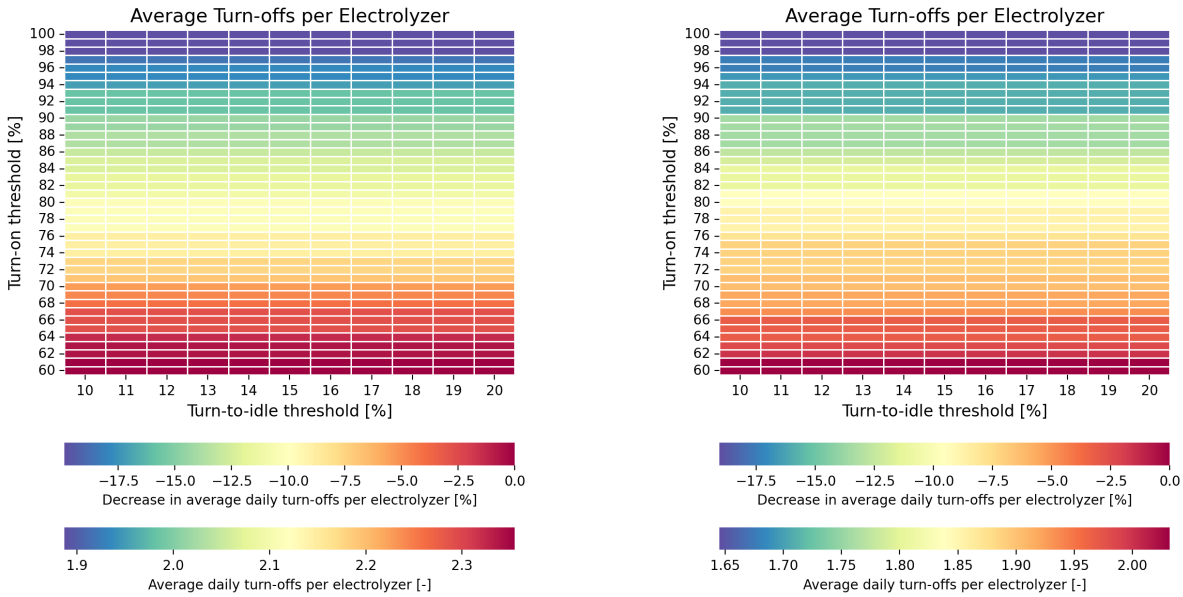
Figure E.4: Average daily curtailed energy of different versions with and without a 5-minute moving average

E.2.2. 2x10 MW - Strategy 1



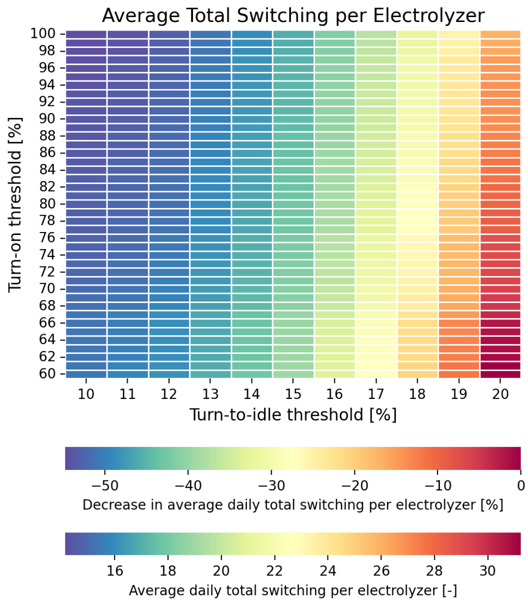
(a) Without moving average **(b)** 5 minute moving average

Figure E.5: Hydrogen production of different versions with and without a 5-minute moving average

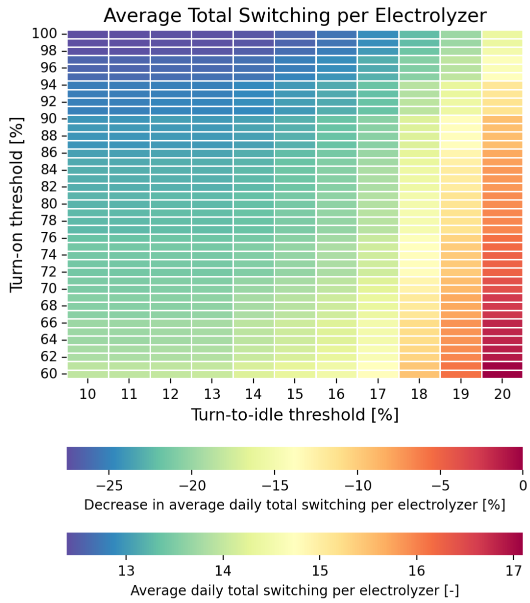


(a) Without moving average **(b)** 5 minute moving average

Figure E.6: Average daily turn-off rate per electrolyzer of different versions with and without a 5-minute moving average

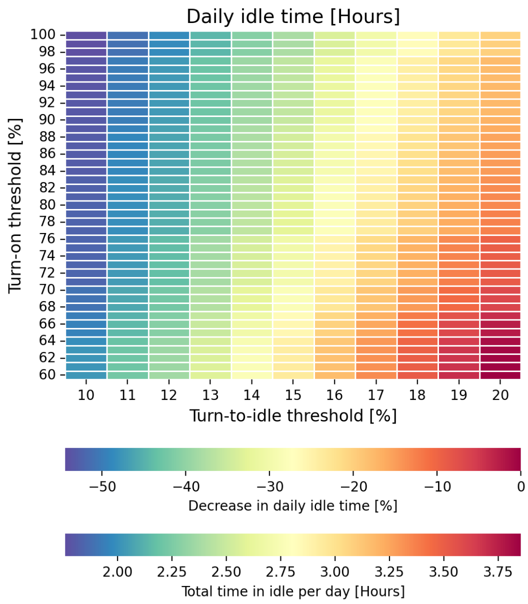


(a) Without moving average

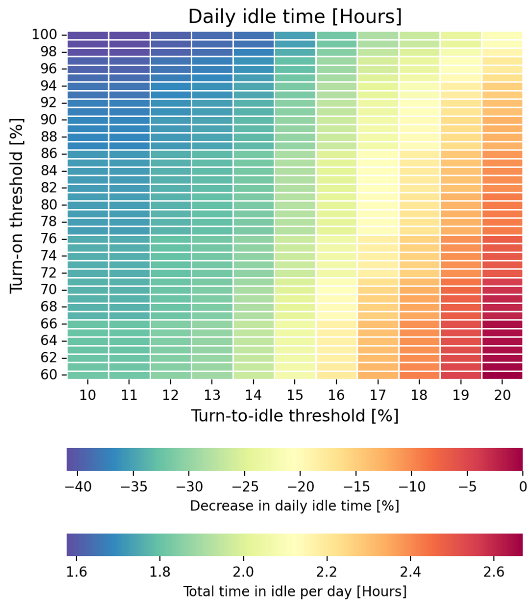


(b) 5 minute moving average

Figure E.7: Average daily switching rate per electrolyzer of different versions with and without a 5-minute moving average

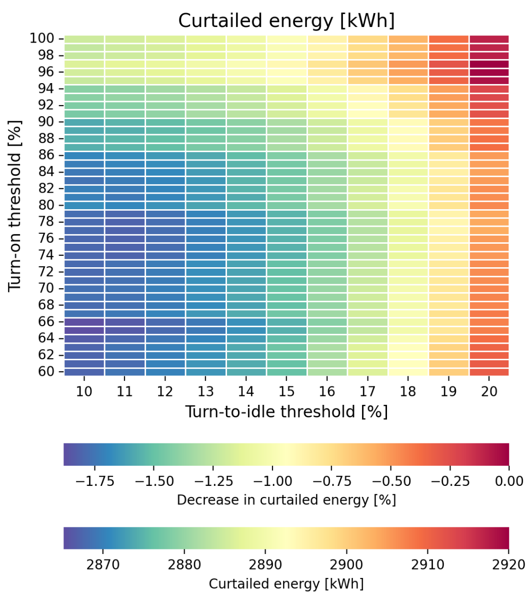


(a) Without moving average

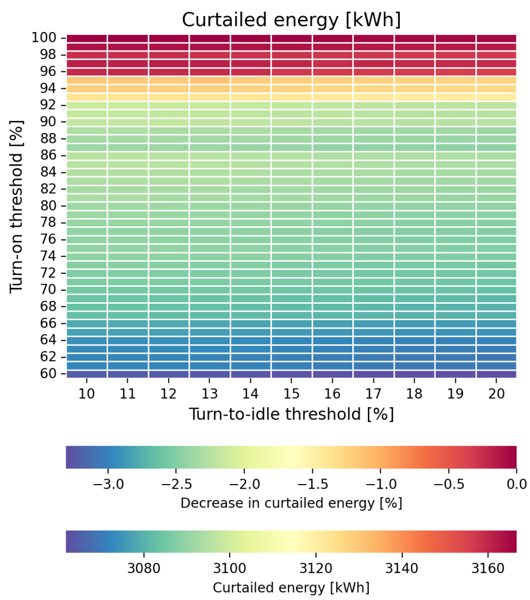


(b) 5 minute moving average

Figure E.8: Average daily idle time of different versions with and without a 5-minute moving average



(a) Without moving average



(b) 5 minute moving average

Figure E.9: Average daily curtailed energy of different versions with and without a 5-minute moving average

E.3. Results of the 5 KPIs with different moving average lengths

Table E.1: Results of the 5 KPIs when simulating case 2 with the 4x5 MW configuration, with and without a moving average.

Simulation setting	Daily hydrogen production [kg]	Daily turn-off rate per electrolyzer	Daily switching rate per electrolyzer	Daily idle time [Hours]	Daily curtailed energy [kWh]
	Turn-on threshold: 100% Turn-to-idle threshold: 10%				
Without moving average	3,408.1	1.77	7.77	1.41	1207
2 minute average	3,399.6 (-0.2%)	1.59 (-10%)	7.10 (-8.7%)	1.31 (-6.9%)	1,408 (+16.6%)
5 minute average	3,393.3 (-0.4%)	1.52 (-13.7%)	6.85 (-11.8%)	1.23 (-12.5%)	1,583 (+31.1%)
10 minute average	3,384.3 (-0.7%)	1.41 (-20.1%)	6.54 (-11.8%)	1.13 (-12.5%)	1,862 (+54.3%)
	Turn-on threshold: 60% Turn-to-idle threshold: 20%				
Without moving average	3,417.5	2.97	19.1	3.53	1,204
2 minute average	3,414.4 (-0.1%)	2.32 (-21.7%)	12.6 (-34.4%)	2.91 (-17.7%)	1,296 (+7.7%)
5 minute average	3,410.4 (-0.2%)	2.09 (-29.6%)	10.3 (-46%)	2.81 (-20.6%)	1,389 (+15.4%)
10 minute average	3,405.8 (-0.3%)	1.94 (-34.8%)	9.0 (-52.8%)	2.48 (-29.9%)	1,505 (+25.1%)

Table E.2: Results of the 5 KPIs when simulating case 2 with the 2x10 MW configuration, with and without a moving average.

Simulation setting	Daily hydrogen production [kg]	Daily turn-off rate per electrolyzer	Daily switching rate per electrolyzer	Daily idle time [Hours]	Daily curtailed energy [kWh]
	Turn-on threshold: 100% Turn-to-idle threshold: 10%				
Without moving average	3372.4	1.89	14.1	1.76	2885
2 minute average	3366.9 (-0.2%)	1.69 (-10.3%)	12.71 (-10%)	1.63 (-7.6%)	3092 (+7.2%)
5 minute average	3364.6 (-0.2%)	1.65 (-12.8%)	12.39 (-12%)	1.58 (-10.4%)	3167 (+9.8%)
10 minute average	3360.1 (-0.4%)	1.61 (-14.5%)	12.16 (-14%)	1.48 (-16.0%)	3299 (+14.4%)
	Turn-on threshold: 60% Turn-to-idle threshold: 20%				
Without moving average	3373.5	2.35	31.2	3.86	2911.0
2 minute average	3372.8 (0.0)	2.11 (-10.3%)	20.4 (-35%)	3.03 (-21%)	3040.6 (+4.5%)
5 minute average	3372.2 (0.0)	2.03 (-13.7%)	17.1 (-45%)	2.67 (-31%)	3061.8 (+5.2%)
10 minute average	3370.7 (-0.1%)	1.97 (-16.4%)	15.3 (-51%)	2.41 (-37%)	3104.2 (+6.6%)

F

Weather forecast and additional storage element

F.1. 9 month power output time series data

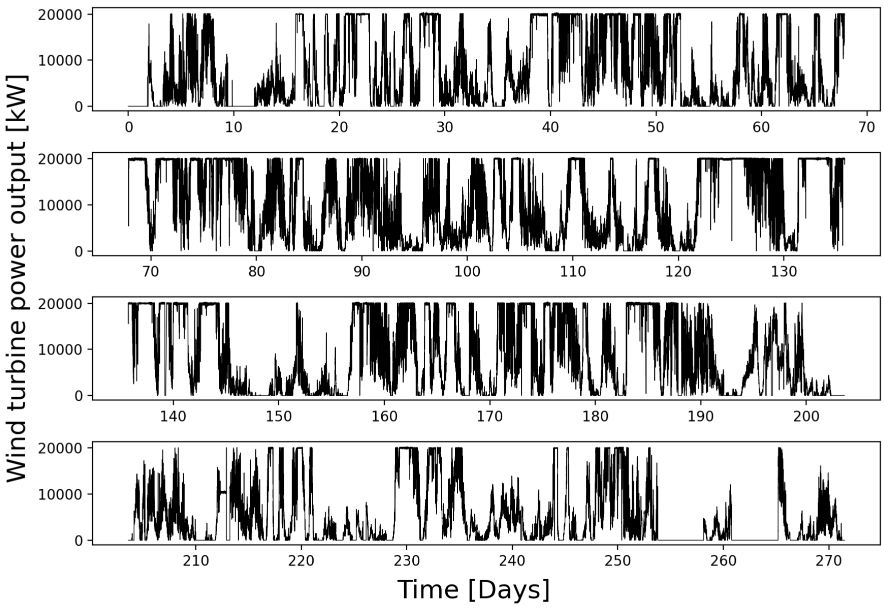


Figure F.1: 9 month power output time series data - 5 second resolution

F.2. Selecting the percentage increase on top of the MAFP

This section will describe the analysis of using different percentage increases on top of the MAFP. The analysis is based on the 4x5 MW configuration, using a 5 minute moving average, using the selected version from Section 7.1.5. To understand the affect of different percentage increases on top of the MAFP, time horizons were simulated from 15 minutes to 120 minutes with a step size of 15 minutes. Those simulations were coupled with

F.2.1. 2x10 MW

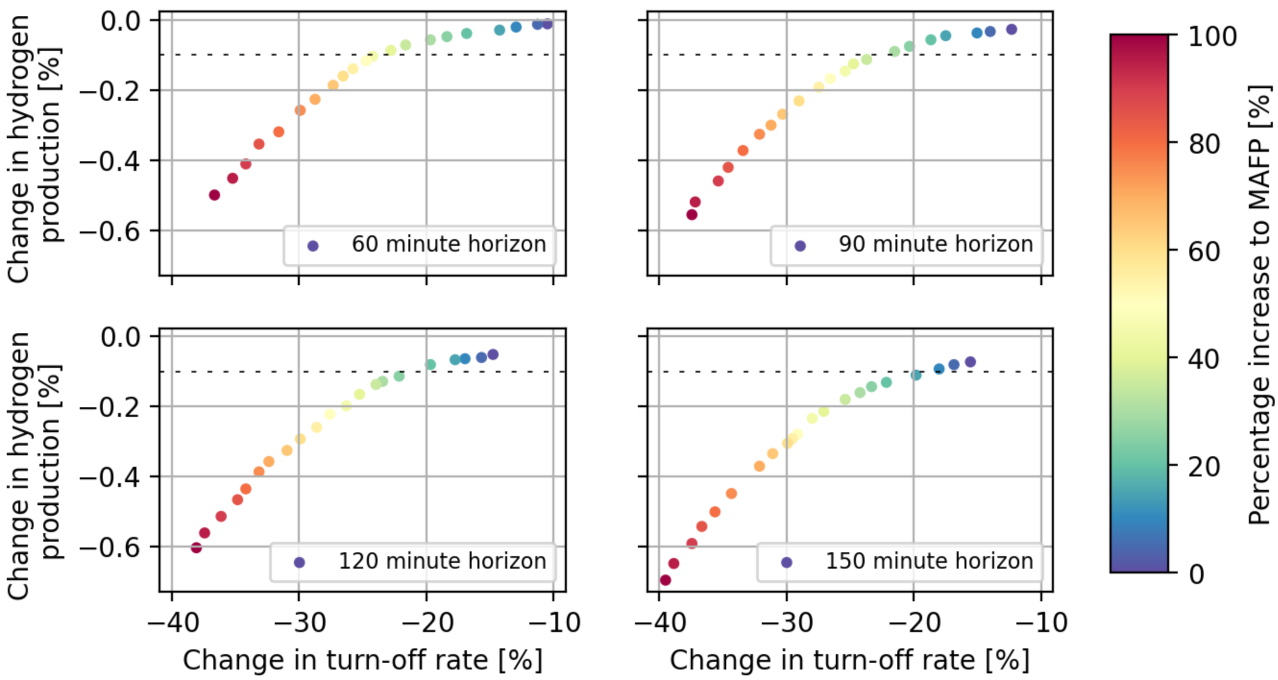


Figure F.2: H2 vs average number of turn-offs with different MAFP for the 2x10 MW configuration.

Table F.1: MAFP cross-over points where the decrease in hydrogen production is around 0.1%

Time Horizon [minutes]	Decrease in hydrogen production [%]	Decrease in the turn-off rate [%]	Percentage increase to the MAFP [%]
60	-0.1	-24.4	45
90	-0.09	-23.7	35
120	-0.1	-22.2	25
150	-0.09	-18	10

F.3. Selecting the time horizon for the 2x10 MW configuration

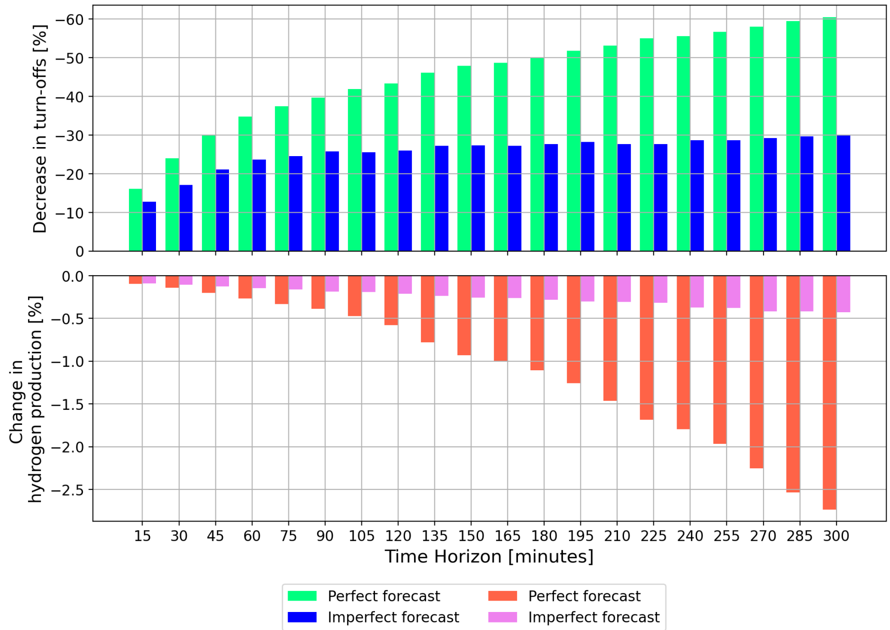


Figure F.3: Perfect vs imperfect forecast: Change in hydrogen production and daily turn-off rate with different time horizons

Table F.2: Changes in the 5 KPIs with an imperfect forecast with 4 selected time horizons for the 2x10 MW configuration.

Weather forecast settings	Electrolyzer system configuration	Change in Hydrogen production [%]	Change in the daily turn-off rate per electrolyzer [%]	Change in the daily switching rate per electrolyzer [%]	Change in the daily idle time [%]	Change in curtailed energy [%]
30 min forecast Imperfect	4x5 MW	-0.09	-17.2	-6.9	-9.5	+3.2
60 min forecast Imperfect	4x5 MW	-0.15	-23.7	-11.4	-16.7	+6.3
90 min forecast Imperfect	4x5 MW	-0.19	-25.7	-13.0	-19.2	+8.7
120 min forecast Imperfect	4x5 MW	-0.21	-26.0	-13.0	-19.9	+10.6

F.4. Testing new turn-on threshold for the first electrolyzer when using a 1-hour imperfect forecast and an ASE with 10 minute capacity

The results in this section are mainly showing that decreasing the turn-on threshold does not bring any benefits for the 4x5 MW, as the increase in hydrogen production is outweighed by the increased energy required for the ASE. However, for the 2x10 MW, a roughly 0.3% increase in hydrogen production is observed while the turn-off rate increases the same amount. It was expected that this would be more beneficial for the 2x10 MW, because of the increased minimum operating point.

Table F.3: 4x5 MW: Changes in hydrogen production and turn-off rate for different turn-on thresholds for the first electrolyzer

Turn-on threshold	Change in hydrogen production [%]	Change in daily turn-off rate [%]
13%	-0.11	+0.93
14%	-0.09	+0.83
15%	-0.07	+0.73
16%	-0.04	+0.62
17%	-0.02	+0.41
18%	-0.01	+0.21
19%	0.00	+0.10
20%	-	-

Table F.4: 2x10 MW: Changes in hydrogen production and turn-off rate for different turn-on thresholds for the first electrolyzer

Turn-on threshold	Change in hydrogen production [%]	Change in daily turn-off rate [%]
13%	+0.33	+0.49
14%	+0.31	+0.49
15%	+0.28	+0.24
16%	+0.23	+0.24
17%	+0.18	+0.00
18%	+0.13	+0.24
19%	+0.07	+0.24
20%	-	-

G

Economic analysis

G.1. Wind turbine full load hour

Table G.1: 2005 - 2021, 20 MW wind turbine power output and full load hours

Year	Energy obtained from wind data [MWh]	Equivalent FLH [Hours]
2005	97556	4878
2006	87690	4385
2007	86034	4302
2008	93182	4659
2009	87502	4375
2010	84722	4236
2011	92085	4604
2012	81701	4085
2013	86822	4341
2014	86204	4310
2015	92701	4635
2016	84999	4250
2017	91745	4587
2018	87921	4396
2019	87974	4399
2020	87335	4367
2021	81544	4077
Average:	88101	4405

G.2. Wind turbine LCOE analysis

The section will test the methodology presented by NREL and summarized in **??**, to see whether the calculated LCOE is close to the estimated costs from IRENA.

Any currency estimates which are obtained from sources that are older than 2020 will be adjusted for inflation to the end of 2021 values.

The values and the corresponding LCOE are summarized in Table 8.1, while the following paragraphs will provide the background information on how those values were selected.

In 2019, IRENA published an outlook on onshore and offshore wind energy until 2050. The CAPEX per kW was provided for both 2030 and 2050 in 2018 dollars. Those values were be converted to end of 2021 values in euros [1]. In 2030 it is estimated that the CAPEX for offshore wind will be in the range of 1550 - 2930 $[€_{2021}/kW]$. Those costs represented the entire capital costs relating to wind turbine costs, civil works, grid connection, planning, and project costs [11, p. 47]. As the SAHO wind turbine is not grid-connected, it can be expected that these costs will be slightly lower.

Another report from 2018, estimates that a reference CAPEX for offshore wind, excluding grid costs is 2290 $[€_{2021}/kW]$ [2]. A value of 2290 $[€_{2021}/kW]$ will be used for the CAPEX.

Regarding the OPEX, an estimate of offshore annual OPEX is 3.2% of the initial CAPEX [61, p. 56]. That is roughly 73 $[€/kW]$. In 2018, offshore projects had O&M costs in the range of 70-129 $[€/kW]$ [3], with a lower range observed for projects close to shore [6, p. 117]. O&M costs have decreased in recent years due to increased competition, O&M optimization, and synergies in offshore wind farm clustering [6, p. 117]. Considering further innovation and improvements, alongside larger wind turbines leading to fewer O&M visits, a value of 2.5% of CAPEX will be used.

The full load hour results are shown in Section G.1, with the average FLH equal to 4405 hours.

Vattenfall provided information that an estimated availability of the 20 MW wind turbine is around 97%, and that a reference plant lifetime is around 30 years.

The only input that is further required, is the full load hours. The 17 year long ERA5 data, from 2005 - 2021, with 1 hour average wind speeds was used, using the synthetic 20 MW power curve to convert those average wind speeds to power output (see Figure 4.1). The resulting power output and corresponding full load hours for each year can be seen in Table G.1. The average FLH over the 15 years will be taken as the representative FLH value. Considering a 97% availability, the FLH value is decreased accordingly.

Table G.2: Levelized cost of energy for the 20 MW wind turbine - setup

Parameters	Wind turbine
CAPEX [€/kW]	2200
Annual OPEX [% of CAPEX]	3.2
Availability [%]	97
Full load hours assuming 100% availability [Hours/Year]	4405
Full load hours assuming 97% availability [Hours/Year]	4273
Plant lifetime [Years]	30
WACC [%]	7

Based on the setup in Table 8.1, the resulting crf and LCOE could be calculated based on the equations in Section 8.1. The result is summarized below in Table G.3, with the LCOE breakdown for the OPEX

[1] The average exchange rate in 2018 was 1 USD = 0.8475€ [62], and 1 USD in 2018 was worth 1.08 USD at the end of 2021 [60]

[2] 1 $[€_{2018}/kW]$ = 1.04 $[€_{2021}/kW]$ [63]

[3] It was not stated whether those numbers took inflation into consideration

and CAPEX also shown. Table G.3 shows that the LCOE is 0.057 $[\frac{€}{kWh}]$. That is near the lower end of the projected LCOE for offshore wind in 2030 from [11], published in 2019. The OPEX cost is 0.013 $[\frac{€}{kWh}]$, or 23% of the LCOE which is in the identified range of [16%,25%] mentioned in [6, p. 117].

Table G.3: Levelized cost of energy for the 20 MW wind turbine

Parameters	Wind turbine
crf [-]	0.0806
crf*CAPEX $[\frac{€}{kWh}]$	0.043
OPEX $[\frac{€}{kWh}]$	0.013
LCOE $[\frac{€}{kWh}]$	0.057

G.3. Electrolyzers LCOH analysis

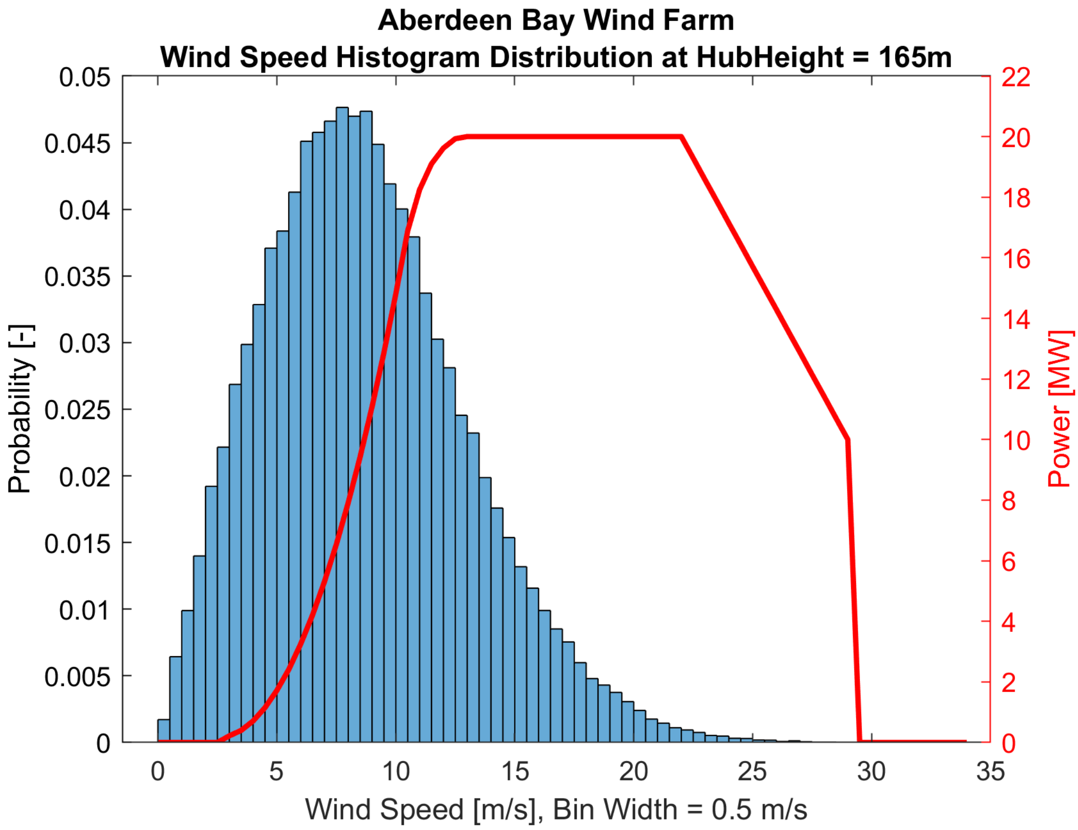


Figure G.1: Aberdeen Bay wind farm wind speed distribution

Table G.4: System level efficiency of the two system configurations over the 30 year lifetime

Year	4x5 MW	2x10 MW
2030	49.8	50.0
2031	50.0	50.3
2032	50.3	50.5
2033	50.6	50.8
2034	50.8	51.0
2035	51.1	51.3
2036	51.3	51.5
2037	51.6	51.8
2038	51.8	52.0
2039	52.1	52.3
2040	52.3	52.6
2041	52.6	52.8
2042	52.9	53.1
2043	53.1	53.3
2044	53.4	53.6
2045	44.8	45.0
2046	45.0	45.2
2047	45.3	45.5
2048	45.5	45.7
2049	45.7	45.9
2050	46.0	46.1
2051	46.2	46.4
2052	46.4	46.6
2053	46.6	46.8
2054	46.9	47.1
2055	47.1	47.3
2056	47.3	47.5
2057	47.6	47.8
2058	47.8	48.0
2059	48.1	48.3
Average:	**49**	**49.2**