Stabilizing green hydrogen

Simulating the use of energy storage systems for the stabilization of renewable hydrogen production

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Preface

After years of building models, analyzing policies and having fun in the process, this thesis is my final work before completing my M.Sc. Engineering and Policy Analysis at the Technology, Policy and Management faculty of the Delft University of Technology. For my thesis, I studied the influence of European Union level policies on the production of renewable hydrogen and thereby on the feasibility of the renewable hydrogen goals of the European Union. This topic allowed me to combine a lot of the knowledge on modelling, simulation, systems thinking and policy analysis that I have gathered during my time at Delft University of Technology. At the same time as I was writing this thesis, I did an internship at HyCC, a company developing renewable hydrogen production projects. I am very grateful for this opportunity as it allowed me to expand my knowledge on hydrogen production and the use of modelling and simulation in project development.

There are a few people without whom I would not have been able to write this thesis and I would like to take this opportunity to thank them for all their help and input. I would like to thank the Chair of my Graduation Committee, Haiko van der Voort, for making the process of my thesis run smoothly. I always really enjoy working with you, also outside of the context of my thesis. Your input helped me greatly when using the outcomes of the simulation study to formulate meaningful policy advice. Secondly, I would like to thank the First Supervisor of my Graduation Committee, Stefan Pfenninger. I am very grateful for all the feedback and ideas you supplied me with throughout the whole process of writing my thesis. From when I was formulating my problem outline to when I was writing my executive summary, you were always there to have useful discussions with. And last, but definitely not least, I would like to thank the External Supervisor in my Graduation Committee, Marnix de Vries. Not only did you introduce me to the use of modelling and simulation in a hydrogen context, but you also provided me with great guidance during my first internship. You really showed me how to use modelling in a meaningful way outside of university and were always there when I had questions.

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Executive summary

To mitigate the effects of climate change, CO_2-emmissions will have to be reduced. This can be done by substituting the use of fossil, CO_2-heavy by the use of renewable, CO_2-neutral energy carriers. Hydrogen is such a renewable energy carrier that can be produced in a CO_2-neutral way. The potential of hydrogen is recognized by the European Commission as specific renewable hydrogen goals are stated in their Fit for 55 package, which is a plan to reduce greenhouse gas emissions within the European Union with 55% by 2030. These goals relate to both the production and use of renewable hydrogen within the European Union.

For hydrogen to be qualified as renewable, the European Commission has proposed a set of requirements that its production has to comply with. One of them is temporal correlation, requiring the amount of energy used by a hydrogen production plant to match the amount of energy generated by one or more connected renewable energy plants. Renewable energy plants generate a variable output of energy as they rely on variable energy sources such as wind. This causes the production of renewable hydrogen to be variable as well. The fact that this production of hydrogen is variable can be problematic as some industrial processes require or perform better with a constant input of hydrogen. Energy storage systems, such as lithium-ion batteries, can be integrated in hydrogen plants to stabilize the hydrogen production from a renewable energy source. This works through locally storing part of the energy generated during peaks to be used at times when there is a deficit of energy.

The purpose of this study is to see how different energy storage systems influence the performance of wind-hydrogen plants. A wind-hydrogen plant is a hydrogen plant producing hydrogen with an electrolyzer powered with energy from a wind park. Based on the outcomes of the study, wind-hydrogen plants can be designed incorporating the most adequate energy storage system for its purpose. The outcomes of the study can also be used by policy-makers to see how the temporal correlation requirement of the European Commission influences the feasibility of the hydrogen goals in the Fit for 55 package.

The performance of wind-hydrogen plants with different energy storage methods is evaluated using a simulation model. After performing experiments for wind-hydrogen plants with different types of energy storage systems, their influence on the performance of the wind-hydrogen plant can be analyzed.

Results show that the hydrogen production from a variable energy source is lower and less stable than that from a continuous source. These effects can be mitigated with the use of energy storage systems. However, the introduction of these systems makes wind-hydrogen plants less efficient and drive up the costs of hydrogen production. This illustrates a trade-off as energy storage systems do increase and stabilize hydrogen production, but at a lower efficiency and higher cost.

Comparing the performance of individual energy storage systems shows that the use of lithium-ion batteries to store energy results in the highest and most stable hydrogen. At the same time, the use of lithium-ion batteries is by far the most expensive option. The use of a hydrogen energy storage system results in the most efficient and cheapest hydrogen production. This shows that another trade-off is at play when selecting an energy storage system to integrate in a wind-hydrogen plant.

Based on the results, the effects of the temporal correlation requirement on the feasibility of the Fit for 55 renewable hydrogen goals can be analyzed. The requirement makes the hydrogen goals in the Fit for 55 package less feasible as it causes a decrease in renewable hydrogen production. It also makes it less fit for use by the industry as the hydrogen supply will become less stable. Energy storage systems can be used to mitigate these negative effects, however, these cause a decrease in hydrogen plant efficiency and therefore an increase in loss of renewable energy. Also, it drives up the production cost, making renewable hydrogen less attractive to use by industry and increasing barriers for new renewable hydrogen production to enter the market. The recommendation is for the European Commission to investigate an alternative requirement than the temporal correlation to ensure the renewable production of hydrogen.

1. Introduction

Climate change is one of the biggest challenges ever faced by humanity. According to the IPCC (2021), human-induced climate change can cause extreme events like heatwaves, heavy precipitation, droughts, and tropical cyclones to occur more often. One of the major drivers of climate change is the emission of CO_2 resulting from the use of fossil fuels. To reduce CO_2 emission, the use of polluting fossil fuels can be replaced with that of renewable, CO_2-neutral fuels such as hydrogen. Hydrogen can be a zero-carbon energy carrier if produced in a renewable manner and is under serious consideration to be used for low carbon transport, industrial decarbonization, and heat provision in many countries (Velazquez Abad & Dodds, 2020).

While hydrogen is a zero-carbon energy carrier, its production can still result in CO_2-emissions. Hydrogen can be produced in several ways, using various feedstocks and energy pathways (Velazquez Abad & Dodds, 2020). A lot of the hydrogen produced nowadays is produced using fossil fuels, causing high CO_2-emissions (Velazquez Abad & Dodds, 2017). A pathway to produce renewable hydrogen without causing CO_2-emission is through electrolysis powered by wind energy (wind-hydrogen plants) (Alavi et al., 2016). The hydrogen produced by these wind-hydrogen plants has significant potential to be used for extensive and cost-effective greenhouse gas mitigation because of its low life cycle greenhouse gas emission and the low price of wind energy (Olateju et al., 2014).

Renewable hydrogen plays a large role in the plans of the European Commission to reduce the emission of greenhouse gasses in the European Union (EU). In the Fit for 55 package, which aims to reduce greenhouse gas emissions in the EU with 55% by 2030, multiple goals relating to renewable hydrogen have been defined (European Commission, 2021). These goals have been defined both in terms of production and use of renewable hydrogen. In terms of production, the goal is to produce 10 million tonnes of renewable hydrogen in the European Union by 2030. In terms of use, half of all hydrogen used in the EU by industry needs to be of renewable origin by 2030 and 2,6% of all fuel used in transport in the EU needs to be renewable fuel of non-organic origin (RFNBO).

For fuels to qualify as RFNBO, the European Commission (2018) has proposed a set of requirements that their production needs to meet. These requirements have been proposed in the EU Renewable Energy Directive (RED II) and apply to hydrogen when produced to be used as RFNBO. One of these criteria is that a party producing hydrogen needs to purchase the required energy from an energy producing party that generates their energy from a renewable source (European Commission, 2018). To ensure that this requirement is met, these parties need to close a bilateral power purchasing agreement (PPA). Another requirement is that the amount of energy consumed by the hydrogen producing party needs to match the amount of energy generated by the energy generating party over a certain timeframe. This requirement can be referred to as temporal correlation. While these requirements are currently proposed for production of hydrogen to be used as RFNBO, expectations are that these requirements will be imposed on the production of renewable hydrogen for all purposes (Frontier, 2021; Hocksell, 2022).

Compliance with the temporal correlation requirement can cause the output of renewable hydrogen from a wind-hydrogen plant to be variable. The reason for this is that the supply of wind energy to the plant is not constant. After all, a turbine will generate more energy when it is very windy and less energy when there is less wind. This variability can be problematic for industrial processes that require hydrogen as a highly variable input of hydrogen would mean these processes would need to be scaled up and down at a high rate. This can be costly since the scaling of chemical processes is a matter in which many factors need to be considered (Hitchin, 2022). Therefore, industrial processes benefit from a more stable input of hydrogen.

To stabilize the hydrogen output from a wind-hydrogen plant using energy from a variable source, energy storage systems could be used. When hydrogen is produced at a constant rate using wind energy, more energy might be generated than used (Gökek, 2010). After all, during wind peaks, more wind energy can be generated than used for the hydrogen production process. To decrease the variability in wind energy supply and thereby in renewable hydrogen production, this excess energy can be stored temporarily to be used when there is a deficit. Figure 1 conceptually depicts a wind-hydrogen with an energy storage system to stabilize the hydrogen output. When the electricity output from the wind turbines is larger than required for the stable production of the desired amount of hydrogen, some of the electricity is stored in the energy storage system. At times when the electricity output from the wind turbines is lower than required for the stable production of the desired amount of hydrogen, electricity is supplied to the electrolyzer from the energy storage system.

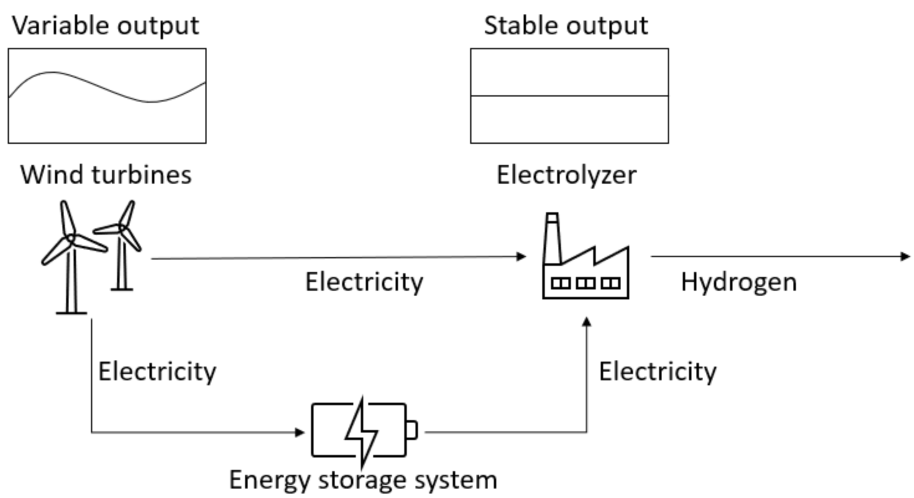

Figure 1: Conceptual model of a wind-hydrogen plant with integrated energy storage system

Various energy storage systems exist that can be used to temporarily store wind energy for later use (Díaz-González et al., 2012). Examples of such wind energy storage systems are the usage of batteries or compressed air. The different wind energy storage systems that are available have various characteristics that need to be considered when being considered for application in a bigger system (Zhao et al., 2015). This implies that different energy storage systems will influence the performance of a wind-hydrogen plant in different ways when implemented.

To stimulate the production of CO_2-neutral hydrogen from wind-hydrogen plants and thereby reduce CO_2-emissions, it is detrimental that insight is gained in the effects of different wind energy storage systems being implemented in wind-hydrogen plants. After all, the performance of wind-hydrogen plants could be improved when it becomes clear what the optimal wind energy storage system would be to incorporate.

The use of different energy storage systems in wind-hydrogen plants can be explored using mathematical simulation. Following this this method, a number of equations is formulated that represent the way that different components of wind-hydrogen plants and their relations affect the performance of this plant. Using this set of equations, the performance of wind-hydrogen plants with different energy storage systems can be calculated. By analyzing the outcomes of these calculations, the performance of the different energy storage systems when used in wind-hydrogen plants becomes can be determined. Also, these outcomes can be used to reflect on how the requirements for the production of RFNBOs as listed in RED II affect renewable hydrogen production and thereby the feasibility of the renewable hydrogen goals of the Fit for 55 package. Interpreting the outcomes of the mathematical simulation study in the context of the renewable hydrogen goals of the Fit for 55 can offer a comprehensive view that combines technical and economical insights to evaluate the proposed temporal correlation requirement. If meeting these requirements turns out to have a negative impact on the technical and economic performance of wind-hydrogen plants, they may be counterproductive for reaching the renewable hydrogen goals of the Fit for 55 package. This is especially relevant as these requirements are announced to be proposed for all the production of renewable hydrogen for all uses (Hocksell, 2022).

Chapter 2 provides a background for the problem as described above and defines the existing knowledge gap around it. In chapter 3, a method is described for addressing the knowledge gap. In chapter 4, the results of the study are presented. These results are then discussed in chapter 5. A conclusion is provided in chapter 6.

2. Background

To illustrate the background of the problem as described in chapter 1, some relevant topics are highlighted. Section 2.1 discusses the most relevant components of a wind-hydrogen plant: the electrolyzer and wind-turbines, section 2.2 discusses the various energy storage system that can be used to stabilize the hydrogen output of wind-hydrogen and section 2.3 discusses the role of renewable hydrogen (production) in various EU policies. Before specifying the exact knowledge gap to be addressed in this study, section 2.4 provides a systematic review of the research that has been done on the topic of renewable hydrogen production with wind energy. Section 2.5 then specifies the exact knowledge gap in a systematic way and provides a research question addressing it.

2.1 Wind-hydrogen plants

Different pathways exist to produce (renewable) hydrogen. Of all pathways, the ones using water-based electrolyzers are deemed to produce the hydrogen with the lowest possible life cycle greenhouse gas emissions (Olateju et al., 2014). Together with the wind turbines powering them, these electrolyzers can be seen as (some of) the main components of a wind-hydrogen plant.

2.1.1 Electrolyzers

An electrolyzer is a piece of equipment that facilitates electrolysis. The general principle of electrolysis is passing an electric current through an electrolyte to enable chemical reactions at the connected electrodes. When electrolysis is performed to produce hydrogen, two electrodes are placed in water. When passing an electric current through these electrodes, reactions are enabled that cause hydrogen to appear at the cathode and oxygen to appear at the anode. Depending on the type of electrolysis performed, the materials of the electrodes can differ as well as the materials separating them (Carmo et al., 2013).

Two types of electrolyzer variants that can be used to produce hydrogen are alkaline electrolyzers and polymer electrolyte membrane (PEM) electrolyzers (Schnuelle et al., 2020). In alkaline electrolysis, two electrodes separated by a diaphragm are immersed in an alkaline electrolyte (Carmo et al., 2013). This diaphragm has the function of separating the gases that result from the reactions at each of the electrodes for the sake of efficiency and safety. At the same time, the diaphragm does need to allow hydroxide ions to pass through from the cathode to the anode. PEM electrolysis works in a different way. In PEM electrolysis, a solid sulfonated polystyrene membrane is used as an electrolyte (Carmo et al., 2013). Through this membrane, hydrogen ions move from the cathode to the anode. The fact that PEM and alkaline electrolyzers operate differently causes them to have different characteristics. PEM electrolyzers can generally operate more flexible as they have a broader load flexibility and a higher ramp-speed (Schnuelle et al., 2020). Load flexibility is a measurement for how broad the range of energy consumption is under which an electrolyzer can operate. Ramp speed is a measurement for how quick an electrolyzer can ramp their load consumption up or down.

Over time, the technologies for electrolysis are being developed as room for improvement exists. The costs of hydrogen production have not been driven down yet by mass production or supply chain optimization and room for improvement of electrolyzer technology is significant (Bertuccioli et al., 2014). For example, the capital costs for alkaline electrolyzers can be reduced between 25% and 60% by scaling the components (Morgan et al., 2013). It is also likely that the performance of hydrogen production technologies will improve and thereby become cheaper

(Schmidt et al., 2019). For example, lifetime and durability and system efficiency can be improved (Bertuccioli et al., 2014). As a result, the estimated investment costs for alkaline electrolyzers in 2030 are between €787 and €906 per kW (Saba et al., 2018). For PEM electrolyzers, these costs are estimated to be €397 and €955. According to experts, the majority of the electrolyzers in 2030 will be PEM electrolyzers as these are preferred when coupled with a renewable energy generator (Schmidt et al., 2017). These experts also think that by 2030, this technology will also result in lower costs than alkaline electrolysis as it has a high operational flexibility.

2.1.2 Wind turbines/wind farms

Wind turbines are used in the wind parks that generate the energy for the hydrogen production by wind-hydrogen plants. These turbines generate electric energy from the kinetic energy coming from wind. The blades attached to the turbine are brought into motion by wind, allowing the kinetic energy from the wind to be transferred to the generator in the wind turbine. This generator then generates electricity from this kinetic energy. The use of energy generated by wind turbines has been growing significantly over the past decades, making wind energy the second-biggest installed renewable energy source (Almutairi et al., 2021).

Three design factors that play a large role in determining the amount of electricity a wind turbine can generate are its capacity, its hub height and the generator capacity to blade length ratio (specific power) (McKenna et al., 2022). The hub height of a wind turbine is measured from the platform it is standing on to its rotor and influences the wind speed expected around the blades. McKenna et al. (2022) have studied the development of these three design factors over time. Their research shows that the capacity of wind turbines has been increasing steadily since 1990. At the same time, the hub height has increased to 2.5 times the level of 1990 but has stagnated since 2015. The specific power of wind turbines has been relatively stable since 1990 and is approximately 400W/m^2.

Besides developments surrounding the performance of wind turbines, there are also developments around the locations where they are deployed. Where wind turbines are traditionally deployed on land, a lot of developments have been made during the past decades when it comes to the generation of offshore wind energy (Jiang, 2021). For the generation of offshore wind energy, wind turbines are placed on water. The installed offshore wind capacity has increased a lot recently (Diaz & Guedes Soares, 2020). While it is declining, the levelized cost of energy for offshore wind energy is currently still high when compared to onshore wind energy or solar energy (Jiang, 2021). One of the reasons for the development of offshore wind energy capacity is that the wind speed ratios (ratio between the wind speed and the speed of the tips of the wind turbine blades) might be higher offshore (Diaz & Guedes Soares, 2020).

2.2 Energy storage systems

Wind energy can be stored in using different energy storage systems. Reviews discussing and comparing these different energy storage systems mention seven different main methods to store energy: pumped hydro energy storage, compressed air storage, battery storage, superconducting magnetic energy storage, hydrogen storage, flywheels and (super)capacitors (Beaudin et al., 2010; Díaz-González at al., 2012; Lund et al., 2015). More recent reviews also mention the possibility of thermal energy storage (al Shaqsi et al., 2020; Hossain et al., 2020). Some of the considered energy storage systems can be implemented in different ways. For example, multiple different types of batteries exist (Divya & Østergaard, 2009). In the sections below, a description of each of the energy storage system is given.

Pumped hydro energy storage

Pumped hydrogen energy storage systems (PHSS) work by the principle of pumping water to a larger height in order to increase the gravitational potential energy of the (Díaz-González et al., 2012). At a later moment, when the energy demand is higher than the supply, the water flows back down past a turbine to generate electricity. The use of PHSS can be limited by the fact that large portions of land (10-20 km2) need to be flooded to create reservoirs to store water and the fact that the development of a PHSS takes relatively long (10 years) (Beaudin et al., 2010).

Compressed air energy storage

Compressed air energy storage systems (CAESS) store energy by compressing air in an underground cavern (Díaz-González et al., 2012). To later generate electricity again from this compressed air, it is drawn from the underground cavern to then be heated in high- and low-pressure turbines connected to an electrical generator. As this type of energy storage system typically requires an existing underground site, the locations at which it can be deployed are restricted.

Battery energy storage

Battery energy storage systems (BESS) consist of stacked cells in which electricity can be converted to chemical energy (Divya & Østergaard, 2009). This process takes place when the supply of electricity is higher than the demand. When the demand for electricity becomes higher than the supply, the chemical energy will be converted back into electricity. A distinction can be made between conventional BESS and flow-BESS (FBESS). Unlike conventional BESS, FBESS contain two tanks of aqueous electrolytic solutions that are pumped through the storage system (Díaz-González et al., 2012). A hurdle for certain types of BESS, such as lithium-ion batteries, their use on large scale can be the additional circuitry needed for safety and protection around them (Beaudin et al., 2010). Additionally, the performance of most BESS decreases per cycle that they are used, affecting their available capacity.

Superconducting magnetic energy storage

Superconducting magnetic energy storage systems (SMESS) work through storing energy by passing it through an inductor coil made of superconducting material that can circulate electricity with almost zero loss (Cheng et al., 2009). This technique can also be used to store energy in the magnetic field around this superconducting coil (Díaz-González et al., 2012). When there is a deficit of electricity, the energy can be drawn again from the coil and magnetic field. As the use of SMESS requires the inductor coil to be in a cryogenic state, an advanced cooling system is required for its operation (Díaz-González et al., 2012).

Hydrogen storage

In hydrogen-based energy storage systems (HESS), energy can be stored as hydrogen by using electricity to power an electrolyzer that produces hydrogen and oxygen from water (Beaudin et al., 2010). This energy can later be converted back to electricity by using a fuel cell. This fuel cell generates electricity while converting hydrogen and oxygen back into water. Hydrogen can be stored in different forms. When stored in a large quantity for more than 30 hours, storage as gas in metal tanks is suitable (Díaz-González et al., 2012).

When used within a wind-hydrogen plant, the use of a fuel cell to generate electricity from the stored hydrogen is not optimal. Instead, the generated hydrogen can be supplied to the client directly from the storage in case of a shortage in electricity to produce hydrogen with. This pathway circumvents the energy loss that takes place when using a fuel cell to generate electricity from hydrogen.

Flywheels

Flywheel energy storage systems (FESS) consist mainly of a flywheel that can be used to store and release energy by increasing or decreasing its rotational velocity (Beaudin et al., 2010). When energy needs to be stored, electricity is runs through an electric motor that accelerates the flywheel (Lund et al., 2015). When energy needs to be converted into electricity, energy is taken from the flywheel by a generator that converts kinetic energy into electricity. In this process, safety concerns can arise as FESS involves a rotor moving at high speed that can possibly break (al Shaqsi et al., 2020).

(Super)capacitors

(Super)capacitors energy storage systems (SCESS) can store energy in an electric field produced by a separation of charges (Lund et al., 2015). These charges (negative and positive) are accumulated on parallel electrodes separated by a dielectric (Beaudin et al., 2010). The difference between capacitors and supercapacitors is that supercapacitors can provide higher energy densities due to the type of electrodes that is used (Díaz-González et al., 2012). Apart from this distinction, there is also a difference between symmetrical and asymmetrical supercapacitors. In symmetrical supercapacitors, the positive and negative electrodes are made of the same material whereas this is not the case for asymmetrical supercapacitors (Díaz-González et al., 2012).

Thermal energy storage

Thermal energy storage systems (TESS) consist of materials that can be preserved at either a low or high temperature (al Shaqsi et al., 2020). Energy can be stored by bringing these materials to either high or low heat. This energy can then be recovered later by reverting the cooled or heated material back to normal conditions and use the resulting energy to generate electricity through heat engine devices (Hossain et al., 2020).

2.3 Renewable hydrogen policy in the European Union

In the context of the European Green Deal, the binding target for the EU has been set to reduce its net greenhouse gas emissions to zero by 2050 (Council of the European Union, n.d.-a). In an effort to reach his target, an intermediate climate ambition for 2030 has also been formulated. This climate ambition entails the reduction of the greenhouse gas emissions of the EU with 55% by 2030 in comparison to emissions in 1990. To align the current climate, energy and transport legislations with the ambitions as set for 2030 and 2050, the European Commission has launched the *Fit for 55* package (Council of the European Union, n.d.-a).

In the Fit for 55 package, the European Commission (2021) has formulated various goals for the production of renewable hydrogen. In terms of the production capacity, the goal is to have 40GW of renewable hydrogen electrolyzer capacity in the EU by 2030. Utilizing this capacity, the goal is to produce 10 million tonnes of hydrogen by 2030. Besides goals related to production (capacity) of renewable hydrogen, the European Commission (2021) also set goals for the usage of renewable hydrogen. By 2030, at least half of all hydrogen consumed in industry needs to be renewable. Also, at least 2,6% of the fuels used in the transport sector will need to be renewable fuels of non-biological origin (RFNBO), of which renewable hydrogen can be one.

More than one definition of renewable hydrogen exists and there is no international standard for what hydrogen can be considered green (Velazquez Abad & Dodds, 2020). In the energy industry, standards have been created to ensure energy users that the energy they use is sustainable. This works through a certification scheme in which Guarantees of Origin can be traded that represent a certain amount of energy that is generated following a set of standards. To include renewable hydrogen in government policies, a similar system is needed that guarantees the production of hydrogen according to a certain set of standards (Velazquez Abad & Dodds, 2020). Velazquez Abad & Dodds (2020) have identified a number of challenges that need to be overcome when developing such a system:

- **Greenhouse gas emissions accounting**: A suitable manner to account for the difference in greenhouse gas emissions from different production pathways and end-uses of hydrogen needs to be found. In doing this, clear boundaries need to be defined in terms of which emissions are accounted for. Also, a clear trade-off between accuracy in and costs of accounting for greenhouse gas emissions.
- **Economic viability**: The standards guaranteeing the renewable production of hydrogen need to be economically viable. Besides the capital investment for producing hydrogen in compliance with the renewable hydrogen standards, additional operational costs are also introduced as data needs to be collected and audited to ensure this compliance. If these costs are too high, new hydrogen producers could face high market barriers.
- **Emission intensity threshold**: To determine what is qualified as green or low-carbon hydrogen, an emission intensity threshold can be defined. This can be done in an absolute fashion, defining the exact allowed carbon intensity. Alternatively, a relative threshold can be set, referring to the carbon intensity of, for example, a fossil fuel. The emission intensity needs to be set in a way that prevents perverse effects. Such a perverse effect could be that instead of pursuing the cleanest hydrogen production, hydrogen producers could pursue the dirtiest hydrogen production that still qualifies as clean.
- **Qualification of feedstocks and production technologies**: When setting standards for renewable hydrogen production, a set of feedstocks and production technologies to be used for this production process can be defined. A challenge here can be to define this set in a way that is in line with technology neutrality, but ensures the production of green hydrogen according to a renewable standard.

In the EU Renewable Energy Directive (RED II) by the European Commission, a standard is defined for fuels to qualify as RFNBO. This standard consists of a set of requirements for the production of hydrogen that needs to be met for the hydrogen to qualify as RFNBO. These requirements are proposed based on several policy theories. A policy theory can be defined as the set of causal and other assumptions underlying a policy (Hoogerwerf, 1990). The general policy theory behind the proposal of the RED II requirements for the production of RFNBOs is that if they are met, the production and use of RFNBOs contribute to the reduction of greenhouse gas emissions (European Commission, 2018). These requirements are the following ones (Hocksell, 2022):

- **Renewable origin**: The electricity used for hydrogen production must be generated from a renewable energy source. The hydrogen producing party and the energy generating party need to conclude a bilateral power purchasing agreement (PPA) in order to meet this requirement.

- **Geographical correlation**: The energy used to produce the hydrogen must be generated in the same geographical area as where the hydrogen is produced, for example in the same bidding area. The policy theory behind this requirement is that it will help prevent congestion on the electricity grid (European Commission, 2018).
- **Temporal correlation**: The amount of energy used to produce hydrogen needs to match the amount of energy generated by the energy generating party with which the hydrogen producing party has concluded a PPA. For example, if the energy generating party generates 10MWh of energy during an hour, this would be the amount of energy that can be used to produce hydrogen by the hydrogen producing party during this hour. The policy theory behind this is that this requirement can be used as a means to the end of ensuring the renewable origin of the energy used for hydrogen production (European Commission, 2018). This is under the assumption that if only energy from within the PPA is consumed for renewable hydrogen production, it can be ensured that this energy is renewable. To ensure that only energy from within the PPA is consumed, the temporal correlation requirement is proposed.
- **Additionality**: The hydrogen producing party needs to add to the financing or use of renewable energy. This means that the process of hydrogen production needs to cause an increase of the use of renewable energy and not just utilize renewable energy that would otherwise be purchased by a different party. The policy theory behind this requirement is that if fulfilled, it will ensure that the production of renewable hydrogen contributes to the use of renewable energy (European Commission, 2018).

These requirements are already proposed for the production of renewable hydrogen to be used as RFNBO in the transport sector and are expected to be proposed for the production of renewable hydrogen to be used in other sectors as well (Frontier, 2021; Hocksell, 2022). This could for example happen in a new version of the EU Renewable Energy Directive (RED III) to be proposed by the European Commission. Before the EU Renewable Energy Directive can be adopted as a series of laws, it needs to be passed by the European Parliament in a series of negotiations that can lead to revisions of the EU Renewable Energy Directive (Council of the European Union, n.d.-b).

2.4 Systematic literature review

To collect relevant academic literature in a systematic manner, a search was conducted with the search term “hydrogen AND production AND wind AND electrolyzer” in the Scopus search engine. When the results had been limited to articles relating to the subject area Energy, 168 results were found. After limiting the results further to articles containing the keyword “Hydrogen Production”, 129 search results were left. These results have been scanned and the articles that did not study the production of hydrogen with wind energy powered electrolyzers as a main topic of interest have been discarded. The remaining 28 articles have been analysed to create a clear image of the body of literature surrounding the production of hydrogen with wind powered electrolyzers. To present the existing literature in an orderly manner, the articles found have been grouped by topic and will be discussed in the separate sections below. After systematically determining which topics are covered in literature already, a knowledge gap can be defined.

2.4.1 Potential of hydrogen production from wind energy

Among the literature found on the topic of hydrogen production from wind energy, several articles were found discussing the potential of specific locations for this production process. Lin et al. (2021) discuss the potential of hydrogen production from wind to stimulate decarbonization in the West Inner Mongolia area in China by simulating the performance of a wind-hydrogen system in this area. In their analysis, they also consider the economic feasibility of hydrogen production from wind in this area. According to the results of the analysis, hydrogen production with wind could be a feasible alternative for the current dominant, coal-based, hydrogen manufacturing system in the area.

Another study looking at the potential for hydrogen production in a larger area is performed by Posso & Zambrano (2014). Instead of only looking at the potential to produce hydrogen from wind energy, they also consider hydrogen production from energy generated from solar and mini-hydro energy. The results of the simulation that Posso & Zambrano (2014) performed using satellite data suggest that solar power has the biggest potential to be used for hydrogen production in Venezuela. This is the case as 95% of the potential total production is realized by using solar energy.

A study looking at the potential for hydrogen in more specific areas is that by Genç et al. (2012). They performed this study in Turkey by simulating the production of hydrogen from wind energy at five different locations throughout Turkey. From their research, the potential yield and costs for these five different locations were determined. Three of these five locations turned out to have remarkable potential for the production of hydrogen from wind. Alavi et al. (2016) performed a very similar study, but for locations in Iran. The simulation results from this study describe the potential for the different locations. Another result from this study is that there is a linear relationship between the amount of wind energy generated and hydrogen produced. This suggests that the larger the turbine, the more hydrogen can be produced with the energy generated from it.

To study the potential of hydrogen production from wind in the Córdoba province of Argentina, a simulation study was performed by Rodríguez er al. (2010). Besides looking at the potential yield and costs of hydrogen production from wind energy, they also look at the annual requirements of wind energy in order to fuel the vehicular transport within the Córdoba province with hydrogen. The results of the performed study suggest the potential for hydrogen production from wind energy is large enough to fuel automotive transportation in the studied area.

2.4.1.1 Potential of hydrogen production from wind energy for specific purposes

Similar to the study by Rodríguez et al. (2010), there is more literature considering the potential of hydrogen from wind energy for transportation. Levene et al. (2007) studied the potential of hydrogen production from wind energy to be used at transportation fuelling stations in the United States. Through analysing data on the availability, they assessed the renewable hydrogen resources, the cost of hydrogen through electrolysis and the annual energy requirements of producing hydrogen for refuelling. The results of the analysis suggest that ample renewable energy resources exist in the United States to produce clean hydrogen for transport fuelling stations, but that the challenge remains to find optimal economic and technical configurations to make this economically feasible.

Mathur et al. (2008) also explored possibilities for fuelling transport with hydrogen produced with wind energy. More specifically, they looked into the feasibility of producing hydrogen with offshore wind energy to fuel the transport sector in India. After performing a modelling study, Mathur et al. (2008) concluded that the production of hydrogen from offshore wind energy was not economically attractive at the moment of conducting the study. Another insight from their analysis was that in case of fast technological learning, the production of offshore hydrogen would become feasible well before 2020. In case of slow technological learning, they predicted that the production of offshore hydrogen would only become economically feasible at a point in time after 2020.

A different study assessing the feasibility of the usage of offshore hydrogen for transportation fuelling is that by Bonacina et al. (2022). By modelling and simulating an offshore hydrogen plant powered by wind energy, they determined its potential for fuelling ships. The simulation study outcomes show that the use of an offshore hydrogen production plant for fuelling ships would be economically feasible. They add to this that the plant as analysed would be fit for use at various locations if the technologies used in the design would be rescaled.

Like Bonacina et al. (2022), Nagasawa et al. (2019) also study the possibility to fuel a specific type of transportation with hydrogen produced with wind energy. Using various models, they explore the technical and economic potential for fuelling light-duty vehicles with hydrogen produced from wind in different locations in the United States. The results of the study show that from the wind energy in Texas in 2015, about 22% of the light-duty vehicles in Texas could be fuelled with hydrogen produced with this energy.

2.4.2 Design of hydrogen production systems

Next to that on the potential of hydrogen production from wind energy, there is also a body of literature studying the performance of various possible designs of plants that can be used for this production process. Guo & Sepanta (2021) looked at the performance of a specific setup of a wind-hydrogen plant. The analyzed plant consists of a wind turbine, an electrolyzer and a pumped-hydro-compressed air system. This pumped-hydro-compressed air system is included in the design to temporarily store excess wind energy that is not immediately used to produce hydrogen. This system was chosen over a separate pumped-hydro or compressed air system as combining them can reduce costs. The results of the simulation in this study showed that the use of storage system components in areas with higher wind speeds can improve the overall performance of systems producing hydrogen from wind energy.

Khouya (2020) explored the use of renewable energy sources to produce hydrogen at different locations throughout Morocco. Using mathematical models, they compared the performance and efficiency of wind and solar energy for the production of hydrogen. The modeling results from this study show that the energy consumption of the used electrolyzer is lower for wind energy than for solar energy and that the efficiency of hydrogen production with wind energy is higher than that with solar energy. Another result from this study is that the levelized cost of the produced hydrogen decreases when renewable energy generation capacity is increased.

Cheng et al. (2021) assessed four different low-carbon hydrogen supply routes for supplying a fueling station in Shanghai. The different pathways considered are ones for the production of hydrogen with wind and solar PV that is either done on-site or off-site and either stand-alone or grid connected. The results show that the pathway for off-site and grid-connected production of hydrogen from wind and solar energy performs best. Besides analyzing the performance of various hydrogen production pathways, Cheng et al. (2021) also proposed a design for a microgrid to be used in this production pathway. They did this by optimizing the design of this microgrid using dedicated optimization software.

Besides that by Cheng et al. (2021), more studies have been performed featuring optimization techniques to improve the design of hydrogen production systems powered by wind energy. Won et al. (2017) proposed a methodology to optimize the design of hydrogen production systems using renewable energy sources. The optimization model they present is designed to integrate multiple energy sources and production techniques in order to minimize the total annual cost of the hydrogen production system. Based on a case study in which they deployed their optimization model, they concluded that capital expenditure is a large burden for the development of new renewable energy systems.

A different study featuring design optimization of hydrogen production systems using wind energy is that by Olateju et al. (2014). By developing a techno-economic model and a simulation model of a hydrogen plant for the upgrading of bitumen from oil sands, they assessed various possible designs for this plant. The outcome of the modeling study consisted of the optimal number and size of the electrolyzers to minimize the production cost of hydrogen for this plant. Based on the hydrogen production price of the optimal design for the plant, it was concluded that hydrogen produced with wind energy was unable to compete with fossil fuel hydrogen production.

Another study optimizing the electrolyzer setup for a hydrogen plant powered with wind energy was performed by García Clúa et al. (2018). The plant that they consider in their study is assisted with energy from the grid at moments when there is an insufficient amount of wind energy available for hydrogen production. This design fails to ensure that the hydrogen production process is carbon free as the energy from the grid might not be renewable. In an effort to compensate for this, the excess amount of wind energy produced is delivered back to the grid at times when there is an excess amount of wind energy for the production of hydrogen. Optimization is used by Garcí Clúa et al. (2018) to determine the optimal electrolyzer size to be used in order to fully compensate for the yearly emissions and thereby canceling out the emissions from the used grid energy.

2.4.3 Use of specific electrolyzers

Apart from literature analyzing the performance of hydrogen plants as a whole, there is also literature discussing the performance of specific components of hydrogen plants powered by wind. Gandía et al. (2007) investigated the performance of an alkaline electrolyzer when powered by wind. They do this by operating the electrolyzer under a power supply emulating wind conditions and analyzing its behavior. Results of the study show that the studied electrolyzer performed well, with high efficiencies, substantial gas purities and a dynamic response to the varying power supply. Zhang et al. (2021) performed a very similar study by looking into the performance of a bigger alkaline electrolyzer under simulated wind power supply. The outcome of this study is in line with those of Gandía et al. (2007) and confirm that alkaline electrolyzers can perform well under varying power supply.

Gökek (2010) also investigates the performance of an electrolyzer under variable supply of wind energy, but instead of an alkaline electrolyzer they consider a PEM electrolyzer. By simulating the operation of a PEM electrolyzer, they discuss its techno-economic performance in two different power matching modes, grid-integrated and grid-independent. Results of the study indicate that the production of both wind and hydrogen highly depend on the height of the turbine(s) used. Also, when the system is grid-integrated, it can be profitable to sell the excess energy produced to the grid. Sarrias-Mena et al. (2015) performed a similar study on PEM electrolyzers powered with wind energy. Instead of analyzing the performance of one electrolyzer, they analyzed that of multiple different ones by simulating their performance under varying energy supply. Their results show that for all the considered electrolyzers, the models representing them were able to operate in coordination with the wind turbine models they were coupled to.

Instead of looking only at alkaline or PEM electrolyzers, Schnuelle et al. (2020) compare the two types in a study. They perform this comparison by simulating the performance of the different types and analyze their relative performance. In their study, Schnuelle et al. (2020) conclude that while PEM electrolyzers have higher electricity rates than alkaline electrolyzers, alkaline electrolyzers can achieve higher production rates.

Pino et al. (2011) discuss the validity of the assumptions made when modelling the production of hydrogen with a wind energy powered electrolyzers. They do this by validating a model incorporating more accurate parameters and comparing the outcomes. The results of this study put the other studies in this section in context as they indicate that models using the common consumptions can overestimate the hydrogen production of a plant by more than a quarter.

2.4.4 Design of control mechanisms

Besides literature studying (the performance of) specific components of a wind-hydrogen plant, there is also a body of literature discussing different manners and mechanisms to control these plants. Valenciaga & Evangelista (2010) developed and evaluated a control scheme for an autonomous hydrogen production system powered by wind. This control scheme consists of two levels: one determining the general operation mode of whole system and one consisting of the individual controllers regulating specific components of the system. Simulation results show that the designed control scheme was able to keep the system in the desired state under influence of external permutations and parameter variations. Fang & Liang (2019) performed a similar study by designing and evaluating a hydrogen production system incorporating a control strategy to mitigate the effects of fluctuating wind power on the production of hydrogen. Results of this simulation study suggest that the use of the designed control strategy can increase the production of hydrogen with over 40% when compared to other control strategies.

García Clúa et al. (2010) studied a grid-assisted wind-hydrogen plant and evaluated a control strategy for this plant. The goal of the evaluated control strategy is to keep the current of the electrolyzer at its rated value under varying wind power and temperature and therewith optimize the efficiency of the hydrogen production. After performing simulations to determine the performance of the control strategy at hand, it turned out that it provides stability and robustness against wind and temperature fluctuations. In a later study, García Clúa et al. (2011) discuss various other control strategies for grid-assisted hydrogen production strategies powered by wind. Each of the control strategies evaluated in this study belongs to a different operation mode of the system, all with their own optimization goals: optimum wind capture, maximum hydrogen production rate or maximum clean hydrogen production.

Valdés et al. (2013) proposed two specific control strategies for a hydrogen production system powered by wind. The idea behind both strategies is to adjust the power consumption of the electrolyzer according to the expected amount of available wind energy available. Based on calculations, Valdés et al. (2013) conclude that this incorporating this idea in control strategies can lead to substantial improvements in performance when compared to a control strategy in which electrolyzer consumption is constant. Another specific type of control strategy for hydrogen production systems is proposed and discussed by Cano et al. (2015). The control strategy proposed here is designed for an off-grid hydrogen production system powered by renewable energy sources and incorporates a prediction of the available amount of renewable energy available for the system as well as one of the load consumption of the production system. After validating and performing experiments with the proposed control strategy, Cano et al. (2015) concluded that it performed better than other optimization approaches discussed in literature. A similar control strategy is proposed by Serna et al. (2017). The control strategy proposed by them is designed for offshore hydrogen production and takes predictions of the available power and the load consumption into account. Based on two case studies using simulation they conclude that the proposed strategy causes the system to operate adequately.

2.5 Knowledge gap and research question

The literature review above shows that the body of knowledge surrounding wind-hydrogen plants focusses on various aspects of this topics. Studies have been performed focussing on the potential of hydrogen production from wind in specific areas. The results show that there is potential for hydrogen production in very diverse locations throughout the world. Other studies focus on the potential of hydrogen from wind energy for specific purposes. These studies indicate that hydrogen has potential to be used as fuel for various modes of transportation. Studies looking into different design configurations for wind-hydrogen plants reveal that these configurations can have large implications for the performance of such a plant. Other studies show us that this is also the case for the implementation of specific types of components and control strategies.

While there is an existing body of literature looking into specific design configurations and the use of specific wind-hydrogen plant components, only one article has been found discussing the implementations of incorporating an energy storage system in a wind-hydrogen plant. This article by Guo & Sepanta (2021) analyses the performance of a wind-hydrogen plant including a compressed air system to store wind energy. What still lacks in the current body of literature is research analyzing and comparing the performance of wind-hydrogen plants incorporating different types of energy storage systems. In other words, when observing wind-hydrogen plants as systems consisting of wind-turbines and an electrolyzer, there is a vast body of literature studying the main components and their interaction. What is still unclear is how the introduction of different energy storage systems in wind-hydrogen plants influences the interaction between their components and ultimately the performance of the system as a whole. To address this knowledge gap, the following research question has been formulated:

“How does the integration of energy storage systems influence the performance of wind-hydrogen plants?”

Besides gaining insight in the interaction between an energy storage system and a wind-hydrogen plant, the answers to the formulated research question can be put to a broader use. As the EU Renewable Energy Directive is still in development, the effects of the temporal correlation requirement on renewable hydrogen production can be evaluated. After all, this requirement would introduce the need for energy storage systems in wind-hydrogen plants in the first place.

3. Methods

The methods chapter describes the methodology applied to explore the performance of wind-hydrogen plants with energy storage systems. In section 3.1, the general modelling strategy is elaborated on. Sections 3.2 and 3.3 define the boundaries of the system to be modelled and what output should be generated to evaluate the performance of different wind-hydrogen plants. In section 3.4, a conceptual model is composed. Section 3.5 elaborates on the model development process, the result of which is then described in section 3.6. Section 3.7 describes how the model is implemented so that experiments can be performed with it. The input values used for these experiments are described in section 3.8 and the main assumptions made when constructing the model are reflected upon in section 3.9.

3.1 Mathematical modelling

To determine the effect that different energy storage systems have on the performance of wind-hydrogen plants, data on the performance of these plants incorporating different types of energy storage systems would have to be gathered and compared. As this data cannot be gathered in the field and is not available in literature, a modelling approach is chosen. A modelling approach aims to replicate rules that describe the interaction between different elements within a system (Herbst et al., 2012). From a systems perspective, a wind-hydrogen plant with an energy storage system can be seen as a system consisting of wind turbines, an electrolyzer and an energy storage system. Following a modelling approach, a set of rules can be formulated that represents how these components interact with each and influence the performance of the system. As demonstrated in the research of Guo & Sepanta (2021), Khouya (2020), Cheng et al. (2021), Olateju et al. (2014) and García Clúa et al. (2018), a such modelling approach can be suitable for analyzing the performance of hydrogen production plants.

When using a modelling approach to determine the effects of different energy storage systems on hydrogen production, a numerical model will be constructed that represents the interaction between the different components of a wind-hydrogen plant with an energy storage system. Numerical models consist of a model and a numerical method (Sirois & Grilli, 2015). This model contains a mathematical representation of physical behavior based on hypothesis and assumptions. Within this research, this model will be a mathematical representation of how energy storage systems influence the performance of wind-hydrogen plants and will consist of a number of equations. By determining the solution of the system of equations for the various constructed models, the performance of wind-hydrogen plants incorporating different energy storage systems can be quantified.

The insights gained as a result of mathematical modelling largely depend on how the mathematical model is used. Perhaps the most straightforward use is to gain insight how a specific setup of a system would perform if it were to exist in the real world. An example of this use is that by Guo & Sepanta (2021). After constructing a mathematical model representing a wind-hydrogen plant with a pumped-hydro-compressed air system, they use it to gain insight how a specific design of such a plant would perform if it were to be build.

Two other ways in which mathematical models can be used are exploratory modelling and optimization modelling. Exploratory modelling is the use of a model to perform a number of experiments representing different assumptions being true and investigating how these assumptions affect the model outcomes (Bankes, 1993). The goal of exploratory modelling is to explore the behavior of the system that the model represents under different conditions. This method is favorable when critical information about the system of study is unavailable (Bankes, 1993). An example of the use of exploratory modelling to study the behavior of wind-hydrogen plants is that by Khouya (2020). After defining mathematical models representing a wind-hydrogen plant and a solar-hydrogen plant, Khouya (2020) performed a number of experiments to see how different hydrogen plants would perform at different locations in Morocco. The results of this study allow for more generalizable claims about the behavior of hydrogen plants than the results of the study by Guo & Sepanta (2021) as more configurations of hydrogen plants have been considered at various locations.

Optimization modelling also involves performing a set of experiments using a model, however, the goal is different. The goal of optimization modelling is to find the circumstances for a model that yield the optimal outcome (Singh, 2012). These circumstances are represented by a set of model input parameters. The optimal outcome is often defined by an output variable of the model and a desired direction, for example, minimal cost. The model circumstances that yield this outcome are found by systematically changing the model input parameters, often within certain boundaries, until the optimum is found. Studies using optimization modelling in the context of wind-hydrogen plant are those by Cheng et al. (2021), Olateju et al. (2014) and García Clúa et al. (2018). After constructing a mathematical model of a wind-hydrogen plant, they use it to optimize the design for such a plant. For example, Olateju et al. (2014) use it to determine the optimal size and number of electrolyzers to be used in a wind-hydrogen plant producing hydrogen for the upgrading of bitumen from oil sands in Canada. While these results can be very relevant for the development of such a wind-hydrogen plant, might not be generalizable. After all, the optimal number and size of electrolyzers may vary per purpose, location and other design variables of a wind-hydrogen plant.

To gain insight in how the performance of wind-hydrogen plants is influenced by the introduction of energy storage systems, exploratory modelling will be used. This method is fitting as the goal is not to determine what the optimal wind-hydrogen plant with energy storage system would look like, but to see how its behavior would be influenced by the introduction of an energy storage system. Exploratory modelling allows to perform experiments for a large range of possible wind-hydrogen plant configurations with different energy storage systems. This is relevant as there is uncertainty around exact design and configuration of wind-hydrogen plants with energy storage systems if these were to be build. The analysis of the outcomes of these experiments allows for generalizable conclusions about the behavior of wind-hydrogen plants with energy storage systems as a lot of different designs and configurations are considered. To evaluate the effects of the temporal correlation requirement on the performance of wind-hydrogen plants, it is important that outcomes of the analysis are representative for many different designs of these plants. This is the case as the temporal correlation requirement applies to all different designs of wind-hydrogen plants. When performing a case study on a specific set of wind-hydrogen plants with energy storage system, optimization might result in more realistic results to evaluate their performance. This is under the assumption that when constructed in the real world, commercial wind-hydrogen plants with energy storage systems would be designed to maximize profitability to some degree.

Once the effects of the introduction of energy storage systems on the performance of wind-hydrogen plants have become clear, they can be used to analyze the renewable hydrogen policies of the European Commission in the context of their renewable hydrogen production goals. The outcome of this policy analysis will show whether the temporal correlation requirement for the production of RFNBOs as defined in RED II is adequate to stimulate the achievement of the renewable hydrogen production goals as specified in the Fit for 55 package.

3.2 System boundaries

As a starting point for a model to evaluate the performance of wind-hydrogen plants incorporating different energy storage systems, the system boundaries are defined. These boundaries dictate what elements of the production chain of renewable hydrogen the model needs to represent. As mentioned in section 2.1, the electrolyzer of a wind-hydrogen plant and the wind park that provides it with electricity are considered the main components of a wind-hydrogen plant. As the aim of this study is to determine how energy storage systems influence the performance of wind-hydrogen plants, these will also be considered as a main component of a wind-hydrogen plant. Similar to the study by Guo & Sepanta (2021), these main components are the ones that will be represented the mathematical model.

Besides an electrolyzer and a wind park, the constructed model needs to represent several energy storage systems. Not all energy storage systems as described in section 2.2 are fit to be integrated in a wind-hydrogen plant and these will thus not all be included in the model. Wind-hydrogen plants rely solely on wind energy and thus require an energy storage system that is fit to regulate the flow of wind energy to an electrolyzer in a manner that allows for a stable output of hydrogen throughout the year. The availability of wind can vary greatly between the seasons of a year (Graabak & Korpås, 2016). Therefore, in order to ensure a constant output of hydrogen throughout the year, energy needs to be stored seasonally. To store energy over the seasons, an energy storage system needs to be capable of storing a large amount of energy and have a low self-discharge rate (Beaudin et al., 2010; Díaz-González at al., 2012; Lund et al., 2015).

Lund et al. (2015) and Díaz-González et al. (2012) consider CAESS, PHSS and HESS as (most) suitable methods to store energy throughout the seasons. Beaudin et al. (2010) adds to this that flow-battery energy storage systems (FBESS) can also be considered for seasonal energy storage. TESS is not considered by the reviews specifying energy storage systems suitable for seasonal energy storage. Al Shaqsi et al. (2020) note that “TESS has limited storing capacity for storing energy” (p.297). Therefore, CAESS, PHSS, HESS and FBESS are considered as energy storage systems suitable to be integrated in a wind-hydrogen plant. As a benchmark, the performance of an integrated lithium-ion battery (LIBESS) as energy storage system for a wind-hydrogen plant will also be investigated. As an alternative for using energy storage systems, the option of increasing the wind energy capacity will also be considered as a solution for ensuring a constant output of hydrogen. This higher capacity could be used to increase the amount of wind energy in case of lower wind speed, making more constant hydrogen production throughout the year possible.

3.3 Model output

Before the performance of wind-hydrogen plants with different energy storage systems can be compared, it needs to be quantified. For this quantification, an appropriate set of performance metrics needs to be compiled. First, an overview is created of metrics used in literature evaluating the performance of hydrogen plants using wind energy, as discussed in section 2.4.2. From this overview, a set of metrics is chosen that allows for the evaluation of performance of wind-hydrogen plants in the context of the hydrogen goals of the European Commission as discussed in section 2.3. The complete overview of considered performance metrics can be found in Appendix A: Overview of performance metrics.

From the metrics considered, the *hydrogen output rate* can be used to evaluate the performance of a wind-hydrogen plant in the context of the goal to produce 10 million tonnes of hydrogen by 2030. As this metric represents the amount of hydrogen that can be produced in a certain amount of time, a high value would be beneficial for reaching the renewable hydrogen production goals of the European Commission. Also, since energy storage systems are introduced in wind-hydrogen plants to make their hydrogen output more constant, the standard deviation of this metric can be used to evaluate whether the performance of a wind-hydrogen plant has been influenced in the desired manner by an energy storage system.

A different metric that can be used to evaluate the performance of a wind-hydrogen plant in the context of the hydrogen production goals of the European Commission is the *efficiency*. This metric represents the amount of energy that the wind-hydrogen plant needs to produce a unit of hydrogen as compared to the amount of energy this hydrogen contains. A high *efficiency* would mean that a high amount of hydrogen could be produced from a unit of energy, which is beneficial for reaching the renewable hydrogen production goals of the European Commission. Additionally, the use of this metric can generate specific insights in the influence of an energy storage system on the performance of a wind-hydrogen plant. For example, a low round-trip efficiency of an energy storage system means a lot of energy going into the wind-hydrogen plant is lost and cannot be used for hydrogen production, which will result in a decrease of the efficiency of a plant.

To evaluate the performance of a wind-hydrogen plant in the context of the goals that the European Commission has set for the usage of renewable hydrogen, the *levelized cost of hydrogen* (LCOH) metric can be used. This metric represents the total costs of producing a certain amount of hydrogen. A low value for this metric means that hydrogen can be produced at a low cost. This would make it more attractive compared to alternative fuels and thus beneficial for the renewable hydrogen usage goals of the European Commission.

3.4 Conceptual model

To visually depict the system to be modelled and the relationships between its main components, conceptual models are created. Figure 2 depicts a wind-hydrogen plant without any type of energy storage system integrated. As can be observed, the wind turbines generate electricity to power the electrolyzer of the plant. This electrolyzer then uses this electricity to produce hydrogen. This output of hydrogen can be very variable as the electricity input of the electrolyzer is directly dependent on the windspeed around the wind turbines. To decrease the variability of the hydrogen output of this system, the capacity of the wind turbines can be increased as this raises the amount of electricity generated given a certain windspeed. The excess amount of energy that is generated by the wind turbines, but not used by the wind-hydrogen plant is sold to the grid.

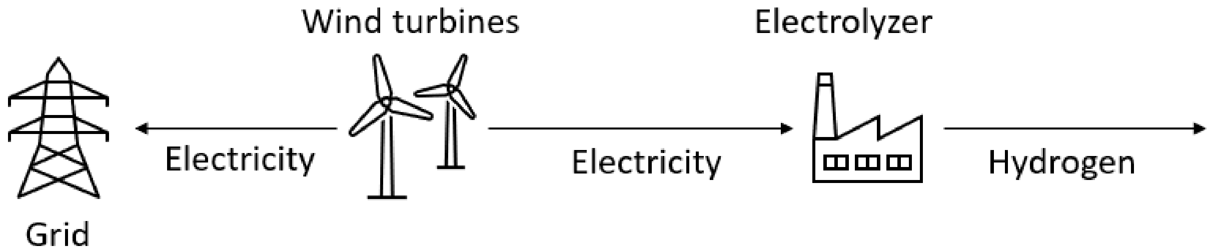

Figure 2: Conceptual model of wind-hydrogen plant

Figure 3 depicts a wind-hydrogen plant in which an energy storage system is integrated. Energy storage systems that are represented here are CAESS, PHSS, FBESS or LIBESS. As shown, the electricity generated by the wind turbines can flow to both the electrolyzer and the energy storage system. The ratio between these electricity flows depends on the amount of electricity being generated by the wind turbines. During a wind peak, when a relatively high amount of electricity is generated, part of this electricity is stored in the energy storage system. When a relatively low amount of electricity is generated by the wind turbines, this amount is supplemented by electricity from the energy storage system. Again, the energy that is not used by the wind-hydrogen plant will be sold to the grid.

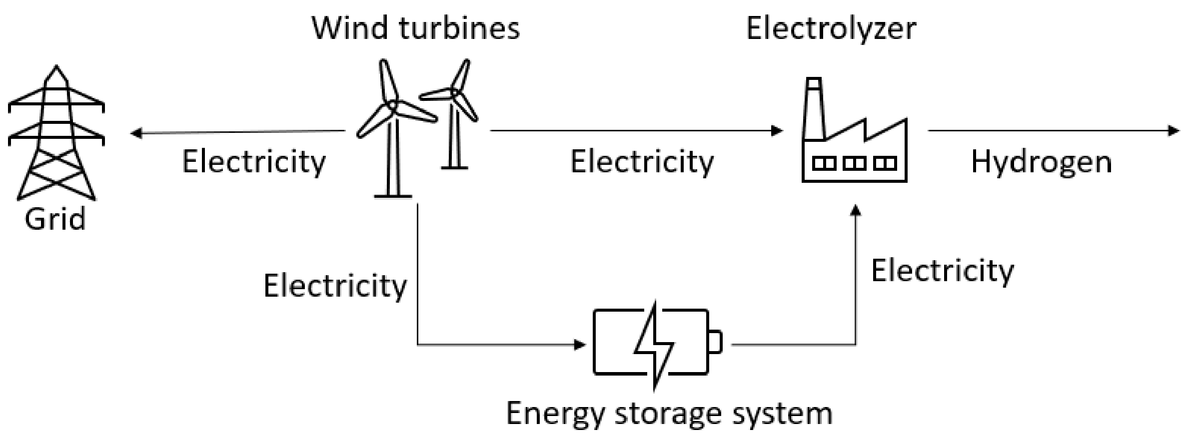

Figure 3: Conceptual model of wind-hydrogen plant with CAESS, PHSS, FBESS or LIBESS integrated

When HESS is integrated in a wind-hydrogen plant, the structure of the system corresponds to that depicted in Figure 4. Instead of excess electricity flowing directly from the wind turbines to the energy storage system, it is used by the electrolyzer to generate hydrogen, which is then stored in a tank. In an event of a deficit of electricity to produce the desired amount of hydrogen, this amount is supplemented with hydrogen from the energy storage system in place. As in the other conceptual models, excess energy generated is sold to the grid.

While a hydrogen energy storage system is an energy storage system, a distinction will be made between hydrogen energy storage systems and other types of energy storage systems (CAESS, PHSS, FBESS or LIBESS) in the remainder of this report. The reason for this distinction is the structural difference between wind-hydrogen plant with integrated HESS or integrated CAESS, PHSS, FBESS or LIBESS.

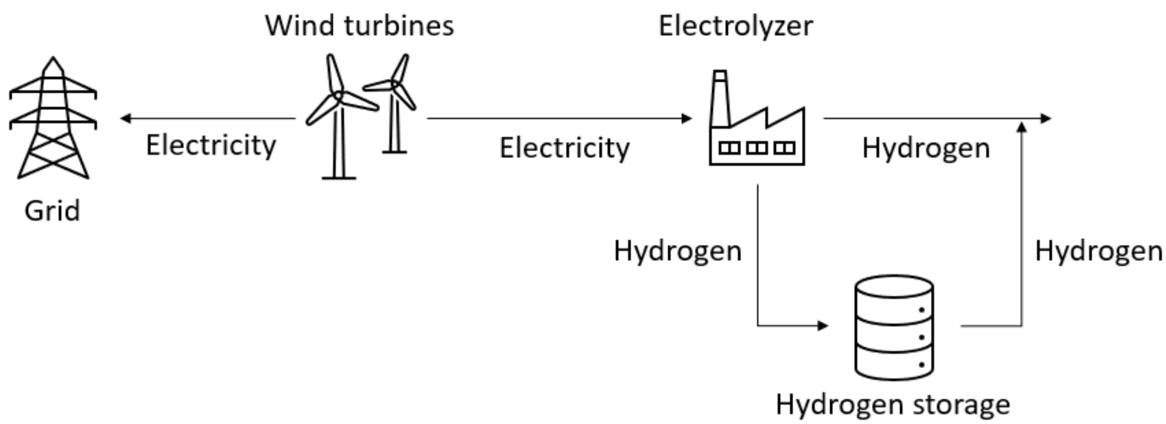

Figure 4: Conceptual model of wind-hydrogen plant with HESS integrated

3.5 Model development process

The study in this report has been executed accompanied with an internship at a commercial hydrogen production company. This internship mainly consisted of performing analyses to be used for the development of a wind-hydrogen plant. This wind-hydrogen plant was being developed to produce hydrogen in accordance with the requirements for the production of RFNBOs in RED II and its preliminary design did include an energy storage system. To ensure the useability of the outcomes of this study and the model used in this study for the development of renewable hydrogen plants, some of the insights gained during the internship were used as input for the development of the operational model as described in section 3.6. Some of these insights and their influence on the operational model are described below.

In the early stages of the development process of a wind-hydrogen plant, a lot of possible designs and configurations can be considered. Therefore, for the outcomes of this study to be useful, they need to be generalizable to a large number of designs and configurations. To accommodate for this, the model to be developed needs defined so that it is robust and can be used to perform experiments for a wide range of differently sized wind-hydrogen plants with different components.

The levelized cost of hydrogen is an important metric when it comes to comparing different designs and configurations of wind-hydrogen plants. After all, it influences the price of the hydrogen produced and the profitability of the plant. This is in accordance with the reasoning to use the levelized cost of hydrogen as a performance metric for wind-hydrogen plants, as discussed in section 3.3. As the levelized cost of hydrogen is such a relevant metric and is one of the performance metrics considered, it will be included in the model to be developed.

Wind-hydrogen plants can be developed in cooperation with the party that will ultimately buy and use the hydrogen that the wind-hydrogen plant will produce. When this is the case, the wind-hydrogen plant to be developed can be tailored to the needs of the prospected end-user of the hydrogen it produces. One of these needs can be a certain amount of hydrogen each hour or day. To gain insight in the ability of a wind-hydrogen plant design to produce a certain amount of hydrogen each hour, the possibility of setting some sort of production goal will be incorporated in the model to be developed. Additionally, the prospected user of the hydrogen can have requirements in terms of how stable the supply of hydrogen needs to be. To assess the stability of the output of hydrogen from different wind-hydrogen plant designs, this a metric for this will be included in the model and discussed as outcome of the study. This metric can also be used to compare the performance of energy storage systems, as mentioned in section 3.3.

3.6 Operational model

An operational model is constructed to express how the various parts of the system of study influence each other and the relevant system outcomes. In the sections below, a set of equations is given that represents these relationships and can be used to quantify the various performance metrics as defined in section 3.3. An overview of all the variables in the constructed model can be found in Appendix B: Overview of model variables.

3.6.1 Hydrogen output rate

1. $\mu_{H_2,t} = \mu_{H_2prod,t} - \mu_{H_2SS\ in,t} + \mu_{H_2SS\ out,t}$

Equation 1 can be used to calculate the hydrogen output rate at which hydrogen is delivered from the wind-hydrogen plant of study during a certain timestep. In this equation, $\mu_{H_2prod,t}$ is the *hydrogen production rate* during a timestep, $\mu_{H_2SS\ in,t}$ is the *hydrogen energy storage system inflow* and $\mu_{H_2SS\ out,t}$ is *hydrogen energy storage system outflow*. As can be derived from this equation, all the hydrogen that is produced during a timestep goes either to the hydrogen storage or is delivered as output. This is coherent with the conceptual model as shown in Figure 4.

2. $\mu_{H_2prod,t} = \frac{E_{elec,t} \times \eta_{elec}}{E_{H_2}}$

Equation 2 represents the hydrogen production rate at a certain timestep by the electrolyzer in the wind-hydrogen plant of study. The size of this production depends on $E_{elec,t}$, the *energy consumption* of the electrolyzer, and η_{elec}, the *efficiency* of the electrolyzer. E_{H_2} is the *higher heating value of hydrogen*. This represents the amount of energy that it would take an electrolyzer with 100% efficiency to produce a kilogram of hydrogen. The higher the efficiency of the electrolyzer, the lower the energy consumption is to produce one unit of hydrogen (Christensen, 2020).

The efficiency of an electrolyzer can be modelled on an element-level where their efficiency is dependent on their temperature. While this approach can increase the accuracy with which the efficiency is calculated, it limits the ability for these models to be generalized as they are based on empirical equations (Olateju et al., 2016). Like the equation used by Olateju et al. (2016), *Equation 2* assumes the efficiency of the electrolyzer to be constant. This allows it to be used to evaluate the performance of a large variety of differently sized electrolyzers.

Electrolyzer modelling

3. $$E_{elec,t} = \begin{cases} if\ E_{wind,t} + E_{ss\ out,t} - E_{ss\ in,t} > E_{elec,min}: \\ MIN\left(E_{wind,t} + E_{ss\ out,t} - E_{ss\ in,t}, E_{elec\ max,t}\right) \\ else: \\ 0 \end{cases}$$

The *energy consumption* of an electrolyzer can be calculated with *Equation 3.* In this equation, $E_{wind,t}$ is the amount of *wind energy* available, $E_{ss\ out,t}$ is the *energy storage system discharge* from the energy storage system to the electrolyzer, $E_{ss\ in,t}$ is the e*nergy storage system charge* from the wind turbines into the energy storage system, $E_{elec,min}$ is the minimum energy consumption of the electrolyzer and $E_{elec\ max,t}$ is the *maximum power consumption of the electrolyzer*.

As can be observed, *Equation 3* contains a conditional statement. $E_{wind,t} + E_{ss\ out,t} - E_{ss\ in,t}$ is the effective amount of energy that is available for the electrolyzer during a timestep. If this amount of available energy is larger than $E_{elec,min}$, energy flows to the electrolyzer. This amount of energy is limited by $E_{elec\ max,t}$. If the amount of energy available is not more than $E_{elec,min}$, no energy flows to the electrolyzer.

4. $E_{elec,goal} = \frac{\mu_{H_2,goal} \times E_{H_2}}{\eta_{elec}}$

$E_{elec,goal}$ is the *energy consumption goal of the electrolyzer* to reach the *hydrogen output goal* ($\mu_{H_2,goal}$). This value is calculated by dividing the product of $\mu_{H_2,goal}$ and E_{H_2} by η_{elec}. *Equation 4* can be derived from *Equation 2*.

5. $E_{elec,min} = E_{elec,cap} \times R_{elec,min}$

Equation 5 determines the *minimum energy consumption* an electrolyzer needs to consume to function. $E_{elec,cap}$ represents the *maximum rated power consumption* of the electrolyzer and $R_{elec,min}$ is the *minimum energy consumption rate* of electrolyzer. The *minimum energy consumption* required is included in the operational model to differentiate between different types of electrolyzers. PEM electrolyzers, are more flexible, allowing them to operate at a lower percentage of their rated capacity (Schnuelle et al., 2020).

6. $E_{elec\ max,t} = MIN(E_{elec,cap}, E_{elec,goal} + MIN(M_{H_2SS,max} - M_{H_sss,t}, \mu_{H_2SS,trans}) \times (\frac{E_{H_2}}{\eta_{elec}}))$

$E_{elec\ max,t}$ is the *maximum power consumption* of the electrolyzer and is characterized by *Equation 6*. In this equation, $M_{H_2SS,max}$ is *hydrogen energy storage system capacity* in place, $M_{H_sss,t}$ is the amount *hydrogen in the hydrogen energy storage system* and $\mu_{H_2SS,trans}$ is the *hydrogen energy storage system transport capacity*. $E_{elec\ max,t}$ is defined by either one of two values: $E_{elec,cap}$ or $E_{elec,goal} + MIN(M_{H_2SS,max} - M_{H_sss,t}, \mu_{H_2SS,trans}) \times (\frac{E_{H_2}}{\eta_{elec}}))$. This second value represents the amount of energy required to produce $\mu_{H_2,goal}$ and let the maximum amount of hydrogen flow to the hydrogen storage system during that timestep. This restriction is put in place so that not more hydrogen can be produced during a timestep than stored or delivered. This is coherent with the conceptual model as shown in Figure 4.

Wind energy modelling

7. $E_{wind,t} = E_{wind,max} \times E_{wind\ uti,t}$

Equation 7 represents the amount of wind energy available for the wind-hydrogen plant of study. $E_{wind,max}$ is the *maximum wind energy output* of the wind turbines connected to the wind-hydrogen plant. $E_{wind\ uti,t}$ is the *wind energy capacity utilization*.

PHSS/CAESS/FBESS/LIBESS modelling

8. $E_{ss,t} = E_{ss,t-1} + E_{ss\ in,t-1} \times \eta_{ss} - E_{ss\ out,t-1}$

Equation 8 can be used to calculate the amount of energy in the energy storage system during a certain timestep. As can be seen, this amount can be determined by $E_{ss,t}$ during the previous timestep, plus $E_{ss\ in,t}$ during the previous timestep minus $E_{ss\ out,t}$ during the previous timestep. η_{ss} is the *round-trip efficiency of the energy storage system* in place. This round-trip efficiency is a measure that can be used to express the relative performance of energy storage systems with varying structures (Hameer & van Niekerk, 2016). The amount of energy being transferred from the energy storage system is scaled with the round-trip efficiency to represent the varying performance of different types of energy storage systems.

9. $$E_{ss\ out,t} = \begin{cases} if\ E_{wind,t} < E_{elec,goal}\ and\ E_{wind,t} + MIN(E_{ss,t}, E_{ss,charge}) > E_{elec,min}: \\ MIN(E_{elec,goal} - E_{wind,t}, E_{ss,t}, E_{ss,charge}) \\ else: \\ 0 \end{cases}$$

Equation 9 represents the outflow from the energy storage system during a certain timestep. In this equation, $E_{ss,charge}$ represents the maximum *energy storage system (dis)charge capacity*.

Equation 9 contains a conditional statement with two conditions. The first condition, $E_{wind,t} < E_{elec,goal}$, requires that less wind energy is available than required to produce the desired amount of hydrogen during a timestep. The second condition, $E_{wind,t} + MIN(E_{ss,t}, E_{ss,charge}) > E_{elec,min}$, requires that this amount of wind energy can be supplemented by the energy storage system to meet the minimum energy requirement of the electrolyzer. If both these conditions are met, energy is transferred from the energy storage system to the electrolyzer. The amount of energy being transferred from the energy storage system to the electrolyzer is $E_{elec,goal} - E_{wind,t}$. The rationale behind this is that the energy storage system will always try to supplement $E_{wind,t}$ to the degree where $E_{elec,t}$ reaches the value of $E_{elec,goal}$. In doing this, it is limited by $E_{ss,t}$ and $E_{ss,charge}$.

10. $$E_{ss\ in,t} = \begin{cases} if\ E_{wind,t} > E_{elec,goal}: \\ MIN(E_{wind,t} - E_{elec,goal}, E_{ss,max} - E_{ss,t}, E_{ss,charge}) \\ else: \\ 0 \end{cases}$$

Equation 10 characterizes the amount of energy being transferred to the energy storage system during a certain timestep.

According to the equation above, energy is transferred into the energy storage system when $E_{wind,t} > E_{elec,goal}$. The rationale behind this is that there is more wind energy available than needed to produce $\mu_{H_2,goal}$. This surplus is defined by $E_{wind,t} - E_{elec,goal}$ and is limited by $E_{ss,max} - E_{ss,t}$ and $E_{ss,charge}$.

HESS modelling

11. $$M_{H_s ss,t} = M_{H_s ss,t-1} + \mu_{H_2 SS\ in,t-1} \times \eta_{H_2 ss} - \mu_{H_2 SS\ out,t-1}$$

Equation 11 represents the amount of hydrogen in *the hydrogen energy storage system*. Like *Equation 8*, it is calculated by the stock and flow of hydrogen during the previous timestep. $\eta_{H_2 ss}$, the *efficiency of the hydrogen energy storage system*, is introduced here with the same reasoning as to why a similar variable is introduced in *Equation 8.*

12. $$\mu_{H_2SS\ out,t} = \begin{cases} if\ \mu_{H_2prod,t} < \mu_{H_2,goal}: \\ MIN(\mu_{H_2,goal} - \mu_{H_2prod,t}, M_{H_sss,t}, \mu_{H_2SS,trans}) \\ else: \\ 0 \end{cases}$$

Equation 12 can be used to calculate the amount of hydrogen flowing out of the hydrogen storage system during a timestep.

Hydrogen flows out of the hydrogen storage system when $\mu_{H_2prod,t} < \mu_{H_2,goal}$ as less hydrogen is produced than the *hydrogen output goal* in this case. The amount of hydrogen that flows out of the hydrogen storage system is defined by $\mu_{H_2,goal} - \mu_{H_2prod,t}$. The reasoning behind this is that the hydrogen storage system is designed to supplement $\mu_{H_2prod,t}$ with enough hydrogen so that $\mu_{H_2,t}$ reaches $\mu_{H_2,goal}$. In doing this, the hydrogen storage system is limited by the amount of *hydrogen in the hydrogen energy storage system* ($M_{H_sss,t}$) and the *hydrogen energy storage system transport capacity* ($\mu_{H_2SS,trans}$).

13. $$\mu_{H_2SS\ in,t} = \begin{cases} if\ \mu_{H_2prod,t} > \mu_{H_2,goal}: \\ MIN(\mu_{H_2prod,t} - \mu_{H_2,goal}, M_{H_2SS,max} - M_{H_2SS,t}, \mu_{H_2SS,trans}) \\ else: \\ 0 \end{cases}$$

Equation 13 determines the *hydrogen energy storage system inflow*. In this equation, η_{H_2ss} is the *round-trip efficiency of the hydrogen storage system*.

Hydrogen flows into the hydrogen storage system from the electrolyzer when $\mu_{H_2prod,t} > \mu_{H_2,goal}$. When this condition is met it means that more hydrogen is being produced than the *hydrogen output goal*. The amount of hydrogen flowing into the hydrogen storage system is defined by $\mu_{H_2prod,t} - \mu_{H_2,goal}$ as this is the surplus of hydrogen produced. This amount is limited by $M_{H_2SS,max} - M_{H_2SS,t}$ (the available storage capacity) and $\mu_{H_2SS,trans}$.

3.6.2 Plant efficiency

14. $$\eta_{plant,T_p} = \frac{E_{H_2}}{\frac{\sum_{t=0}^{T_p} E_{elec,t} + E_{ss\ in,t} - E_{ss\ out,t}}{\sum_{t=0}^{T_p} \mu_{H_2,t}}}$$

Equation 14 determines the efficiency of the wind-hydrogen over the project lifetime. As mentioned in section 3.3, this metric represents the amount of energy consumed by the wind hydrogen plant for the production of a unit of hydrogen. In the equation above, T_p is the wind-hydrogen *plant lifetime*.

As can be derived from the conceptual models in section 3.3, $\sum_{t=0}^{T_p} E_{elec,t} + E_{ss\ in,t} - E_{ss\ out,t}$ defines all the energy entering the wind-hydrogen plant during its lifetime. The amount of energy the wind-hydrogen plant requires to produce a unit of hydrogen is calculated by dividing the total amount of energy going into the system by the total amount of hydrogen produced ($\sum_{t=0}^{T_p} \mu_{H_2,t}$). The efficiency of the plant is then calculated by dividing the amount of energy it requires to produce a kilogram of hydrogen by the higher heating value of hydrogen.

3.6.3 Levelized cost of hydrogen

15. $LCOH_{T_p} = \frac{I_i + \sum_{t=0}^{T_p}(I_t + O_t + E_t - S_{E\,ex,t}) \times (1+i)^{-t}}{\sum_{t=0}^{T_p} \mu_{H_2,t} \times (1+i)^{-t}}$

Equation 15 can be used to calculate the levelized costs of hydrogen over the wind-hydrogen *plant lifetime*. In this equation, I_t are the *investment costs* over a year, O_t are the *operational costs* over a year, E_t are the *energy costs* over a year, $S_{E\,ex,t}$ are the *sales of excess wind energy* over a year and i is the *discount rate*.

The equation above is based on that used by Viktorsson et al. (2017). The basic principle behind it is to divide the discounted costs of the hydrogen production project by the discounted amount of hydrogen produced.

16. $I_i = I_{MW,el} \times E_{elec,cap} + I_{MWh,ss} \times E_{ss,max} + I_{MWh/t,ss} \times E_{ss,charge} + I_{kg,H_2ss} \times M_{H_2SS,max} + I_{kg/t,H_2ss} \times \mu_{H_2SS,trans}$

Equation 16 can be used to calculate the *initial investment cost* for the wind-hydrogen plant of study. In this equation, $I_{MWh,el}$ is the *initial investment per MWh electrolyzer capacity*, $I_{MWh,ss}$ is the i*nitial investment per MWh energy storage system capacity*, $I_{MWh/t,ss}$ is *the initial investment per MWh energy (dis)charge capacity of the energy storage system*, I_{kg,H_2ss} is the *initial investment per kg hydrogen energy storage system capacity* and $I_{kg/t,H_2ss}$ is the *initial investment per kg hydrogen energy storage system transport capacity*.

In this equation, the initial investment costs for the electrolyzer are defined by $I_{MW,el} \times E_{elec,cap}$. This is because investment costs for electrolyzers are expressed in dollar per MW by IEA (2019). Initial investment costs for energy storage systems are defined by $I_{MWh,ss} \times E_{ss,max} + I_{MWh/t,ss} \times E_{ss,charge}$. This calculation is since initial investment costs for energy storage systems have components that depend on their storage capacity in MWh and on their rated capacity in MW (Rahman, 2020). Using similar reasoning, the initial investment costs for the hydrogen storage system are defined as $I_{kg,H_2ss} \times M_{H_2SS,max} + I_{kg/t,H_2ss} \times \mu_{H_2SS,trans}$.

17. $I_t = I_{el} \times I_{MW,el} \times E_{elec,cap} \times R_r + I_{ss} \times (I_{MWh,ss} \times E_{ss,max} + I_{MWh/t,ss} \times E_{ss,charge}) \times R_r + I_{H_2ss} \times (I_{kg,H_2ss} \times M_{H_2SS,max} + I_{kg/t,H_2ss} \times \mu_{H_2SS,trans}) \times R_r$

Equation 17 can be used to determine the investment costs during over a year. In this equation, I_{el}, I_{ss}, and I_{H_2ss} are binary variables that indicate whether investments are needed for the electrolyzer, energy storage system or hydrogen energy storage system. R_r is the *reinvestment rate* that indicates how much of the initial investment needs to be spend to replace a part of the wind-hydrogen plant when it has reached the end of its lifetime. Following the reasoning by Christensen (2020), these costs are assumed to be lower than the initial investment.

18. $I_{el,t} = \begin{cases} t \bmod T_{el} = 0 \text{ and } t \neq 0: \\ \quad 1 \\ \quad else: \\ \quad 0 \end{cases}$

19. $I_{ss,t} = \begin{cases} t \bmod T_{ss} = 0 \text{ and } t \neq 0: \\ \quad 1 \\ \quad else: \\ \quad 0 \end{cases}$

20. $I_{H_2ss,t} = \begin{cases} t \bmod T_{H_2ss} = 0 \text{ and } t \neq 0: \\ 1 \\ else: \\ 0 \end{cases}$

Equation 18, *Equation 19* and *Equation 20* can be used to determine whether any of the parts of the wind-hydrogen plant have reached their maximum lifetime and need replacement. T_{el}, T_{ss} and T_{H_2ss} are the *lifetimes* of the electrolyzer, energy storage system and hydrogen storage system of a wind-hydrogen plant. If the number current timestep can be divided by the lifetime of a part of the wind-hydrogen part without leaving a remainder, it means it needs replacement.

21. $O_t = O_{r,el} \times E_{elec,cap} \times I_{MW,el} + O_{MW,ss} \times E_{ss,trans} + O_{kg/t,H_2ss} \times \mu_{H_2SS,trans}$

Equation 21 defines the operational costs of the wind-hydrogen plant over a year. In this equation, $O_{r,el}$ is the *operational expenses rate of the electrolyzer*, $O_{MW,ss}$ are the *operational expenses per MWh (dis)charge capacity of the energy storage system* and $O_{kg/t,H_2ss}$ are the *operational expenses per kg transport capacity of the hydrogen energy storage system*.

Operational costs of electrolyzers are often expressed as percentage of their initial investment costs (Christensen, 2020). Following this reasoning, they are expressed as $O_{r,el} \times E_{elec,cap} \times I_{MW,el}$. Rahman et al. (2020) expresses the yearly operational costs for PHSS, CAESS, FBESS and LIBESS in dollars per kW per year, therefore the operational costs for these energy storage systems are expressed as $O_{MWh/t,ss} \times E_{ss,charge}$. Following this reasoning, the operational costs for HESS is calculated as $O_{kg/t,H_2ss} \times \mu_{H_2SS,trans}$.

22. $E_t = E_{wind,t} \times LCOE_t$

The energy costs of the wind-hydrogen plant can be calculated with *Equation 22*. In this equation, $LCOE_t$ are the levelized costs of energy during a year. To calculate the energy costs, this variable is multiplied by the amount of wind energy available during a timestep. The costs are calculated based on the available wind energy instead of the used wind energy to represent the influence of the amount of contracted wind energy on the LCOH.

23)$S_{E\,ex,t} = (E_{wind,t} - (E_{elec,t} + E_{ss\,in,t} - E_{ss\,out,t})) \times P_{E,ex}$

Equation 23 determines the income from the sales of excess wind energy. In this equation, $P_{E,ex}$ is the *price of excess wind* energy.

The amount of energy is defined in the same manner as in *Equation 14* ($E_{elec,t} + E_{ss\,in,t} - E_{ss\,out,t}$). By subtracting this amount from the amount of *wind energy* available, the excess amount of energy is calculated. To calculate the income from the sale of this energy, the amount is multiplied by the price for which it can be sold.

3.7 Model implementation

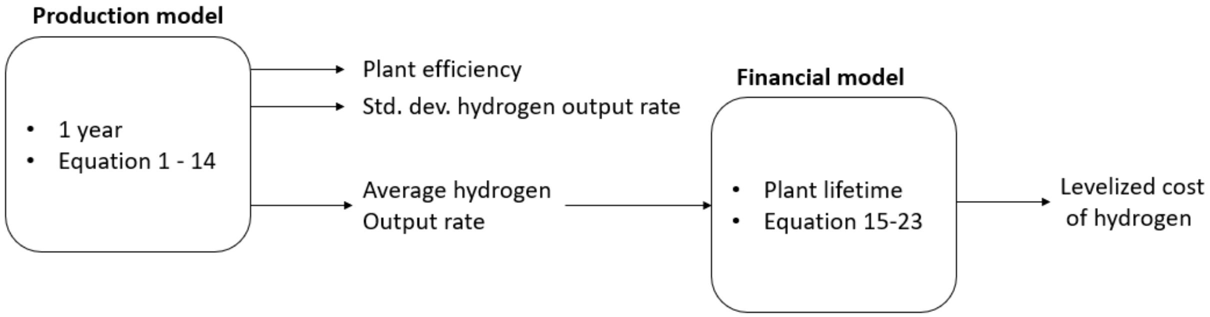

Figure 5: Conceptual model of model implementation

The operational model as described in section 3.6 is implemented as two models that run over a different amount of time. Figure 5 provides a schematic overview of the relationship between these models. The first model, the production model, generates outcomes for the *hydrogen production rate* and the *plant efficiency.* It does this by calculating the values for *Equations* 1-14 as described in section 3.6 for the timespan of a year. Based on the performance of the wind-hydrogen plant over a year, the *plant efficiency* can be calculated under the assumption that the *wind energy utilization* is the same every year over the *plant lifetime*. Also, the *hydrogen output rate* can be determined in terms of average, standard deviation and yearly value.

The yearly *hydrogen output rate* is then used as input for the second model, the financial model. This model calculated the values for equations 15-23 as described in section 3.6. Under the assumption that the *wind energy utilization* is the same every year over the *plant lifetime,* the *levelized cost of hydrogen* can be calculated for the wind-hydrogen plant of study.

3.8 Scenario definition

This section describes the values that the various input variables of the constructed model can have, defining the scenarios for which the model will be explored. Some input variables cannot be assigned a single value, but multiple different values or a range. This is due to uncertainty or the fact that the value of a variable can differ based on its context. To be able to provide a complete analysis of the system of study, experiments are performed in a full factorial manner, combining all the different values that the input variables can take on. The timesteps the values for the input variables are based are hours for the production model as this is the timeframe for temporal correlation as currently proposed by the European Commission (Hodgson, 2022). The timesteps in the financial model are years.

3.8.1 Design input variables

Table 1: Design input variables

Symbol	Name	Unit
$\mu_{H_2,goal}$	Hydrogen output goal	kg
(-)	Electrolyzer type	(-)
(-)	Energy storage system	(-)
$E_{wind,max}$	Maximum wind energy output	MWh

(-)	Wind park location	(-)
T_p	Project lifetime	year

Table 1 contains the various design input variables. Design input variables are the input variables that define the high-level design of the wind-hydrogen plant. The high-level design of the various wind-hydrogen plants that will be investigated is defined by their hydrogen output goal, type of electrolyzer, type of energy storage system, maximum wind energy output and plant lifetime. Some of the design input variables are a direct input for the model and some design input variables influence the values of other input variables of the model. For example, if the *Energy storage system* in a scenario is PHSS, other values of certain input values will be set in such a way that they represent a wind-hydrogen plant with an integrated CAESS. A detailed explanation of how these input variables are influenced can be found in sections 3.8.2 to 3.8.4. The values explored for the design input variables are listed in Table 2.

Table 2: Design input variables values

Symbol	**Name**	**Value(s)**
$\mu_{H_2,goal}$	Hydrogen output goal	1000/5000
(-)	Electrolyzer type	AEL/PEM
(-)	Energy storage system	(-)/PHSS/CAESS/FBESS/LIBESS/HESS
Maximum wind energy output	Maximum wind energy output	$2 \times \mu_{H_2,goal} \times E_{H_2}/3 \times \mu_{H_2,goal} \times E_{H_2}$
(-)	Wind park location	Onshore/offshore
T_p	Plant lifetime	15/30

Hydrogen output goal

The hydrogen output goal of a wind-hydrogen plant determines its desired hydrogen output per timestep. To reach this desired output, a wind-hydrogen plant needs to be scaled accordingly. To explore the performance of differently sized wind-hydrogen plants, different values for this input variable are considered.

Electrolyzer type

The design input variable electrolyzer type represents the kind of electrolyzer that is included a wind-hydrogen plant. Based on the electrolyzer type in a scenario, several other input variables will be adjusted that represent its characteristics. How these variables are influenced is explained in section 3.8.3.

Energy storage system

The design input variable energy storage system determines the energy storage system incorporated in a wind-hydrogen. Like the design input variable *Electrolyzer type*, values of other input variables change based on the value set for the energy storage system. The type of energy storage system considered in a scenario influences the value for several other input variables, this dynamic is explained in section 3.8.2.

Maximum wind energy output

Maximum wind energy output is the maximum amount of energy that can be generated during a certain amount of time by the wind turbines connected to the wind-hydrogen farm. This value is scaled with the amount of energy ideally required to reach the *Hydrogen output goal,* which can be calculated by $\mu_{H_2,goal} \times E_{H_2}$. As this scaling can happen according to multiple factors, multiple values are explored for the maximum wind energy output.

Wind park location

The wind park location determines whether the wind turbines feeding the wind-hydrogen plant with energy are located either onshore or offshore. Based on the wind park location in a scenario, a number of input variables is influenced. Which variables and how these variables are influenced is explained in section 3.8.4.

Plant lifetime

The plant lifetime of a wind-hydrogen plant determines how long it will be operational and therefore influences its total costs and hydrogen yield. The lifetime of a wind-hydrogen plant can differ based on its design.

3.8.2 Energy storage system input variables

As mentioned, several input variables are influenced by the value of the design input variable *Energy storage system*. This section describes what input variables are affected and how.

3.8.2.1 PHSS, CAESS, FBESS or LIBESS input variables

Table 3: PHSS, CAESS, FBESS or LIBESS input variables

Symbol	Name	Unit
$E_{ss,max}$	Energy storage system capacity	MWh
η_{ss}	Round trip efficiency energy storage system	(-)
$E_{ss,charge}$	Energy storage system (dis)charge capacity	MWh
$I_{MWh,ss}$	Initial investment per MWh energy storage capacity	$/MWh
$I_{MWh/t,ss}$	Initial investment per MWh energy (dis)charge capacity	$/MWh
$O_{MWh/t,ss}$	Operational expenses per MWh energy (dis)charge capacity	(-)
T_{ss}	Energy storage system lifetime	years

Table 3 presents the input variables that represent the performance of the energy storage system in place when the design input variable *Energy storage system* is PHSS, CAESS, FBESS or LIBESS. Appendix C contains the values that the input variables in Table 3 can have. When no energy storage system is in place or a hydrogen energy storage system is in place, all the input variables in Table 3 equal zero.

Energy storage system capacity

The energy storage system capacity determines the maximum amount of energy an energy storage system can hold. Like the *Maximum wind energy output*, the energy storage system is scaled with the amount of energy it ideally requires producing the *Hydrogen output goal.* For example, $50 \times \mu_{H_2,goal} \times E_{H_2}$ is the amount of storage capacity required for a plant with an efficiency of a 100% to produce the *Hydrogen output goal* for 50 timesteps, given that the energy storage system is fully charged.

Round trip efficiency energy storage system

The round-trip efficiency is the percentage of electric energy that can later be recovered after loading it into an energy storage system. The values of this input variable for the various energy storage systems are based on Rahman et al. (2020).

Energy storage system (dis)charge capacity

The (dis)charge capacity of an energy storage system represents the speed at which they can be charged with energy and at which they can discharge energy. For FBESS and LIBESS, this (dis)charge capacity is assumed to be inherent to the technology and design by the manufacturer. The (dis)charge speed for these technologies is calculated based on the discharge at rated capacity capabilities of the various energy storage systems as stated by Rahman et al. (2020). The discharge at rated capacity represents the amount of time (in hours) that an energy storage system can release energy at its rated capacity (in MW). To calculate the (dis)charge capacities of FBESS and LIBESS, a linear relationship between the *energy storage system capacity* and the (dis)charge capacity is assumed. Following this logic, the (dis)charge capacity of FBESS and LIBESS is determined by $\frac{E_{ss,max}}{Discharge\ at\ rated\ capacity\ (hours)}$.

The (dis)charge capacity for PHSS and CAESS is assumed to be adjusted to the design of the wind-hydrogen plant as these depend on sizeable components such as pumps and compressors. Therefore, the (dis)charge capacities of these energy storage systems will be scaled according to the amount of energy required to produce the *hydrogen output goal*.

Initial investment per MWh energy storage capacity

The initial investment per MWh energy storage capacity are the investments for the energy storage units in the energy storage system. The fact that these investments are initial means that they need to be made before the wind-hydrogen plant becomes operational. These investment costs are based on Rahman et al. (2020). For CAESS, two different initial investment costs per MWh are reported, one for an underground CAESS and one for an aboveground CAESS. The costs reported for the aboveground CAESS are used as input values.

Initial investment per MWh energy (dis)charge capacity

The initial investment per MWh energy (dis)charge capacity are the investments per MWh energy transportation capacity that need to be made before the wind-hydrogen plant becomes operational. These costs consist of costs for the power conversion system and the balance of plant costs, which are all the costs that are not included in the investment for the power conversion system or for the storage units (Rahman et al., 2020).

Operational expenses per MWh (dis)charge capacity

The operational expenses per MWh (dis)charge capacity are the yearly expenses per MW for keeping an energy storage system operational. The values of this input variable for the various energy storage systems are based on Rahman et al. (2020).

Energy storage system lifetime

The lifetime of an energy storage system is the number of years it can stay operational without being replaced. Input values for the lifetimes of the various energy storage systems are based on Da Silva Lima et al. (2021).

3.8.2.2 HESS input variables

Table 4: HESS input variables

Symbol	Name	Unit
$M_{H_sss,max}$	Hydrogen storage system capacity	kg
η_{H_2ss}	Hydrogen storage system efficiency	(-)
$\mu_{H_2ss,trans}$	Hydrogen energy storage system transport capacity	kg
I_{kg,H_2ss}	Initial investment per kg hydrogen storage capacity	\$/kg
$I_{kg/t,H_2ss}$	Initial investment per kg hydrogen transfer capacity	\$/kg
$O_{kg/t,H_2ss}$	Operational expenses per kg hydrogen transport capacity	(-)
T_{H_2ss}	Hydrogen storage system lifetime	years

Table 4 displays the input variables that represent the performance of a hydrogen energy storage system. The values that these variables can take when the design input variable *Energy storage system* is HESS are listed in Appendix C. When any other or no energy storage system is in place, all input variables as listed in Table 4 equal zero.

Hydrogen energy storage system capacity

The hydrogen energy storage system capacity is the maximum amount of hydrogen that a hydrogen energy storage system can contain. Like the *Energy storage system capacity* for PHSS, CAESS, FBESS or LIBESS, the hydrogen energy storage system capacity is scaled to the *Hydrogen output goal*.

Hydrogen storage system efficiency

The hydrogen storage system efficiency is a measure of how much energy it takes to produce, transport and store a kilogram of hydrogen compared to the amount of energy it contains. This efficiency is calculated by $\frac{E_{H_2}}{E_{H_2} + Energy\ required\ per\ kg\ hydrogen\ transported\ and\ stored\ (MWh/kg)}$. The energy requirements for transporting and storing one kilogram of hydrogen are based on Christensen (2020).

Hydrogen energy storage system transport capacity
The hydrogen energy storage system transport capacity is the amount of hydrogen that can be transported to or from the hydrogen energy storage system during a certain amount of time. This value depends on the size of the compressor and pipeline leading connected to the hydrogen storage system. The transport capacity will be scaled according to the *hydrogen output goal*.

Initial investment per kg hydrogen storage capacity
The initial investment costs per kilogram hydrogen storage capacity are the costs per kilogram hydrogen storage capacity that need to be made before the wind-hydrogen plant becomes operational. Rahman et al. (2020) describe a hydrogen storage system where electrical energy is used to produce hydrogen, which is later converted back into electrical energy using a fuel cell. The initial investment per hydrogen storage capacity is based on the storage unit cost as reported by Rahman et al. (2020). These costs are reported in dollar per kWh. To convert these costs to dollar per kWh, they are multiplied with E_{H_2} in kWh per kilogram.

Initial investment per kg hydrogen transport capacity
The initial investment per kg hydrogen transport capacity is the investment that needs to be made per kilogram of transport capacity of the hydrogen energy storage system. The input values for these costs are based on the balance of plant costs for a hydrogen energy storage system as reported by Rahman et al. (2020).

Operational expenses per kg hydrogen transport capacity
The operational expenses per kilogram hydrogen transport capacity are the yearly costs to keep the hydrogen energy storage system operational. The input value for this variable is based on the fixed yearly operational cost per kilogram hydrogen transport capacity as reported by Prenev et al. (2019).

Hydrogen storage system lifetime
The lifetime of the hydrogen storage system is the time it can stay operational before it needs to be replaced. The lifetime used as input is based on the depreciation period of a hydrogen compression and storage network as described by Prenev et al. (2019).

3.8.3 Electrolyzer input variables

Table 5: Electrolyzer input variables

Symbol	Name	Unit
$E_{elec,cap}$	Maximum rated power consumption electrolyzer	MWh
η_{elec}	Efficiency electrolyzer	(-)
$R_{elec,min}$	Minimum energy consumption rate electrolyzer	(-)
$I_{MWh,el}$	Initial investment per MWh electrolyzer capacity	$/MW

$O_{r,el}$	Operational expenses rate electrolyzer	(-)
T_{el}	Electrolyzer lifetime	(-)

Table 5 contains input variables that vary based on the electrolyzer in place, and thereby on the value of the design input variable *Electrolyzer type*. The values for these variables can be found in Appendix C: Model input.

Maximum rated power consumption electrolyzer

The maximum rated power consumption of an electrolyzer is the maximum amount of energy it can take in during a certain amount of time. Like the *Maximum wind energy output* and *Energy storage system capacity*, the value of this input variable is scaled based on the amount energy it ideally requires producing the *Hydrogen output goal,* which can be calculated by $\mu_{H_2,goal} \times E_{H_2}$.

Efficiency electrolyzer

The efficiency of an electrolyzer is the amount of energy it requires to produce a kilogram of hydrogen in comparison to the higher heating value of hydrogen (E_{H_2}). Input values for the efficiency of PEM and AEL electrolyzers have been based on IEA (2019).

Minimum energy consumption rate electrolyzer

The minimum energy consumption rate of an electrolyzer is the minimum percentage of its *Maximum power consumption* that it needs to consume to function properly. Input values for this variable have been retrieved from Schnuelle et al. (2020).

Initial investment per MWh electrolyzer capacity

The initial investment per MWh electrolyzer capacity are the initial costs per MW electrolyzer capacity before the wind-hydrogen plant becomes operational. Input values for this variable are based on IEA (2019).

Operational expenses rate electrolyzer

The operational expenses rate of an electrolyzer is the percentage of the initial investment for the electrolyzer that needs to be spend each year to keep the electrolyzer operational. Input values for this variable are based on Christensen (2020).

Electrolyzer lifetime

The lifetime of an electrolyzer represents the number of years it can be operational before it needs to be replaced. Input values for this variable are based on Christensen (2020). Christensen (2020) reports the lifetime of electrolyzers in hours. To convert this to years, these values have been divided by the number of hours in a year (8760).

3.8.4 Wind park location

Table 6: Wind park location input variables

Symbol	**Name**	**Unit**
$E_{wind\ uti,t}$	Wind capacity utilization	(-)
$LCOE_{T_p}$	Levelized cost of energy	\$/MWh

Table 6 contains input variables that vary based on the windpark location. The values for these input variables can be found in Table 7 and Table 8.

Table 7: Wind park location input variables values for onshore wind park

Symbol	Name	Value	Source
$E_{wind\ uti,t}$	Wind capacity utilization	51,5% (average)	Renewables.ninja
$LCOE_{T_p}$	Levelized cost of energy	50	Martinez & Iglesias (2022)

Table 8: Wind park location input variables values for offshore wind park

Symbol	Name	Value	Source
$E_{wind\ uti,t}$	Wind capacity utilization	66,3% (average)	Renewables.ninja
$LCOE_{T_p}$	Levelized cost of energy	99	Duffy et al. (2020)

Wind capacity utilization

The wind capacity utilization represents how much of the capacity of the wind park is being utilized to generate wind energy over time. Values for this variable over time are retrieved from Renewables.ninja. When retrieving these values, Renewables.ninja requires input such as a location, hub height and wind turbine type.

For the onshore wind park utilization, a location in the Netherlands without buildings is selected. The hub height is set at 100 meters high, which is the average hub height for onshore wind turbines according to McKenna et al. (2022). The selected wind turbine is the Vestas V110 2000, which has a rotor diameter of 110 meters, a capacity of 2MW and is still in production (TheWindPower, n.d.).

For the offshore wind park utilization in the North Sea is selected. According to Martinez & Iglesias (2022), the LCOE is relatively low at this location. The selected hub height is set at the average for offshore wind turbines. This average value is 120 meters (Costoya et al., 2022). Again, the Vestas V110 2000 was selected. The full set of input entered in Renewables.ninja can be found in Appendix C.

Levelized cost of energy

The levelized cost of energy are the costs per unit of energy over the span of an energy generation project. The levelized cost of energy can differ between onshore and offshore projects due to factors such as difference in wind speed and connection costs Martinez & Iglesias (2022). The input values for the levelized cost of offshore and onshore wind energy are based on Martinez & Iglesias (2022) and Duffy et al. (2020) respectively.

3.8.5 External input variables

Table 9: External input variables

Symbol	Name	Unit

E_{H_2}	Higher heating value of hydrogen	MWh/kg
R_r	Reinvestment rate	(-)
i	Discount rate	(-)
$P_{E,ex}$	Price of excess wind energy	\$/MWh

Table 9 contains the variables that are not influenced by the values of the design input variables. The values for the variables in Table 9 can be found in Table 10.

Table 10: External input variables values

Symbol	Name	Value	Source
E_{H_2}	Higher heating value of hydrogen	0,0394	IEA (2019)
R_r	Reinvestment rate	0,5	Christensen (2020)
i	Discount rate	0,15	(-)
$P_{E,ex}$	Price of excess wind energy	$0{,}75 \times LCOE$	(-)

Higher heating value of hydrogen

The higher heating value of hydrogen is the amount of hydrogen that is released by the combustion of a kilogram of hydrogen. This input value is based on IEA (2019).

Reinvestment rate

The reinvestment rate is the percentage of the initial investment costs that need to be spent to replace a component of a wind-hydrogen plant. As in the study by Christensen (2020) the input value for this variable is set to 0,5.

Discount rate

The discount rate represents the cost of capital for a project and can vary based on the risk of a project. Since wind-hydrogen plants with large energy storage systems incorporated do not exist yet, a relatively high discount rate of 0,15 is set.

Price of excess wind energy

The price of excess wind energy is the price at which wind energy that is generated for, but not used by the wind-hydrogen plant can be sold. Under the assumption that this energy is available at times when there is a relative high amount of wind, and thus supply of wind energy, the price is assumed to be a portion of the LCOE.

3.8.6 Reference scenario with grid connection

A reference scenario of a wind-hydrogen plant connected to the grid is constructed to gain more insight in the effect of the temporal correlation requirements of the RED II on the performance of a wind-hydrogen plant.

Table 11: Design input variables values reference case

Symbol	Name	Value(s)

$\mu_{H_2,goal}$	Hydrogen output goal	1000/5000
(-)	Electrolyzer type	AEL/PEM
(-)	Energy storage system	(-)
$E_{wind,max}$	Maximum wind energy output	(-)
(-)	Wind park location	(-)
T_p	Plant lifetime	10/25/40

The design input variables for the reference case are displayed in Table 11. As can be seen, the reference case does not contain an *energy storage system*, *maximum wind energy output* or wind *park location*. Instead, the wind-hydrogen plant in the reference scenario is assumed to acquire its energy from the grid so that the incoming amount of energy is always equal to $E_{elec,goal}$. Following Mathis (2022), the price for this energy is set at $62/MWh.

3.8.7 Full factorial scenario design

The scenarios that will be used to perform experiments with the model are designed in a full factorial manner. This means that every combination of values for the different input variables as described in section 3.8.1 to 3.8.6 will be explored. This is done to create a clear and complete image of the model behavior. Table 12 shows an overview of the number of scenarios per energy storage system.

Table 12: Number of scenarios per energy storage system type

Energy storage system	**Number of scenarios**
(-)	144
PHSS	512
CAESS	512
FBESS	1024
LIBESS	1024
HESS	256
Total	3472

It should be noted that the set of scenarios without energy storage systems consists of the scenarios representing wind-hydrogen plants without energy storage systems (128) and the reference scenarios representing hydrogen plants with a grid connection (16). There can be differences between the number of scenarios per energy storage system as for some of them there is more uncertainty involved. For example, for LIBESS, two values for the *energy storage system (dis)charge capacity* are considered whereas for CAESS only one value is considered here. This halves the number of scenarios due to the way these are constructed.

3.9 Main assumptions

In the process of constructing the wind-hydrogen plant model as described in section 3.6, several assumptions have been made. These assumptions have been made to keep the model accurate, but also useable and comprehensible. This section discusses some of the main assumptions and their implications for the use of the constructed model.

Electrolyzer efficiency

As mentioned in section 3.6.1, the efficiency of the electrolyzer is assumed to be constant at all times. In reality, this is not the case as the efficiency of an electrolyzer can change based on its temperature (Olateju et al., 2016). As a result of this assumption, the hydrogen production rate in the model might be more stable than it would be in reality.

Another assumption relating to the efficiency of the electrolyzer in the model is that the electrolyzer does not degrade over time and needs the same amount of energy to produce a kilogram of hydrogen over its entire lifespan. In reality, an electrolyzer degrades over time, causing it to need more energy than before to produce a certain amount of hydrogen. As a result of this assumption, the hydrogen production rate over the years may be less stable and lower than the model results reflect.

Hydrogen production costs

An assumption made that relates to the costs for hydrogen production is that only the main components of the wind-hydrogen plant (wind turbines, electrolyzer, energy storage system) contribute to the hydrogen production costs. In reality, more components contribute to this cost. For example, some of the components need to be placed in a building which would need to be constructed. Also, costs need to be made in order to acquire water to produce hydrogen from. The fact that only the costs of the main components of the wind-hydrogen plant are taken into account may result in a lower value for the levelized cost of hydrogen.

Another assumption that is relevant for the calculation of the levelized cost of hydrogen is that no scale effects are taken into account. As mentioned in section 2.1.1, electrolyzers can benefit from scale effects when being acquired. This is not reflected in the model as the price of an electrolyzer per MW capacity is assumed to be independent of its size. This may result in a higher levelized cost of hydrogen. A similar reasoning could apply to other cost components as all costs in the model are assumed to scale linearly.

Lastly it is worth noting that the scenarios in section 3.8 are defined in an exploratory manner. This means that the designs of the hydrogen plants these scenarios represent can be far from optimal. For this reason, some of the output values for the *levelized cost of hydrogen* can be far higher than those reported in other studies.

Energy storage systems

In the constructed model, the self-discharge of the energy storage systems is not incorporated. In reality, an energy storage system will lose some of its charge over time without being charged or discharged (Rahman et al., 2020). As this is not incorporated in the model, the self-discharge is assumed to be neglectable for all the energy storage systems. As a result, the outcomes for the plant efficiency and hydrogen output rate may be portrayed as higher than they would be in reality.

A similar assumption is made regarding the response time of the different energy storage systems. The response time of an energy storage system is the time it needs to provide energy. In reality, this response time can be different per energy storage system. As the response time is not incorporated in the model, all the energy storage systems are assumed to be able to provide energy instantly.

Model structure

The fact that data for one year is used to perform an experiment for multiple years brings the assumption that each year looks exactly the same in terms of performance of a wind-hydrogen plant. In reality this is not the case as weather data will differ per year and thus the energy supply will as well. Therefore, in reality, the performance of a wind-hydrogen plant may be less consistent than portrayed.

Another consequence of using the data for one year to simulate an experiment for multiple years is that at the start of each year, the energy storage system in place is empty. In reality, this would not be the case as some energy from the previous year may be left in the system. This could cause the performance of wind-hydrogen plants with energy storage systems to be portrayed as worse than it would be in reality.

4. Results

After performing experiments for the scenarios as described in section 3.8, their results can be analyzed.

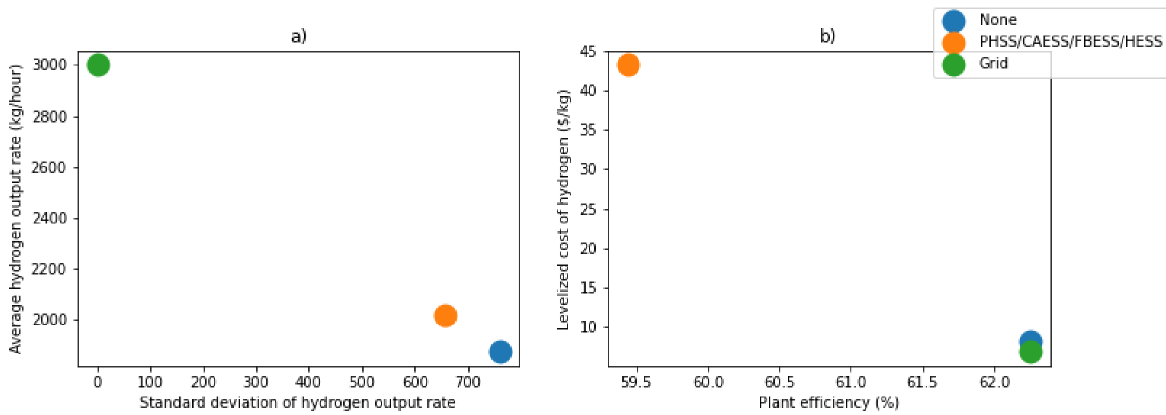

Figure 6: Mean a) average hydrogen output rate, standard deviation of hydrogen output rate, b) levelized cost of hydrogen and plant efficiency of wind-hydrogen plants with no energy storage system, with PHSS/CAESS/FBESS/HESS and hydrogen plants with a grid connection

Figure 6 compares the performance of wind-hydrogen plants with energy storage systems deemed suitable for seasonal energy storage by the existing literature (PHSS/CAESS/FBESS/HESS) to the performance of wind-hydrogen plants without energy storage system and hydrogen plants with a grid connection. The results show that compared to hydrogen plants with a grid connection, wind-hydrogen plants have a lower and less stable *hydrogen output rate*. The integration of energy storage systems can cause an increase and stabilization of the *hydrogen output rate*, but impact the *plant efficiency* and *levelized cost of hydrogen* in a negative manner. Section 4.1 to 4.3 discuss the effect of energy storage systems on the performance of wind-hydrogen plants in more detail.

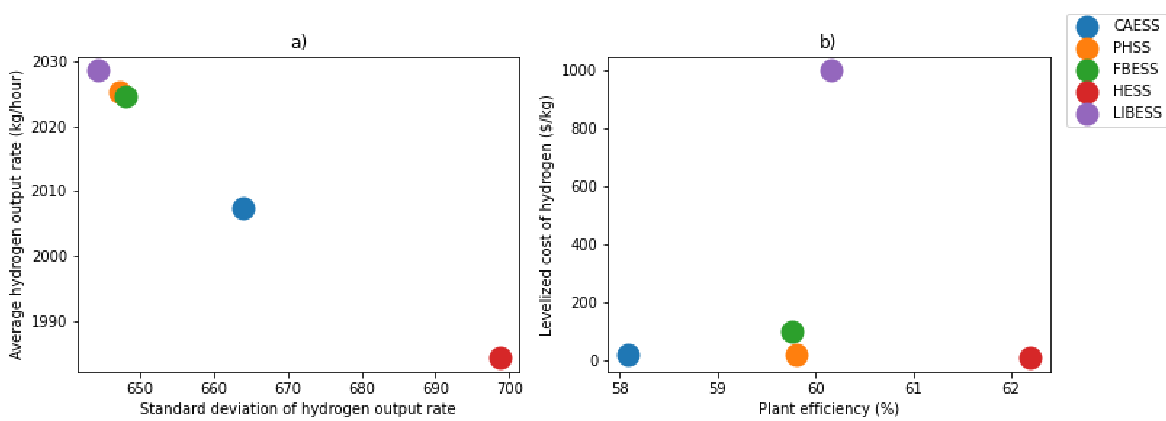

Figure 7: Mean a) average hydrogen output rate, standard deviation of hydrogen output rate, b) levelized cost of hydrogen and plant efficiency of wind-hydrogen plants with PHSS/CAESS/FBESS/HESS or LIBESS.

Figure 7 shows the performance of wind-hydrogen plants with PHSS/CAESS/FBESS/HESS or LIBESS. As explained in section 3.2, LIBESS is not recognized as suitable for seasonal energy storage in literature, but included as a benchmark for the other energy storage systems. When comparing different individual energy storage systems, LIBESS results in the highest and most stable *hydrogen output rate* when integrated in a wind-hydrogen plant. At the same time, LIBESS is the energy storage system resulting in the highest *levelized cost of hydrogen*. The energy storage system resulting in the highest *plant efficiency* and lowest *levelized cost of hydrogen* is HESS. Section 4.4 provides a more detailed comparison of the performance of different energy storage systems when integrated in a wind-hydrogen plant.

The type of energy storage system is not the only design parameter affecting the performance of hydrogen plants. The influence of various other design parameters such as the type of electrolyzer and the location of the wind park are discussed in section 4.5. Section 4.6 contains a model verification. In section 4.7, the validity of the model is discussed by comparing outcomes to those of other studies and section 4.8 contains a sensitivity analysis.

4.1 Hydrogen output rate

The hydrogen output rate of a wind-hydrogen plant is the amount of hydrogen it supplies during a certain amount of time. The performance of a wind-hydrogen plant can be analyzed based on the average hydrogen output rate and based on the standard deviation of the hydrogen output rate.

4.1.1 Average hydrogen output rate

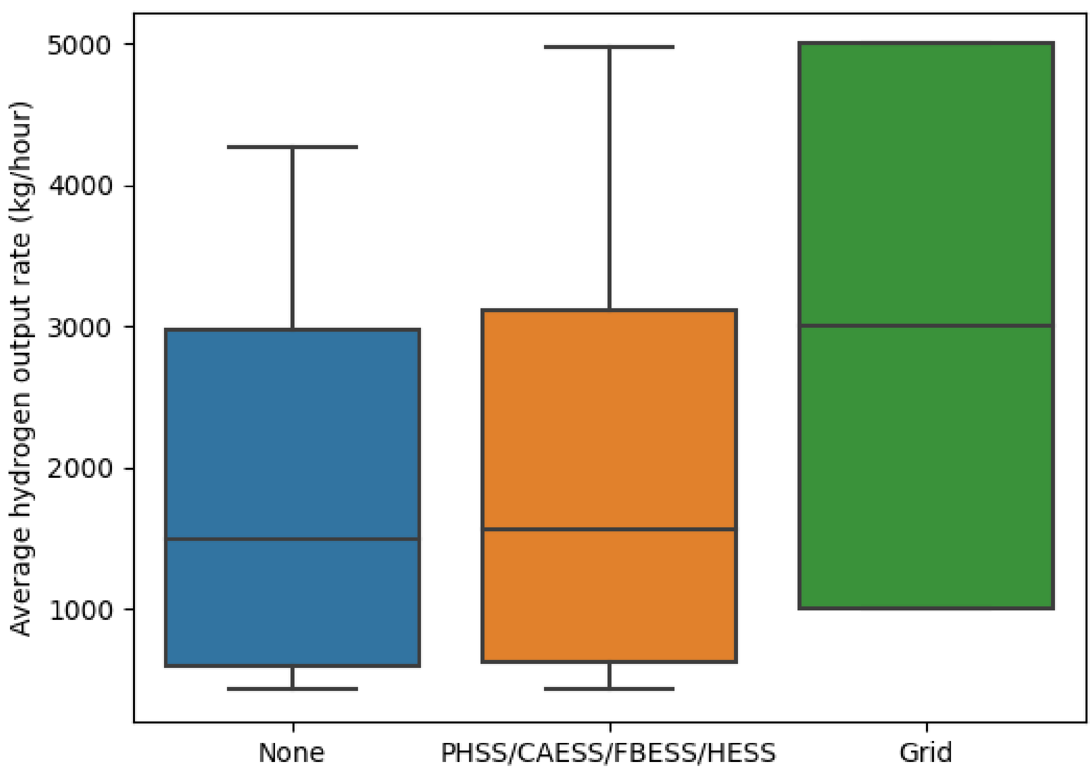

Figure 8: Average hydrogen output rate for wind-hydrogen plants without an energy storage system, with an energy storage system and hydrogen plants with a grid connection (n= 2448)

Figure 8 shows a series of boxplots of the average *hydrogen output rate* of wind-hydrogen plants of 2448 experiments. This number of experiments is lower than the total amount of scenarios constructed as the experiments for scenarios with LIBESS are not included in this figure. This is as LIBESS is mainly included as a benchmark, not as a possibly suitable energy storage system for wind-hydrogen plants (see section 3.2). The outcomes of the scenarios have been divided into three groups, each represented by a box with whiskers in Figure 8. The most left box represents the data of experiments for wind-hydrogen plants without energy storage system. The middle box represents the data of experiments for wind-hydrogen plants with PHSS, CAESS, FBESS or HESS. The right box represents the data of the experiments for hydrogen plants with grid connection. Figure 10, Figure 12 and Figure 14 are compiled in a similar fashion.

The data in Figure 8 shows that the mean average *hydrogen output rate* is lowest for wind-hydrogen plants without an energy storage system and highest for hydrogen plants with a grid connection. This means that the use of a variable energy source causes a decrease in average *hydrogen output rate*.

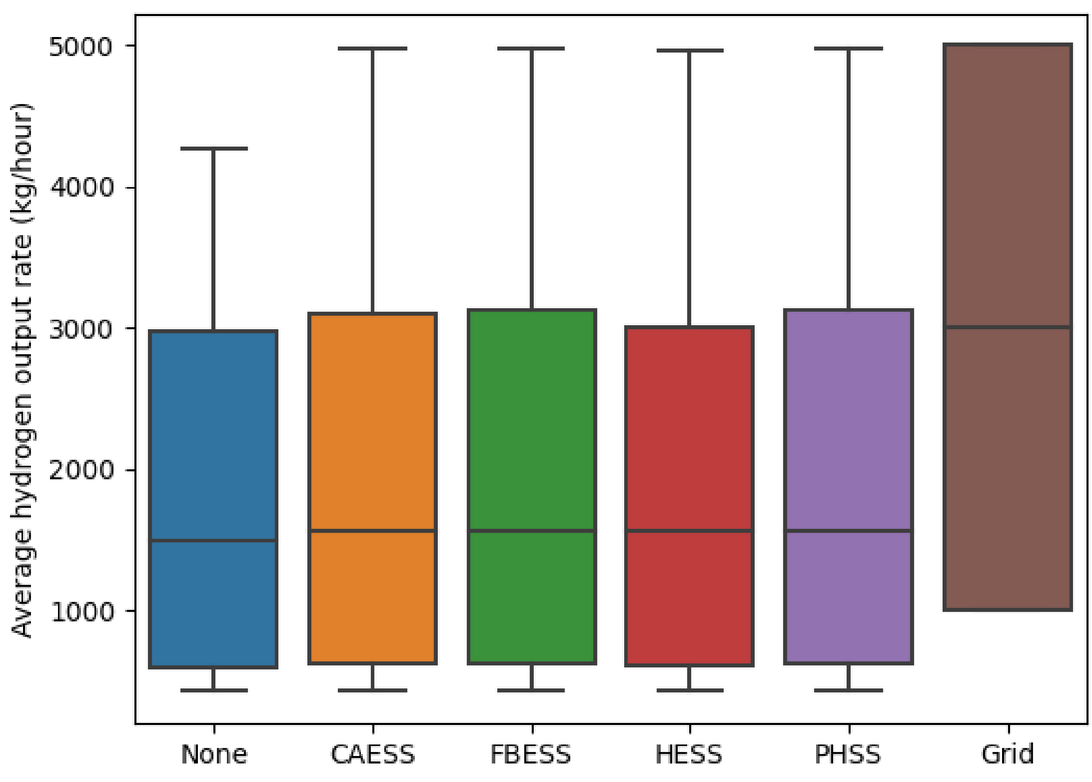

Figure 9: Average hydrogen output rate for wind-hydrogen plants without an energy storage system, with a specific energy storage system and hydrogen plants with a grid connection (n=2448)

Figure 9 displays similar data to Figure 8, however, instead of grouping the outcomes of the experiments for wind-hydrogen plants with CAESS, FBESS, HESS or PHSS, these are displayed separately here. Figure 11, Figure 13 and Figure 15 are constructed in a similar fashion. Figure 9 shows that wind-hydrogen plants with each of the different energy storage systems integrated have a higher average hydrogen output rate than those without, but lower than a hydrogen plant with a grid connection. This indicates that regardless of which of the considered energy storage systems is integrated in a wind-hydrogen plant, it will always cause an increase in the average *hydrogen output rate*. For each of the energy storage systems included in Figure 11, the top whisker of their respective boxplots approaches that of hydrogen plants with a grid connection. This implies that for each of the considered energy storage systems, a configuration of a wind-hydrogen plant is possible that results in nearly the same average *hydrogen output rate* as a hydrogen plant with a grid connection.

4.1.2 Standard deviation hydrogen output rate

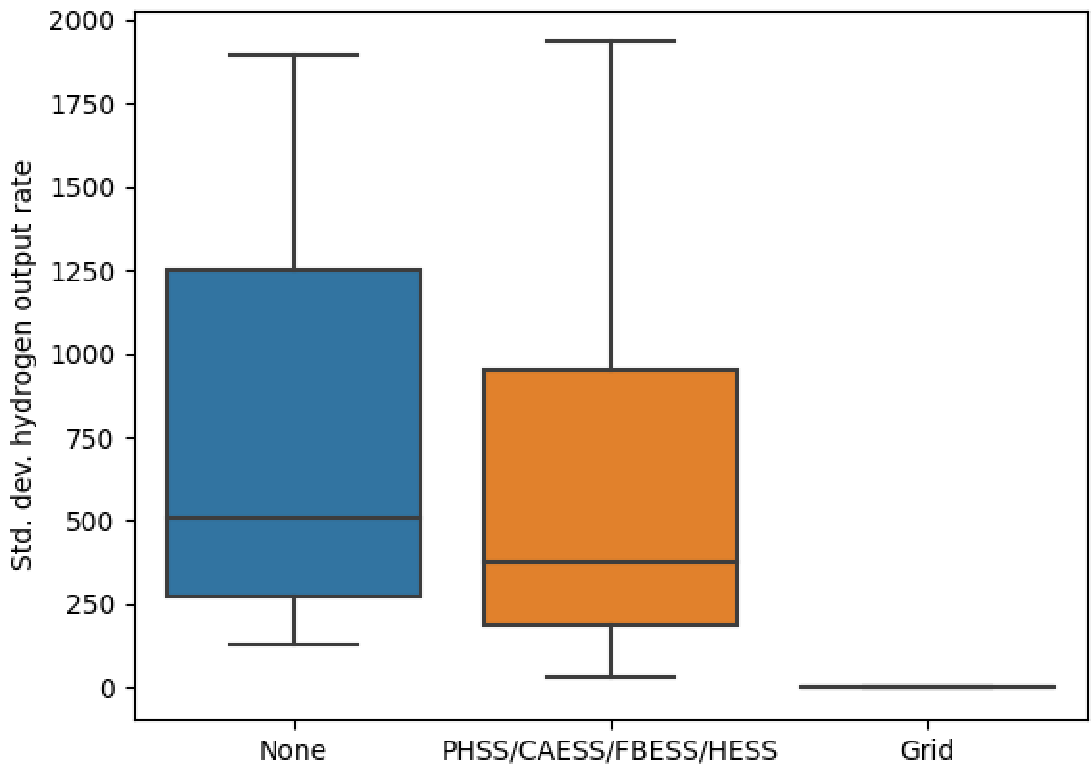

Figure 10: Standard deviation of the hydrogen output rate for wind-hydrogen plants without an energy storage system, with an energy storage system and hydrogen plants with a grid connection (n=2448)

Figure 10 shows that the standard deviation of wind-hydrogen plants decreases as a result of integrating an energy storage system. When comparing the mean standard deviation of the *hydrogen output rate* of wind-hydrogen plants to that of hydrogen plants with a grid connection, that of wind-hydrogen plants is higher. This means that the use of a variable energy source results in a less stable *output of hydrogen*. When comparing the standard deviation of the *hydrogen output rate* of wind-hydrogen plants with energy storage system to those without, it becomes clear that the use of an energy storage system results in a more stable *hydrogen output rate*. When comparing the boxplots for wind-hydrogen plants without energy storage system and those with an energy storage system, it shows that in some cases, the standard deviation of the *hydrogen output rate* is higher for wind-hydrogen plants with energy storage systems than for those without. This can be explained by the fact that, as depicted in Figure 8, energy storage systems cause an increase in average hydrogen *output rate*. When this relative increase in average *hydrogen output rate* is larger than the relative decrease in the standard deviation of the *hydrogen output rate*, the energy storage system causes an increase in the absolute value for the standard deviation of the *hydrogen output rate*.

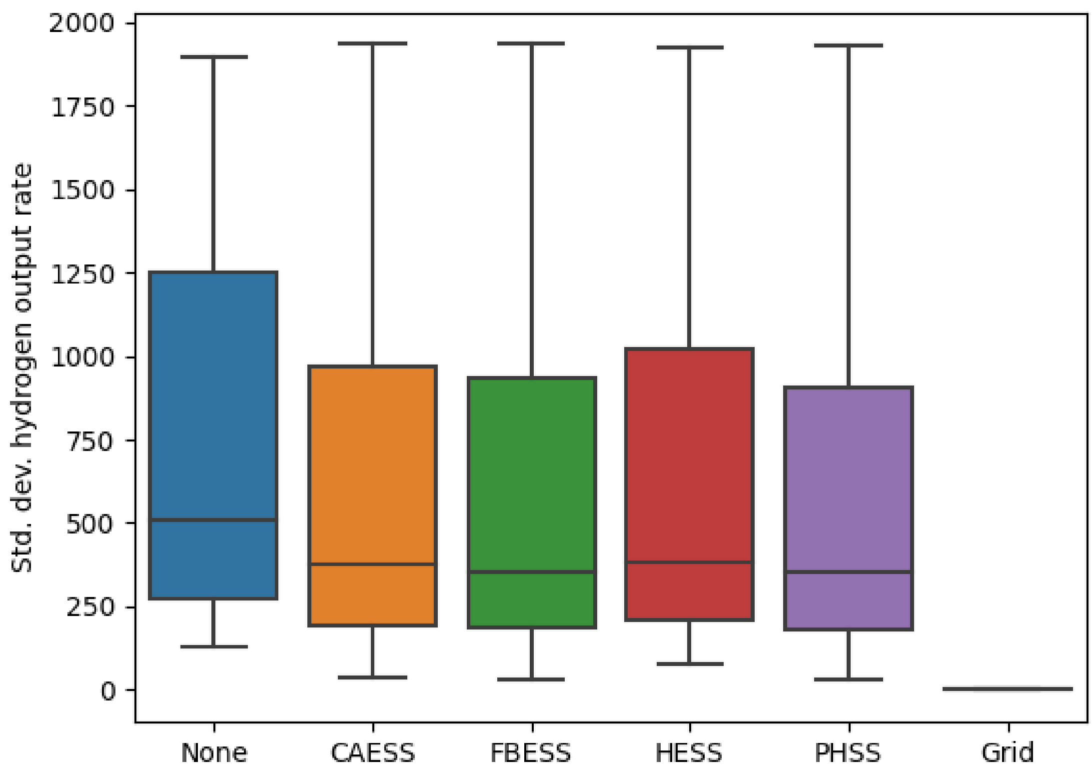

Figure 11: Standard deviation of the hydrogen output rate for wind-hydrogen plants without a specific energy storage system, with an energy storage system and hydrogen plants with a grid connection (n=2448)

Figure 11 shows the standard deviation of the *hydrogen output rate* for wind-hydrogen plants with specific energy storage systems integrated. Wind-hydrogen plants with each of the different energy storage system have a lower mean standard deviation of the *hydrogen output rate* than wind-hydrogen plants without energy storage system, but higher than hydrogen plants with a grid connection. This shows that regardless of which of the considered energy storage systems is implemented, they can stabilize the *hydrogen output rate* of a wind-hydrogen plant. It can also be noted that each of the energy storage systems result in a similar standard deviation of the *hydrogen output rate.*

4.2 Plant efficiency

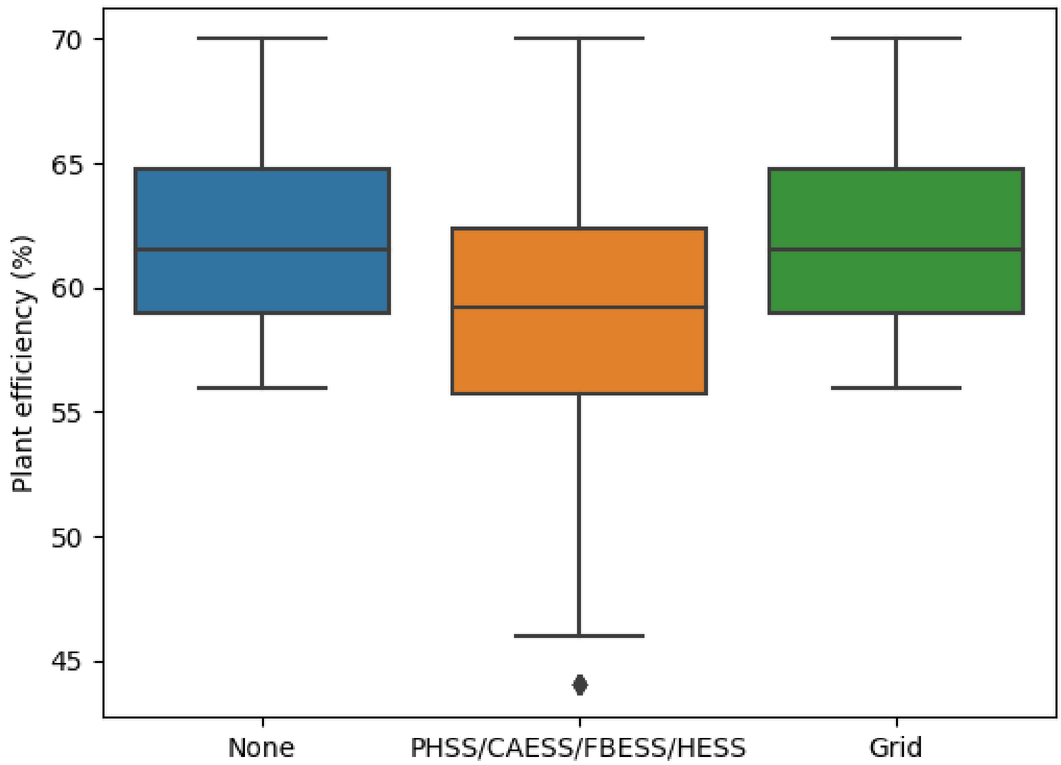

Figure 12: Plant efficiency for wind-hydrogen plants without an energy storage system, with an energy storage system and hydrogen plants with a grid connection (n=2448)

As can be seen in Figure 12, wind-hydrogen plants with an energy storage method have a lower mean *plant efficiency* than those without or hydrogen plants with a grid connection. The figure also shows that wind-hydrogen plants without an energy storage system have the same *plant efficiency* as hydrogen plants with a grid connection.

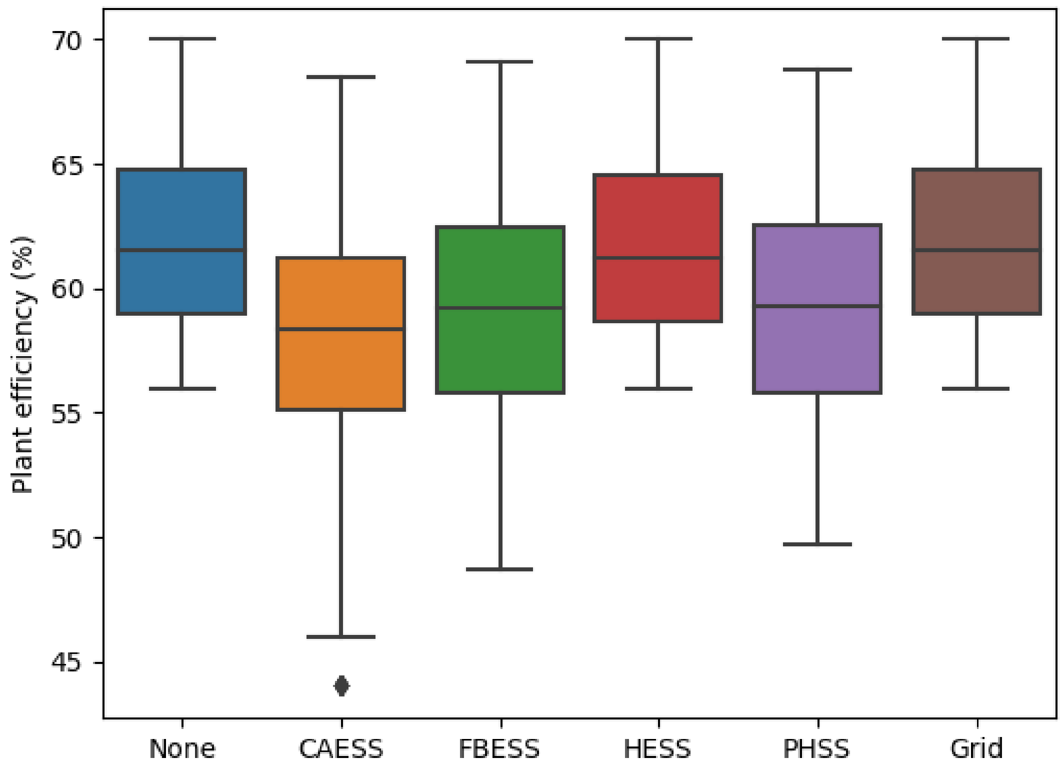

Figure 13: Plant efficiency for wind-hydrogen plants without an energy storage system, with a specific energy storage system and hydrogen plants with a grid connection (n=2448)

Figure 13 shows that all of the considered energy storage systems considered result in a decrease in *plant efficiency.* When comparing wind-hydrogen plants with specific energy storage systems, plants with HESS show the highest plant efficiency. It can also be observed that plants with HESS have a slightly lower mean plant efficiency (62.1%) than wind hydrogen plants without energy storage system and hydrogen plants with a grid connection (62.3%). Wind-hydrogen plants with a CAESS show the lowest plant efficiency.

4.3 Levelized cost of hydrogen

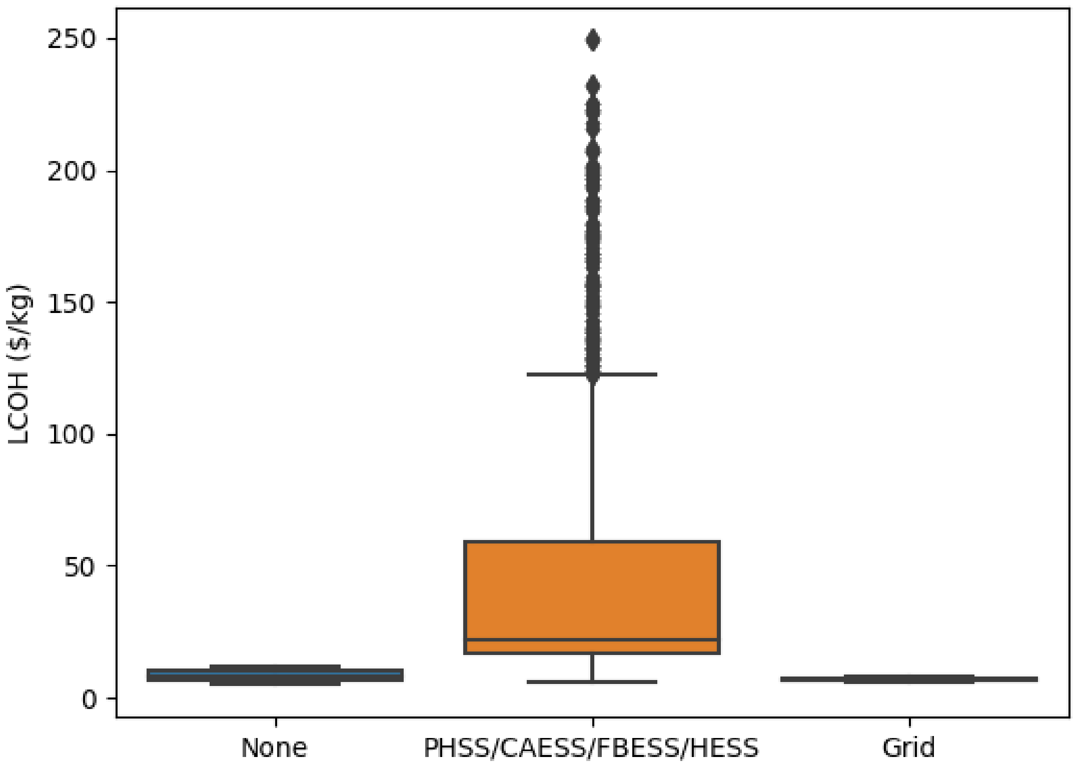

Figure 14: Levelized cost of hydrogen for wind-hydrogen plants without an energy storage system, with an energy storage system and hydrogen plants with a grid connection (n=2448)

Figure 14 compares the *levelized cost of hydrogen* for wind-hydrogen plants with an energy storage system to those without and hydrogen plants with a grid connection. Wind-hydrogen plants with an energy storage system show a higher mean *levelized cost of hydrogen* than those without or than hydrogen plants with a grid connection. Hydrogen plants with a grid connection produce hydrogen at the lowest levelized cost.

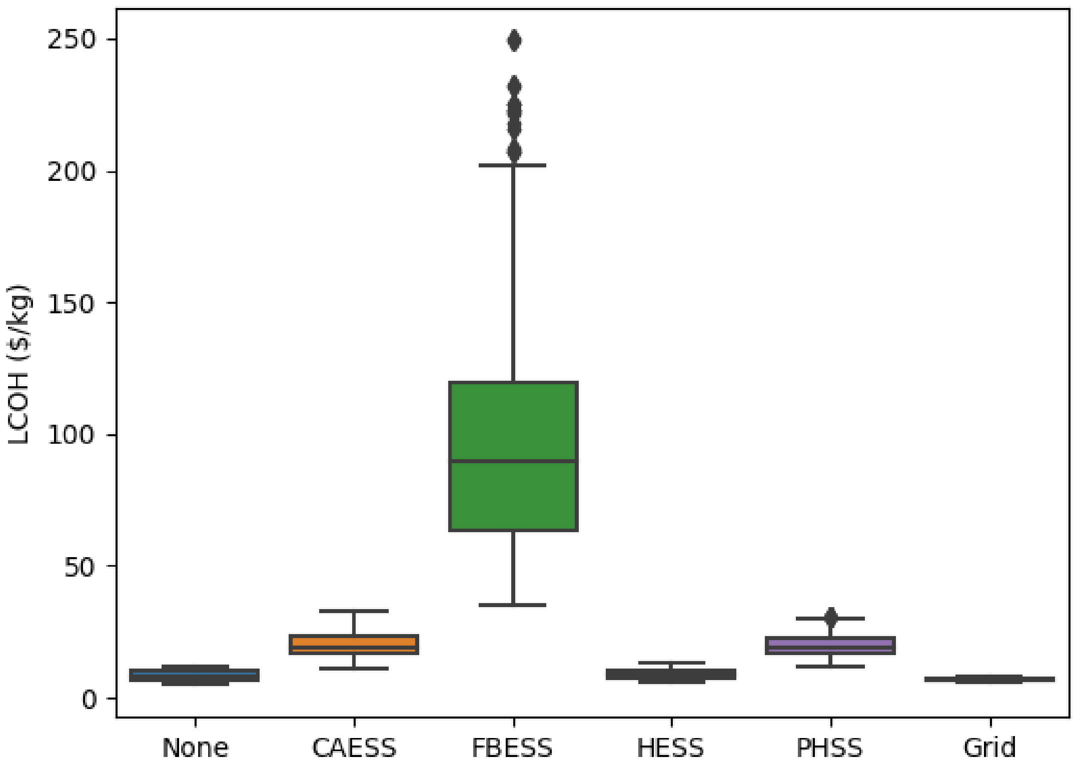

Figure 15: Levelized cost of hydrogen for wind-hydrogen plants without an energy storage system, with an energy storage system and hydrogen plants with a grid connection (n=2448)

Figure 15 shows that of the wind-hydrogen plants with energy storage system, those with FBESS have the highest *levelized cost of hydrogen* and those with HESS have the lowest. Also, wind-hydrogen plants each of the different energy storage systems show a higher mean *levelized cost of hydrogen* than wind-hydrogen plants without or hydrogen plants with a grid connection. When comparing Figure 15 to Figure 14, it becomes clear that the average *levelized cost of hydrogen* for wind-hydrogen plants with energy storage systems is increased a lot by considering FBESS as a potential energy storage system.

4.4 Performance of energy storage systems

For an accurate comparison of the performance of the different energy storage systems, the descriptive statistics of the different performance metrics are provided. As a benchmark, results for wind-hydrogen plants with LIBESS and wind-hydrogen plants without an energy storage system, but with relatively high maximum wind energy output ($3 \times \mu_{H_2,goal} \times E_{H_2}$) are included as well.

4.4.1 Hydrogen output rate

4.4.1.1 Average hydrogen output rate

Table 13: Average hydrogen output rate (kg/hour) for wind-hydrogen plants with different energy storage systems

	CAESS	FBESS	HESS	PHSS	LIBESS	Large maximum wind energy output
Mean	2007,4	2024,5	1984,3	2025,2	2028,5	1990,2
Std. dev.	1460,8	1475,7	1460,2	1476,3	1479,0	1421,9
Max	4974,2	4976,7	4964,0	4975,4	4977,5	4263,4
Min	425,2	425,2	425,1	425,3	425,3	469,2

Table 13 displays the descriptive statistics of the average *hydrogen output rate* for wind-hydrogen plants with different types of energy storage systems and wind-hydrogen plants with additional maximum wind energy output. The mean of the average *hydrogen output rate* is highest for wind-hydrogen plants with LIBESS. This means that to maximize the *average hydrogen output rate,* this energy storage system is most fit. The lowest mean average *hydrogen output rate* is calculated for wind-hydrogen plants with integrated HESS.

4.4.1.2 Standard deviation hydrogen output rate

Table 14: Standard deviation of hydrogen output rate for wind-hydrogen plants with different energy storage systems

	CAESS	FBESS	HESS	PHSS	LIBESS	Large maximum wind energy output
Mean	664	648	699	647	644	726
Std. dev.	558	554	548	554	553	570
Max	1.933	1.933	1.923	1.931	1.931	1.788
Min	35	33	77	34	32	128

Table 14 shows that wind-hydrogen plants with LIBESS have the lowest mean standard deviation of the *hydrogen output rate*. This implies that, of the analyzed energy storage systems, LIBESS is most fit for stabilizing hydrogen production from an intermittent energy source. Wind-hydrogen plants without energy storage system, but with large *maximum wind energy output*, have the highest standard deviation of the *hydrogen output rate*.

4.4.2 Plant efficiency

Table 15: Plant efficiency (%) for wind-hydrogen plants with different energy storage systems

	CAESS	FBESS	HESS	PHSS	LIBESS	Large maximum wind energy output
Mean	58,1	59,8	62,2	59,8	60,2	62,3
Std. dev.	5,3	4,9	5,1	4,8	4,9	5,2
Max	68,5	69,1	70,0	68,8	69,3	70,0
Min	44,0	48,7	55,9	49,7	49,7	56,0

Table 15 shows that the highest mean *plant efficiency* can be achieved with a wind-hydrogen plant without an energy storage system. The lowest plant efficiency is calculated for wind-hydrogen plants with CAESS. Of all the energy storage systems considered, HESS achieves the highest *plant efficiency* when incorporated in a wind-hydrogen plant.

4.4.3 Levelized cost of hydrogen

Table 16: Levelized cost of hydrogen ($/kg) for wind-hydrogen plants with different energy storage systems

	CAESS	**FBESS**	**HESS**	**PHSS**	**LIBESS**	**Large maximum wind energy output**
Mean	20,1	98,5	9,0	19,7	997,4	8,2
Std. dev.	4,8	45,9	2,0	3,9	826,8	2,1
Max	33,0	249,6	13,5	30,7	3491,3	11,9
Min	11,3	35,2	5,6	11,9	143,0	5,0

Table 16 shows that hydrogen can be produced at the lowest *levelized cost* in a wind-hydrogen plant without energy storage system. Wind-hydrogen plants with LIBESS produce hydrogen at the highest levelized cost. When comparing the *levelized cost of hydrogen* of wind-hydrogen plants with an energy storage system, wind-hydrogen plants with HESS show to produce hydrogen at the lowest *levelized cost*.

4.5 Wind-hydrogen plant design

To determine the effect of the design of a wind-hydrogen plant on its performance, designs with different values for the design input variables as defined in section 3.8.1 are compared. Again, these are compared based on their output in terms of the performance metrics as defined in section 3.3.

4.5.1 Hydrogen output goal

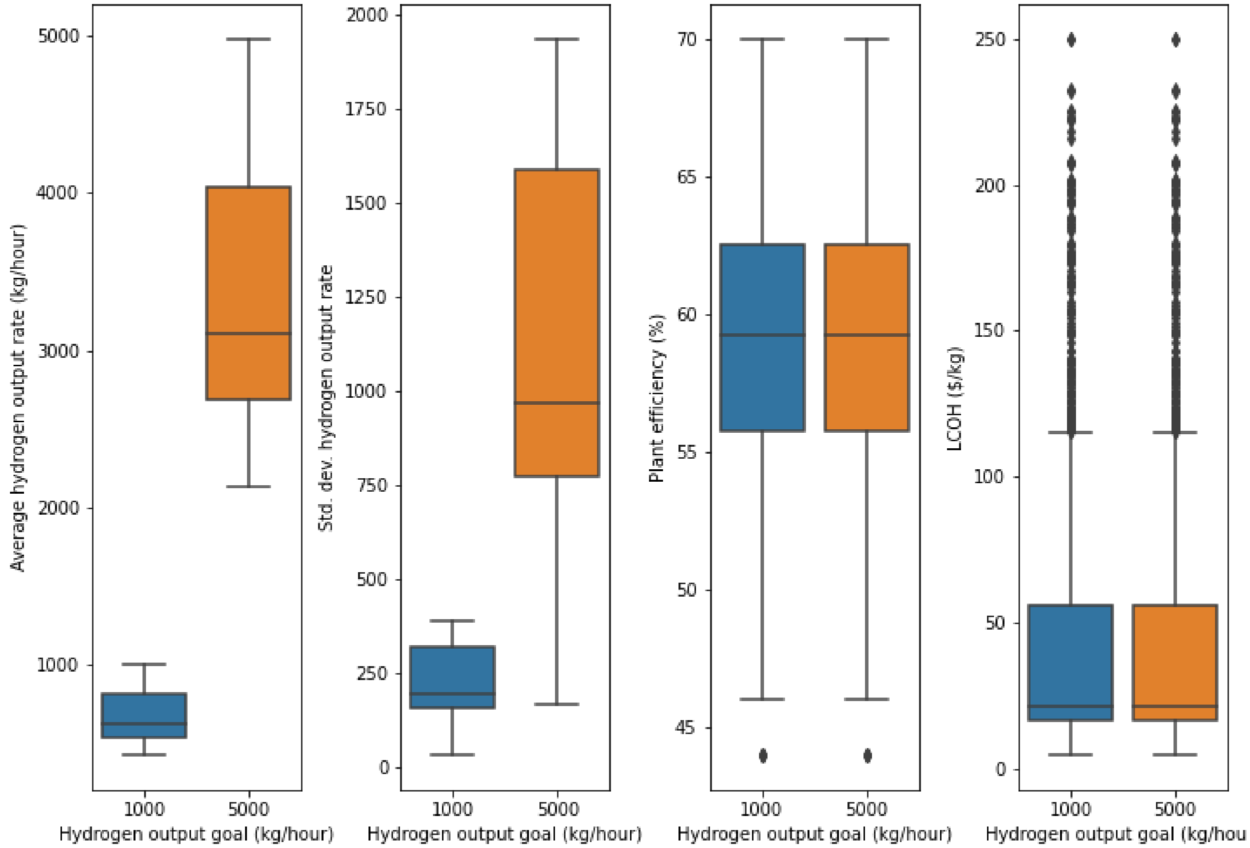

Figure 16: Performance metric values for different hydrogen output goals (n=2432)

Figure 16 displays the outcomes of 2432 experiments. This number is lower than the total number of experiments as experiments for scenarios with LIBESS and the reference scenarios are not included. Experiments for scenarios with LIBESS are not included as it is not deemed a suitable energy storage system in literature. Experiments for the reference scenario are not included as they do not represent wind-hydrogen plants, but hydrogen plants with grid connections. In the figure, the values of the different performance metrics are displayed for the included experiments. As can be seen, the outcomes have been grouped according to the value of the *hydrogen output goal* in the scenario for which they have been calculated. This way, the influence of the *hydrogen output goal* on the different performance metrics becomes clear. Figure 17 to Figure 20 have been compiled in a similar fashion.

Figure 16 shows how hydrogen plants with different hydrogen output goals score on the defined performance metrics. As can be seen, hydrogen plants designed with a hydrogen output goal of 5000kg/h have a higher average *hydrogen output rate* than those with a hydrogen output goal of 1000kg/h. This also goes for the standard deviation of the hydrogen output rate. The reason for this is that certain components of the wind-hydrogen plants are scaled according to the *hydrogen output goal.* If this value is increased, the components that are scaled accordingly will allow the wind-hydrogen plats to produce more hydrogen (see section 3.8). The hydrogen plants with a hydrogen output goal of 5000kg/h have a very similar plant efficiency and levelized cost of hydrogen as those with a hydrogen output goal of 1000kg/h.

4.5.2 Electrolyzer type

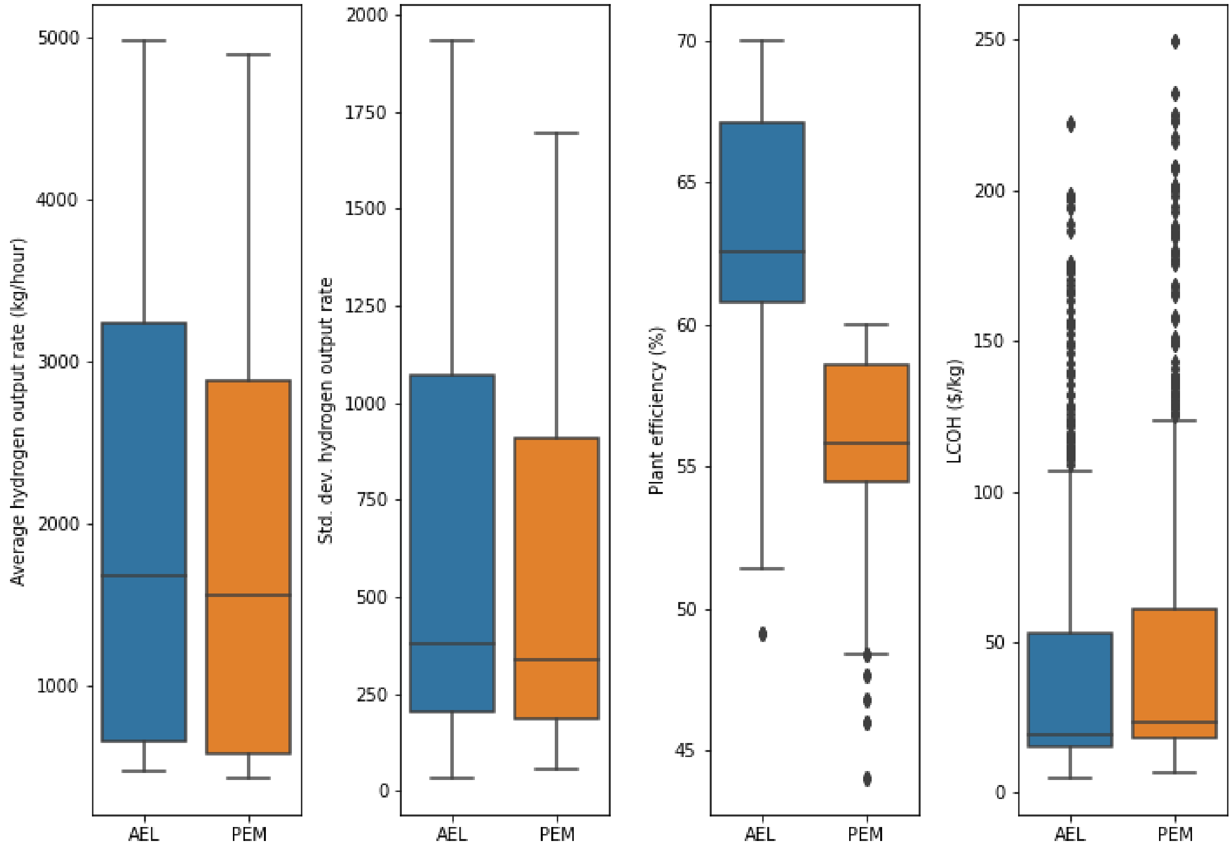

Figure 17: Performance metric values for different electrolyzer types (n=2432)

Figure 17 shows the performance metric values for hydrogen plants with different types of electrolyzers. It can be seen that hydrogen plants with alkaline electrolyzers tend to have a higher average hydrogen output rate, standard deviation of the hydrogen output rate and plant efficiency than those with a PEM electrolyzer. When comparing the average levelized cost of hydrogen, hydrogen plants with alkaline electrolyzers have a lower value than those with a PEM electrolyzer.

4.5.3 Maximum wind energy output

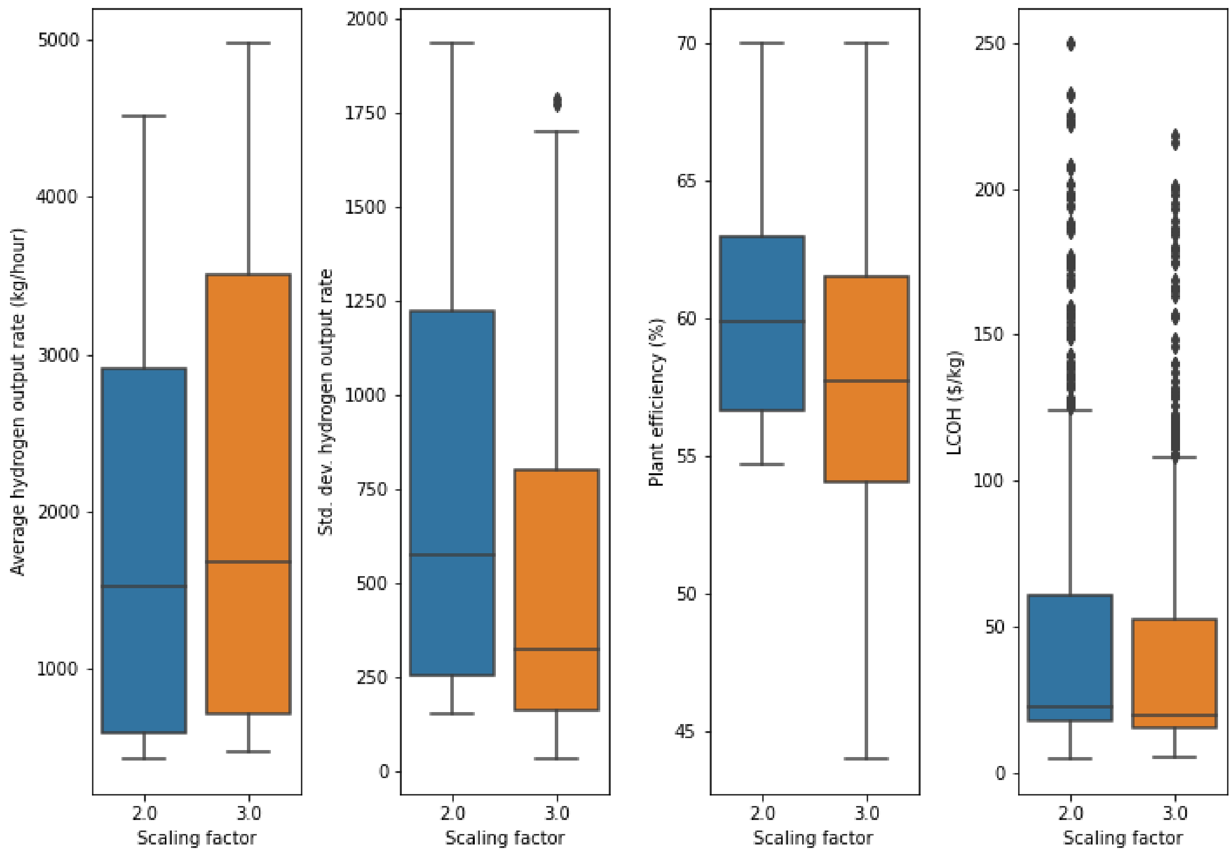

Figure 18: Performance metric values for different maximum wind energy output scaling factors (n=2432)

Figure 18 displays the values for the various performance metrics for wind-hydrogen plants that have been designed using different scaling factors to set their *maximum wind energy output*. The term scaling factor refers to the way in which the *maximum wind energy output* of a scenario is defined in section 3.8.1. For example, a scaling factor of 2.0 means that the *maximum wind energy output* in a scenario has been calculated as $2 \times \mu_{H_2,goal} \times E_{H_2}$. The figure shows that wind-hydrogen plants with a relatively higher amount of maximum wind energy output on average have a higher average hydrogen output rate and a lower standard deviation of the hydrogen output rate. At the same time, wind-hydrogen plants with a relatively higher amount of maximum wind energy output have a lower plant efficiency and levelized cost of hydrogen.

4.5.4 Wind park location

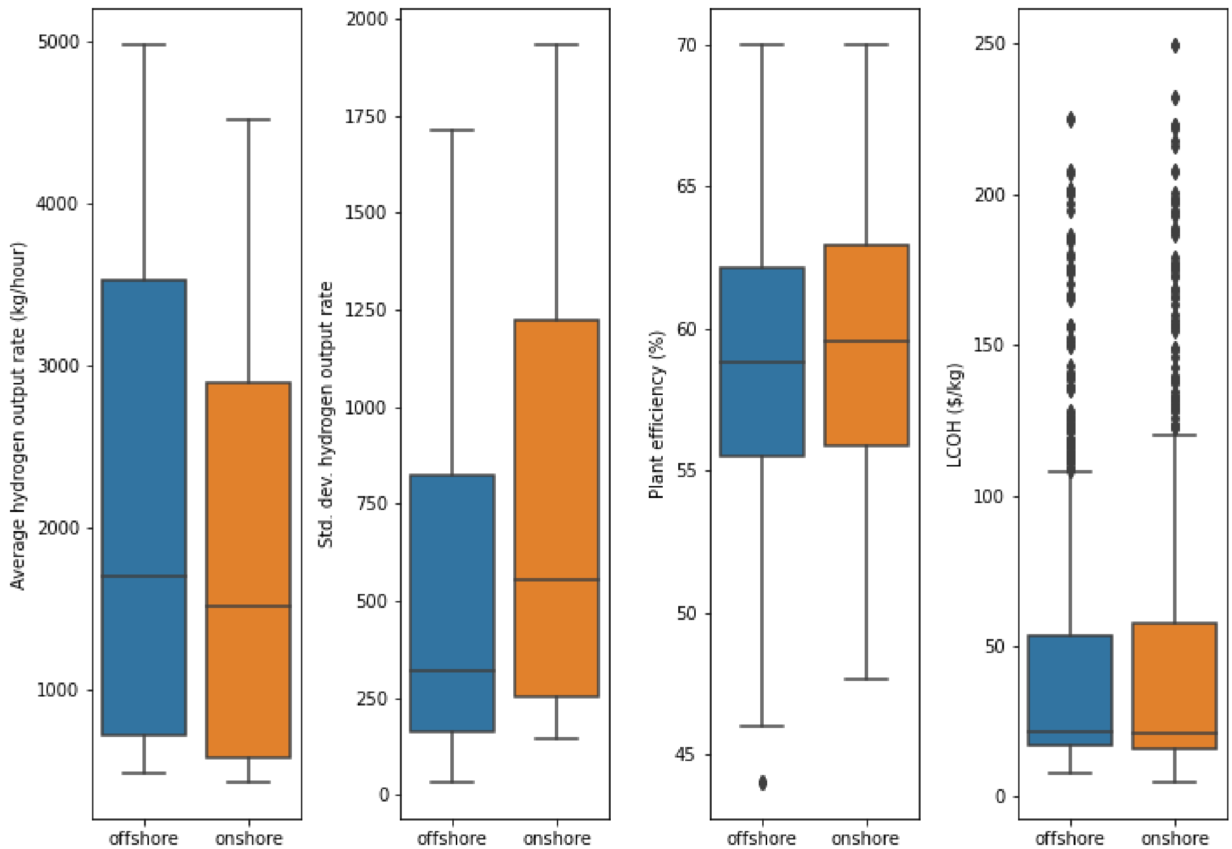

Figure 19: Performance metric values for different wind park locations (n=2432)

Figure 19 shows a comparison of the values of the performance metrics for wind-hydrogen plants that are connected to either onshore or offshore wind parks. On average, wind-hydrogen plants connected to an offshore wind park have a higher average hydrogen production rate and a lower standard deviation of the hydrogen production rate than those connected to an onshore wind park. When looking at the plant efficiency, wind-hydrogen plants connected to an offshore wind park are less efficient on average than those connected to an onshore wind park. The average levelized cost of hydrogen for is slightly higher for wind-hydrogen plants connected to an offshore wind park than for those connected to an onshore wind park.

4.5.5 Project lifetime

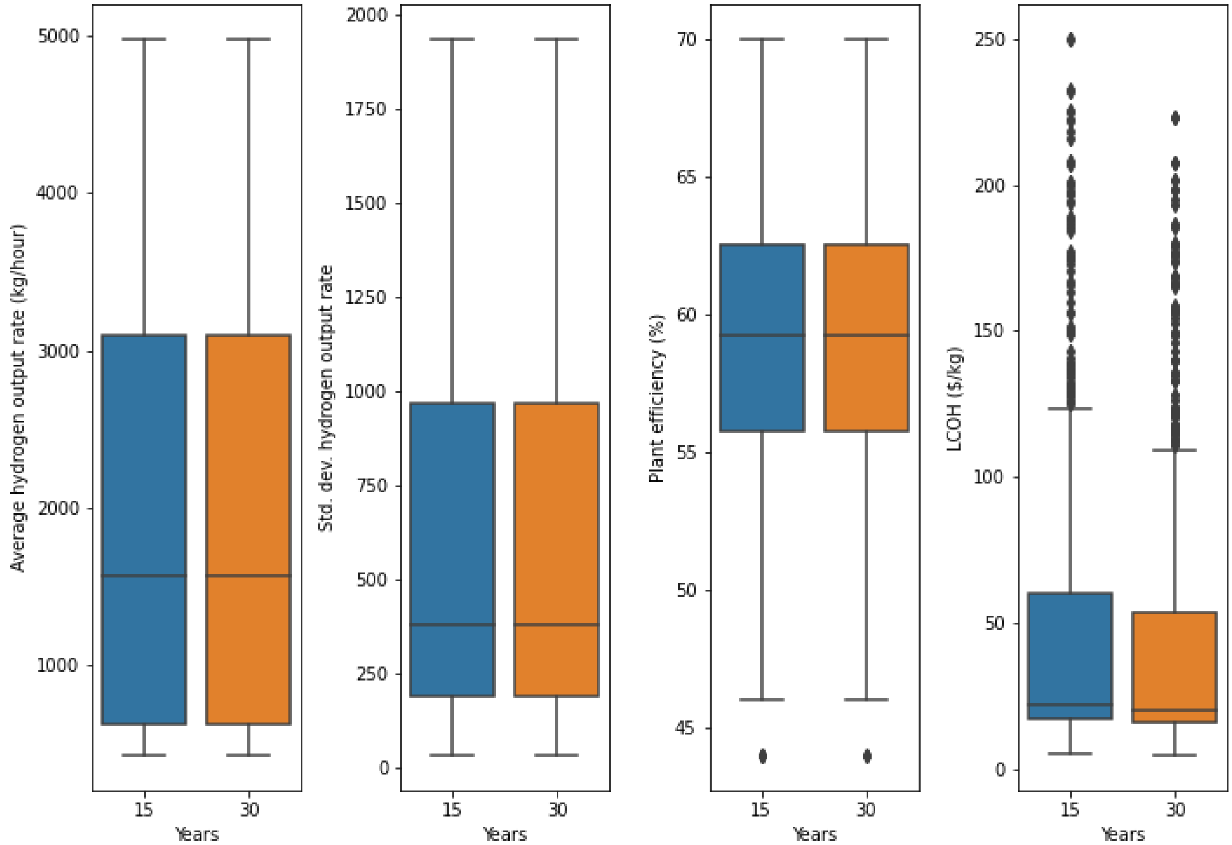

Figure 20: Performance metric values for different project lifetimes (n=2432)

Figure 20 shows the values of the performance metrics for hydrogen plants with different project lifetimes. As can be observed, the project lifetime of a hydrogen plant does not influence the average hydrogen output rate, standard deviation of the hydrogen output rate or the plant efficiency. When looking at the outcomes for the levelized cost of hydrogen, plants with a project lifetime of 30 years have a slightly lower average levelized cost of hydrogen than those with a project lifetime of 15 years.

4.6 Model verification

In order to verify the constructed model, the model behavior is observed in the context of the conceptual models as elaborated on in section 3.4.

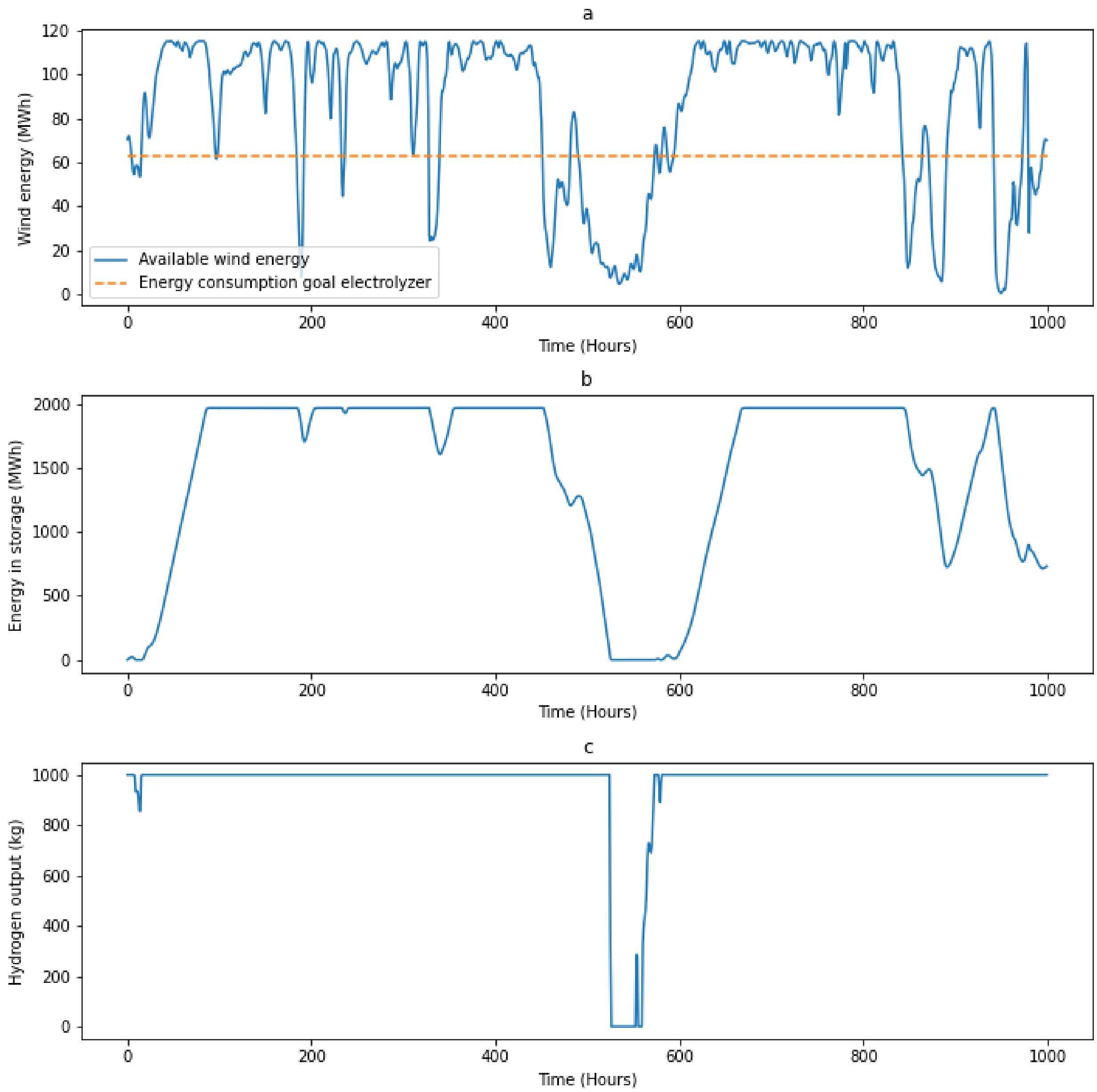

Figure 21: Timeseries of a) Wind energy, b) Energy in energy storage system and c) hydrogen output rate for model run for with CAESS/PHSS/FBESS/LIBESS

Figure 21 displays a timeseries representing the model behavior during a run for a wind-hydrogen plant with CAESS, PHSS, FBESS or LIBESS. As can be observed in Figure 21a and Figure 21b, the amount of energy in the storage system rises at times when more wind energy is available than the amount required to produce the desired amount of hydrogen (*Energy consumption goal electrolyzer)*. Also, the amount of energy in the energy storage system is reduced when less wind energy is available than required to produce the desired amount of hydrogen. The energy taken from the energy storage system is used to supplement the energy consumption of the electrolyzer to the desired level. This dynamic balances out the energy available for the electrolyzer and therewith stabilizes the hydrogen output (Figure 21c). At times when there is an insufficient amount of wind energy available and the energy storage system is empty, the hydrogen output drops. The behavior as shown in Figure 21 is coherent with the behavior of wind-hydrogen plants with CAESS/PHSS/FBESS/LIBESS as described in section 3.4.

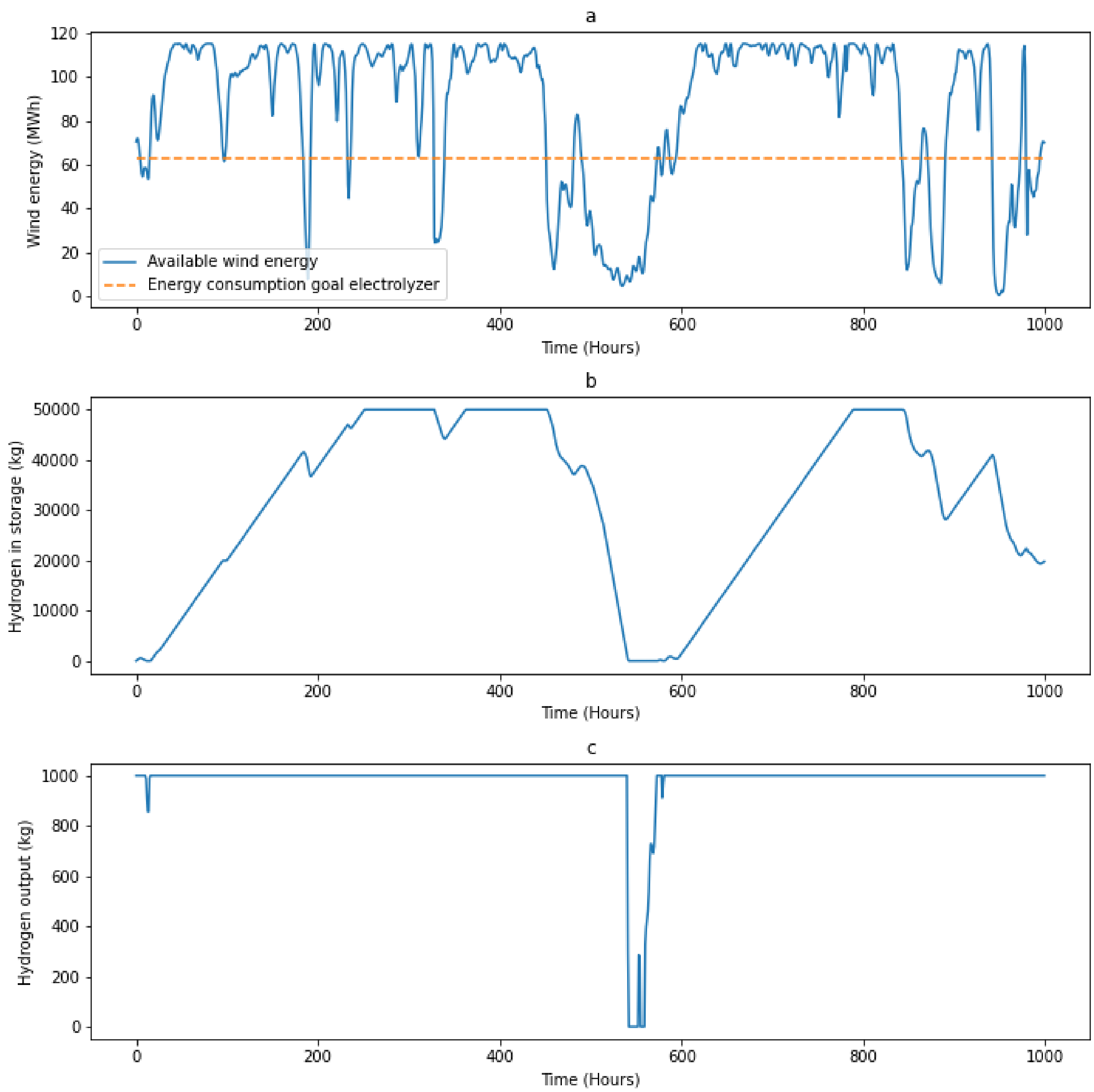

Figure 22: Timeseries of a) Wind energy, b) hydrogen energy storage system and c) hydrogen output rate for model run for with HESS

Figure 22 displays a timeseries representing the model behavior during a run for a wind-hydrogen plant with HESS. The behavior that can be observed is similar to that in Figure 21. Figure 22a and Figure 22b show that when there is an excess amount of wind energy available, the amount of hydrogen in the hydrogen energy storage system rises. At times when the amount of wind energy is insufficient, the amount of hydrogen in the hydrogen energy storage system decreases. The hydrogen being taken from the hydrogen energy storage system is used to supplement the hydrogen output. This dynamic stabilizes the hydrogen output, as can be seen in Figure 22c. The behavior as shown in Figure 22 is coherent with the behavior of wind-hydrogen plants with HESS as described in section 3.4.

4.7 Model validation

To validate the constructed model, its output is compared to those of similar models constructed in other studies. This comparison is conducted per model output. As the average hydrogen output rate and the standard deviation of the hydrogen output rate are calculated based on descriptive statistics of the same output variable, these will be evaluated in the same section.

4.7.1 Hydrogen output rate

Guo & Sepanta (2020) modelled a wind-hydrogen plant with integrated energy storage systems (pumped hydro and compressed air) and have reported the hydrogen output rate calculated by their model. In their model, a PEM electrolyzer with an efficiency of 83,3% is considered. This electrolyzer operates at a constant power consumption rate that allows it to produce 5 mol of hydrogen per hour (~0,005 kg/hour). The power consumed by the electrolyzer is generated by a 10kW wind turbine located in Iran. The rotor diameter and hub height of this wind turbine are reported to be 7 meters and 30 meters respectively. Furthermore, the energy storage system in place is reported to have an efficiency of 75-85% and a charging capacity of 1456W.

To compare the wind-hydrogen plant model in this study to that by Guo & Sepanta (2020), it is simulated with similar input values to that used by Guo & Sepanta (2020). These input values can be found in Appendix D: Validation input values. As part of the input used, wind energy data from Renewables.ninja is used. When retrieving this data, the same wind turbine location and hub height is used as by Guo & Sepanta (2020). Also, a wind turbine with a similar rotor diameter is selected. Using the data retrieved from Renewables.ninja, the average amount of wind energy generated over a year by the turbine is lower than reported by Guo & Sepanta (2020) (1050W versus 1969W). To generate more similar wind energy data, the hub height used as input is increased. With the increased hub height given as input, the wind energy data used to replicate that of Guo & Sepanta (2020) results in a more similar 1800W. The exact parameters used to retrieve wind data can be found in Appendix D: Validation input values.

When ran with similar input values to that used by Guo & Sepanta (2020), the model constructed in this study also gives a stable hydrogen output of 0.005kg per hour. It should be noted that this does not mean that both models generate an identical output. Both models represent a wind-hydrogen plant with energy storage system. However, the model structure is different. The model as described in section 3.6 requires a *hydrogen output goal* as input. This acts as a limit on the amount of hydrogen output of the system and was set to 0.05kg/hour for this experiment. The implication of this is that if this variable had been set to a higher value, a higher stable output could also have been realized. It is unclear whether this is also the case for the model by Guo & Sepanta (2020).

4.7.2 Wind-hydrogen plant efficiency

When running the constructed model with the same input values as described in section 3.7.1, the calculated wind-hydrogen *plant efficiency* is 78,90%. The *plant efficiency* as reported by Guo & Sepanta (2020) is 74,93%. While these output values are similar, they do differ. A potential reason for this difference is that Guo & Sepanta (2020) have modeled the *electrolyzer efficiency* to by dynamic while the model constructed in this study considers it to be static. This different approach can result in a variation of 3% in terms of hydrogen yield and thereby influence the efficiency as calculated by the plant (Olateju et al., 2014).

4.7.3 Levelized cost of hydrogen

Table 1 contains values for the *levelized cost of hydrogen* for wind-hydrogen plants as reported by other studies. As described in section 3.6.3, the levelized cost of hydrogen depends on a lot of different factors. For this reason, the *levelized cost of hydrogen* can vary greatly per wind-hydrogen plant. This is also reflected by the values in Table 17*.* The lowest reported value ($3,41/kg) is that by Won et al. (2017), which is less than half of the highest reported value (9,00$/kg) by Olateju et al. (2016). As can be seen in *Equation 15,* the *levelized cost of hydrogen* is calculated based on a number of factors that depend on the specific design and operation of a hydrogen plant. The wide range of reported values for the *levelized cost of hydrogen* can therefore be explained by the different setups of hydrogen plants for which they have been calculated.

Table 17: Levelized cost of hydrogen for wind-hydrogen plants as reported in other studies

LCOH ($/kg)	**Source**
3.41	Won et al. (2017)
4.54	Khouya (2020)
7.84	Olateju et al. (2014)
9.00	Olateju et al. (2016)

When the model as constructed in this study is used to calculate the *levelized cost of hydrogen* for scenarios without energy storage systems, the resulting *levelized cost of hydrogen* lays between 4,84$/kg and 11,86$/kg with an average of $8,15/kg of hydrogen. It should be noted that the designs are not optimized whereas those for which the *levelized cost of hydrogen* is reported in Table 17 mostly are. While the highest reported *levelized cost of hydrogen* calculated by the model constructed in this report is higher than any of the ones found in other studies, the lowest and average one fall within the range as reported by these other studies.

4.8 Sensitivity analysis

A sensitivity analysis is performed to determine the influence of changes in the input variables on the values of the output variables. Like Fan et al. (2022) and Jülch (2016), this will be done by varying the value of one input variable at a time according to a certain ratio and evaluate how these changes affect the various output variables. As the output variables will be affected differently for scenarios with integrated PHSS, CAESS, FBESS or LIBESS than those with integrated HESS, two separate sensitivity analyses are performed.

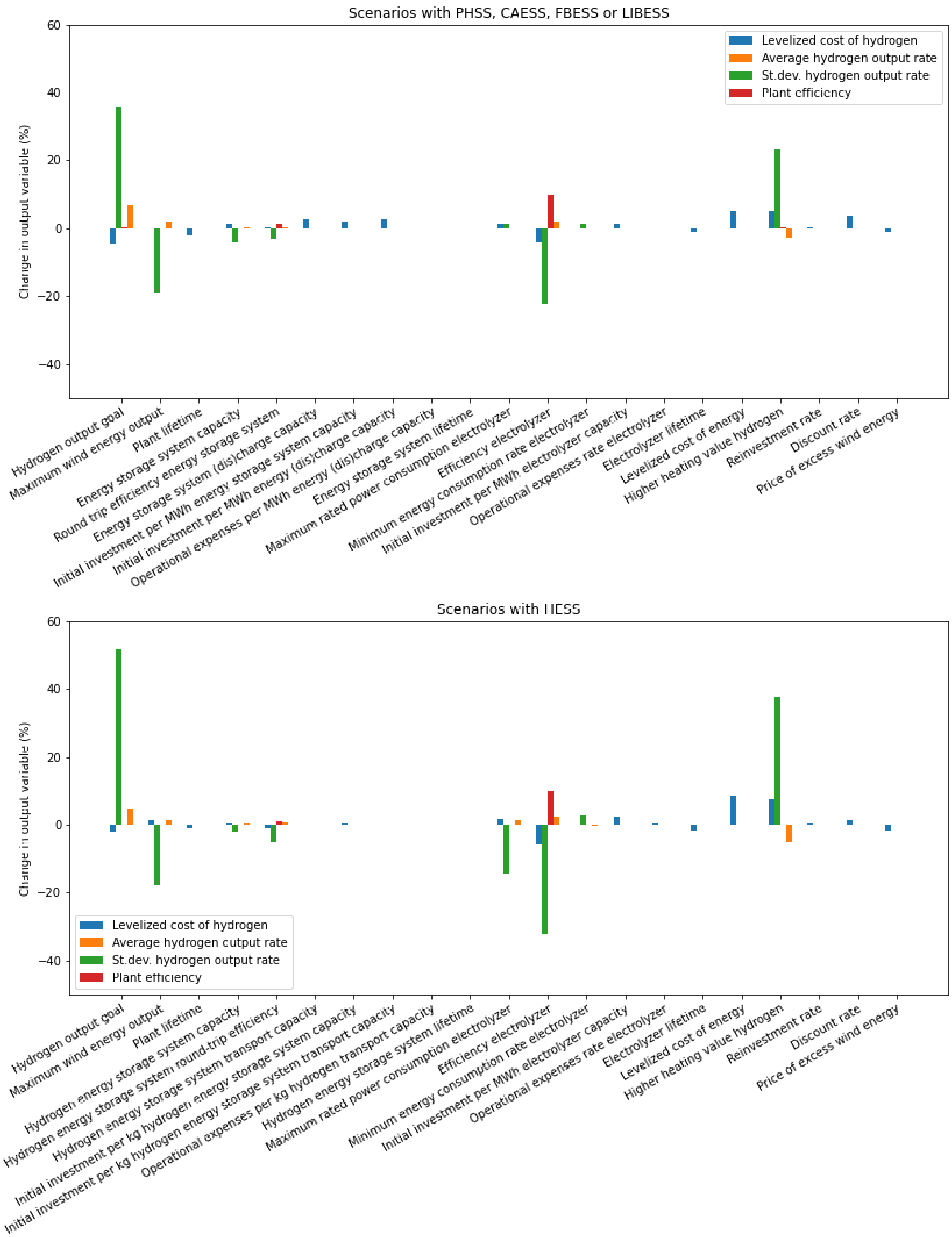

Figure 23: Change in output variables caused by a 10% increase of different input variables

Results of the analysis as depicted in Figure 23 show that the value of each of the performance metrics are influenced mainly by the input values of a small number of variables. One of those values is the *electrolyzer efficiency*. This variable has a significant influence on each of the performance metrics. The *higher heating value of hydrogen* also has a significant influence on most of the performance metrics. However, this value is fixed and will in reality never change. Figure 23 also shows that while calculations for scenarios with PHSS/CAESS/FBESS/LIBESS or HESS can structurally differ, the output variables are influenced by a comparable set of variables in a comparable way.

In section 4.8.1 to 4.8.3, the input variables with the most significant influence on the model outcomes are displayed and discussed. The full set of outcomes of the sensitivity analysis and the base scenarios used can be found in Appendix E: Sensitivity analysis.

4.8.1 Levelized cost of hydrogen

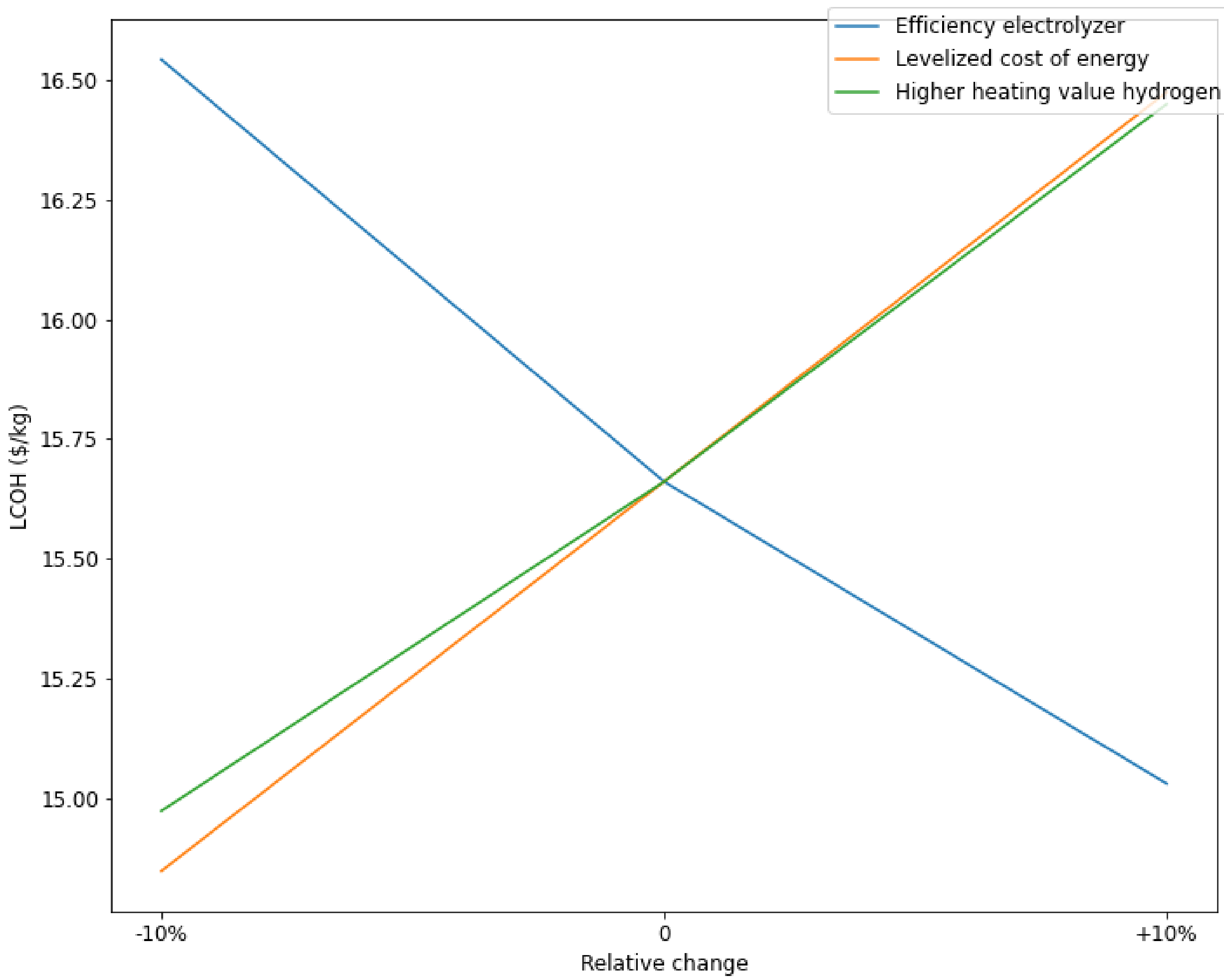

Figure 24: Sensitivity analysis of LCOH and for scenarios with integrated PHSS, CAESS, FBESS or LIBESS

Figure 24 depicts how the *levelized cost of hydrogen* is influenced by changes in the different input variables for scenarios with PHSS, CAESS, FBESS or LIBESS integrated. As can be observed, almost all variables do influence the value for the *levelized cost of hydrogen.* This is in line with the equations in section 3.6.3 as the *levelized cost of hydrogen* is calculated based on the outcomes of almost all other equations in section 3.5. The variables exerting most influence on the value for the *levelized cost of hydrogen* are the *efficiency of the electrolyzer*, the *higher* *heating value of hydrogen* and the *levelized cost of energy.* The large influence of the *efficiency of the electrolyzer* and the *higher heating value of hydrogen* can be explained by the fact that they directly influence the amount of hydrogen that is produced by the wind-hydrogen plant (see *Equation 2).* This amount of hydrogen produced then directly influences the *levelized cost of hydrogen* as this is determined by the total costs divided by the total amount of hydrogen produced (see *Equation 15)*. It should be noted that in reality, the *higher heating value of hydrogen* will never change as this is a standard value. This input variable is still considered in the sensitivity analysis to explore the model behavior in a thorough manner.

The influence of the *levelized cost of energy* can be explained according to *Equation 22* and *Equation 15.* These equations show that the *levelized cost of energy* influence the cost component in calculating the *levelized cost of hydrogen*.

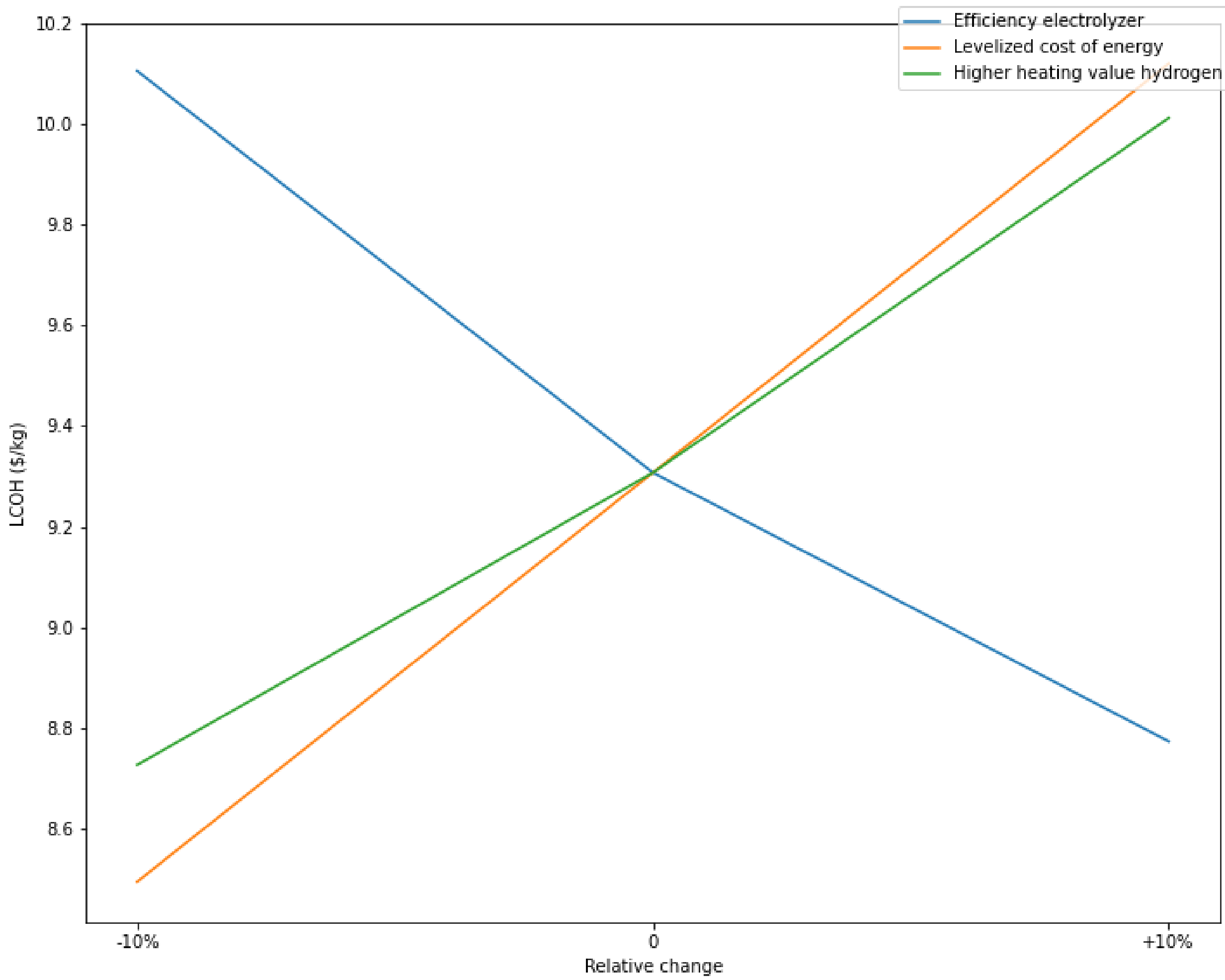

Figure 25: Sensitivity analysis of LCOH and for scenarios with integrated HESS

Figure 25 visualizes how the different input variables influence the *levelized cost of hydrogen* for a wind-hydrogen plant with a HESS integrated. Similar to in the sensitivity analysis for scenarios with PHSS, CAESS, FBESS or LIBESS, the *efficiency of the electrolyzer*, *levelized cost of hydrogen and* the *higher heating value of hydrogen* have the biggest impact on the *levelized cost of hydrogen*.

4.8.2 Average hydrogen output rate

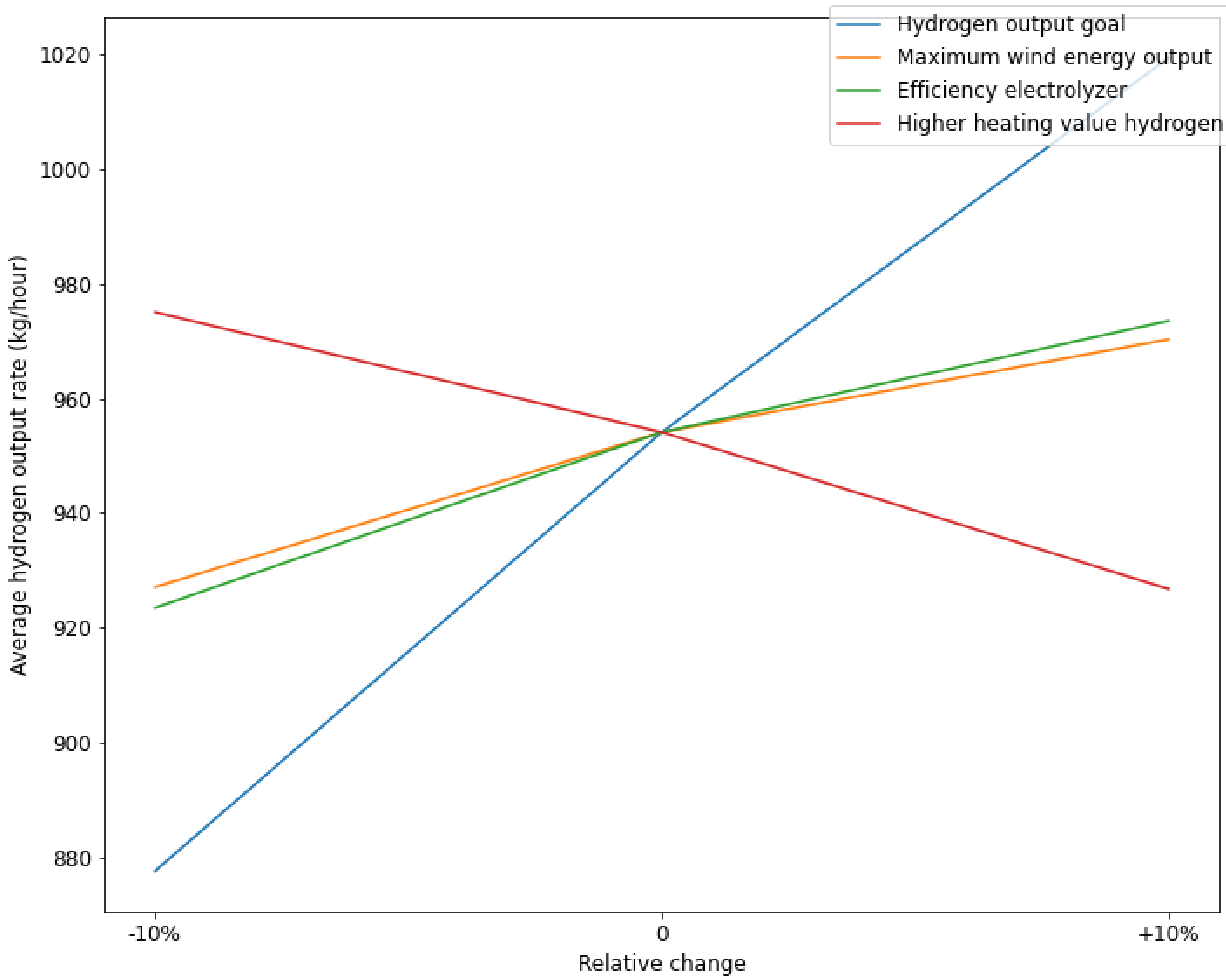

Figure 26: Sensitivity analysis of average hydrogen output rate for scenarios with integrated PHSS, CAESS, FBESS or LIBESS

Figure 26 visualizes how the average *hydrogen output rate* is influenced by changes in the different input variables for scenarios with PHSS, CAESS, FBESS or LIBESS integrated. Not many input variables do not influence the value of the average *hydrogen output rate*. This is because the input values for the financial model do not influence the *hydrogen output rate* at all (see section 3.6.1). Again, changes in the values for the *efficiency of the electrolyzer* and the *higher heating value of hydrogen* have most influence on the output variable of interest. Again, this is because they directly influence the amount of hydrogen produced by the wind-hydrogen plant. After all, the amount of hydrogen produced has a direct relation with the *hydrogen output rate* (see *Equation 1).* The *maximum wind energy output* influences the average *hydrogen output rate* as it influences the amount of energy available for the electrolyzer and the energy storage system (see *Equation 7* and *Equation 3)*. The *hydrogen output goal* acts as a limit for the *hydrogen output rate* (see *Equation 4* and *Equation 6)*, therefore a higher value for the *hydrogen output goal* will allow for a higher *hydrogen output rate* and a lower value for the *hydrogen output goal* will lower the *hydrogen output rate* at a lower value.

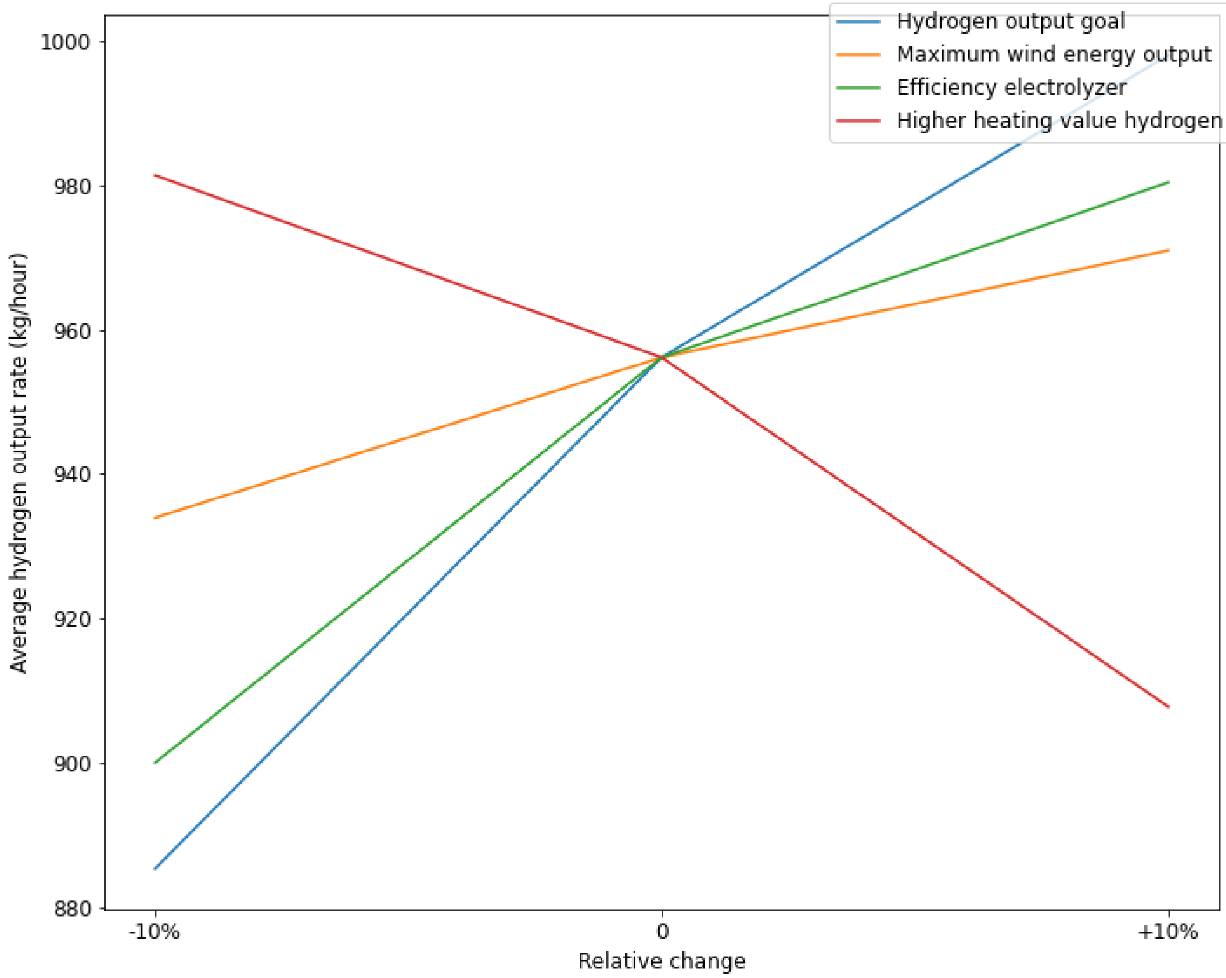

Figure 27: Sensitivity analysis of average hydrogen output rate for scenarios with integrated HESS

Figure 27 depicts the influence of different input values on the average *hydrogen output rate* of a wind-hydrogen plant with a HESS integrated. Like in the sensitivity analysis for scenarios with PHSS, CAESS, FBESS or LIBESS in Figure 26, the the *efficiency of the electrolyzer*, *higher heating value of hydrogen, maximum wind energy output* and *hydrogen output goal* have a substantial influence on the average *hydrogen output rate*.

4.8.3 Standard deviation of hydrogen output rate

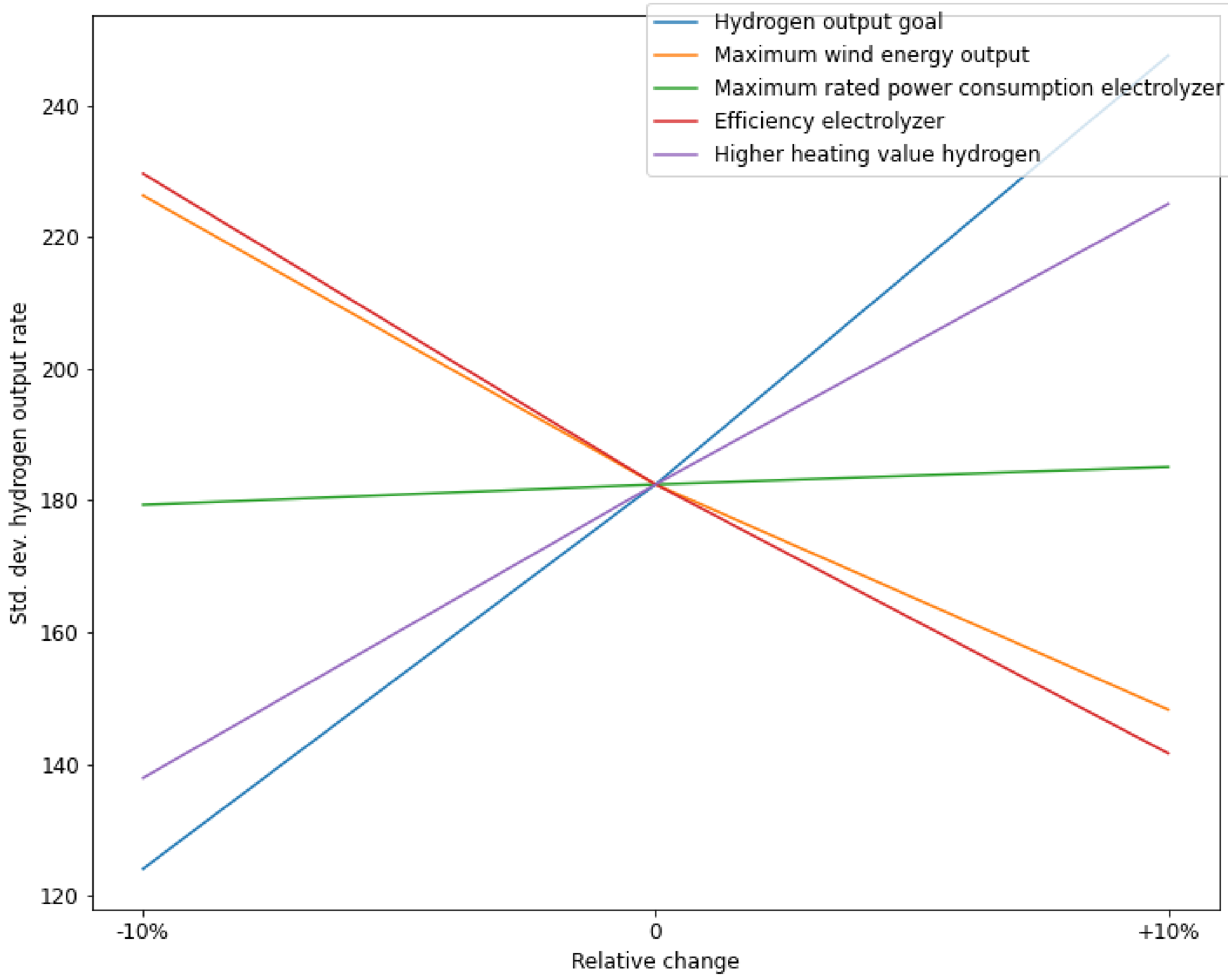

Figure 28: Sensitivity analysis of St.dev. of the hydrogen output rate and for scenarios with integrated PHSS, CAESS, FBESS or LIBESS

Figure 28 shows the influence of different input variables on the standard deviation of the *hydrogen output rate*. The input variable that has most influence on the standard deviation of the *hydrogen output rate* is the *hydrogen output goal*. This input variable acts as a limit for the amount of hydrogen that can be produced (see *Equation 6, Equation 3* and *Equation 2)* and therefore cuts the amount of hydrogen produced off at a stable, lower point when decreased in value. The *maximum wind energy output* has an opposite effect on the standard deviation of the *hydrogen output rate.* When increased, more energy becomes available for hydrogen production and to charge the energy storage system in place (see *Equation 3* and *Equation 10*) and therefore allows the wind-hydrogen plant to reach the *hydrogen output goal* more often, which acts as a stable upper limit for the *hydrogen output rate*. A lower *efficiency of the electrolyzer* results in a lower standard deviation of the *hydrogen output rate* as it lowers the overall production of hydrogen (see *Equation 2).* The opposite reasoning is valid for the effect of the *higher heating value of hydrogen*.

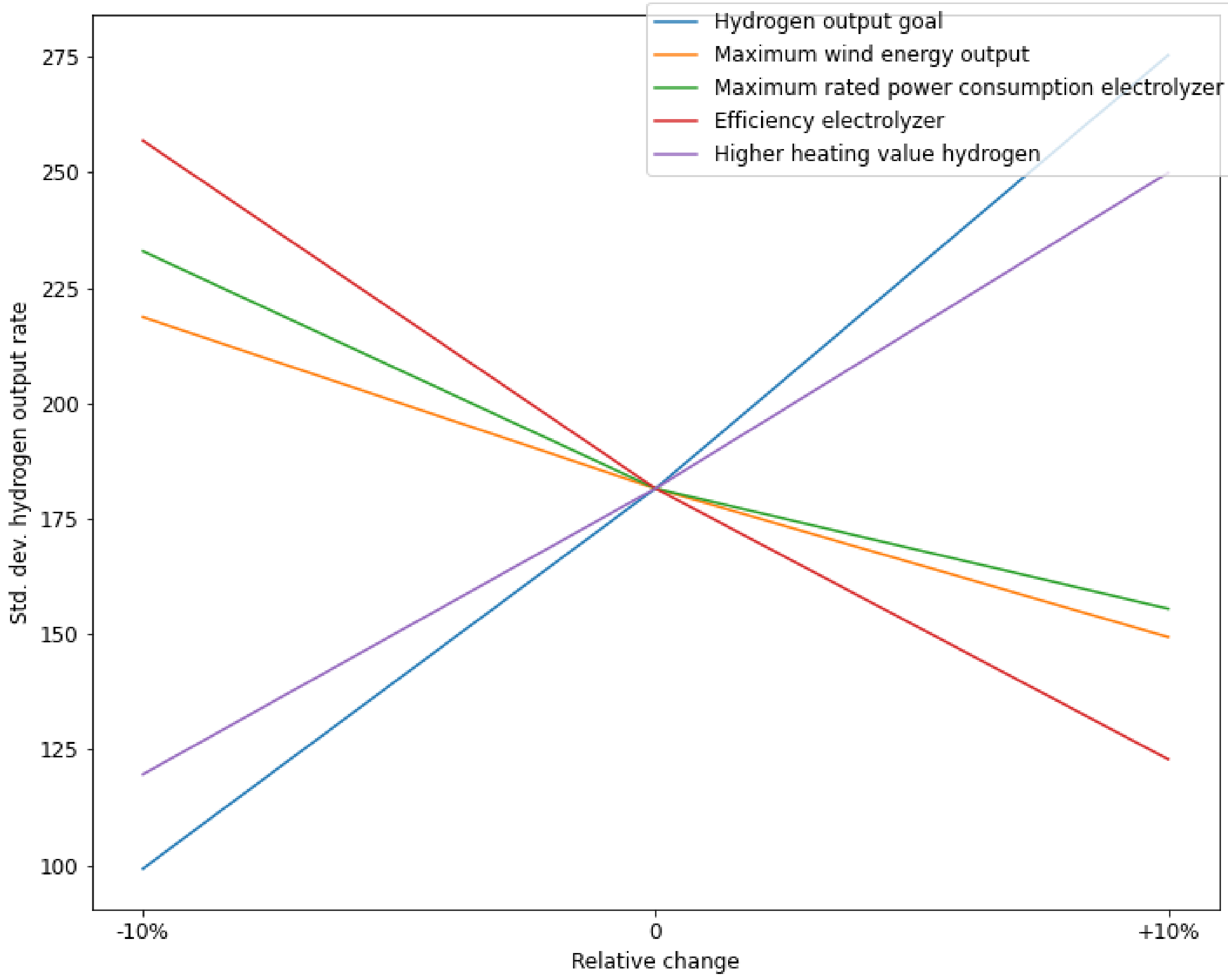

Figure 29: Sensitivity analysis of St.dev. of the hydrogen output rate and for scenarios with integrated HESS

Figure 29 shows the deviation of the *hydrogen output rate.* The variables that have most influence on the standard deviation of the *hydrogen output rate* are the *hydrogen output goal,* the *higher heating value of hydrogen,* the *efficiency of the electrolyzer* and the *maximum wind energy output.* The influence of the *maximum rated power consumption of the electrolyzer* on the standard deviation of the *hydrogen output rate* is higher for wind-hydrogen plants with HESS than those with PHSS, CAESS, FBESS or LIBESS. The reason for this is that wind-hydrogen plants with HESS are restricted by the *maximum rated power consumption of the electrolyzer* in utilizing their storage capacity (See *Equation 13, Equation 1, Equation 2* and *Equation 3*). This is the case as the energy is stored as hydrogen and thus some of the electrolyzer capacity is required for the energy storage process. For wind-hydrogen plants with PHSS, CAESS, FBESS or LIBESS this is not the case. Wind-hydrogen plants with these energy storage systems are only limited by the *(dis)charge capacity* of the energy storage system in utilizing their storage capacity.

4.8.4 Plant efficiency

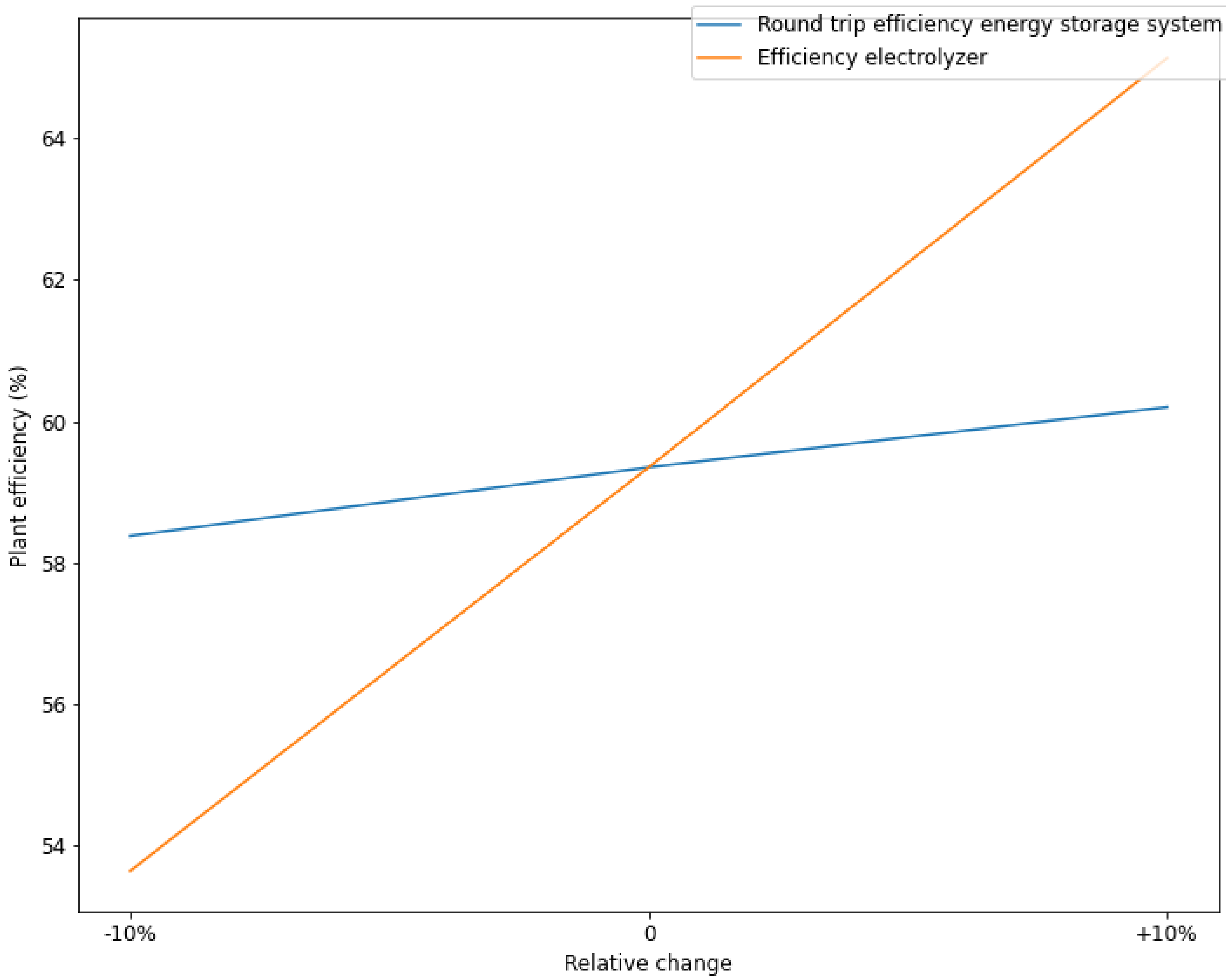

Figure 30: Sensitivity analysis of plant efficiency for scenarios with integrated PHSS, CAESS, FBESS or LIBESS

Figure 30 shows that the *electrolyzer efficiency* has a large influence on the *plant efficiency*. This can be derived from *Equation 2* as it directly influences how much hydrogen the wind-hydrogen plant can generate from a certain amount of energy. Additionally, the round trip efficiency of the energy storage system influences the plant efficiency. This is the case as this value influences the amount of energy that is lost in the process of storing it (see *Equation 8)*

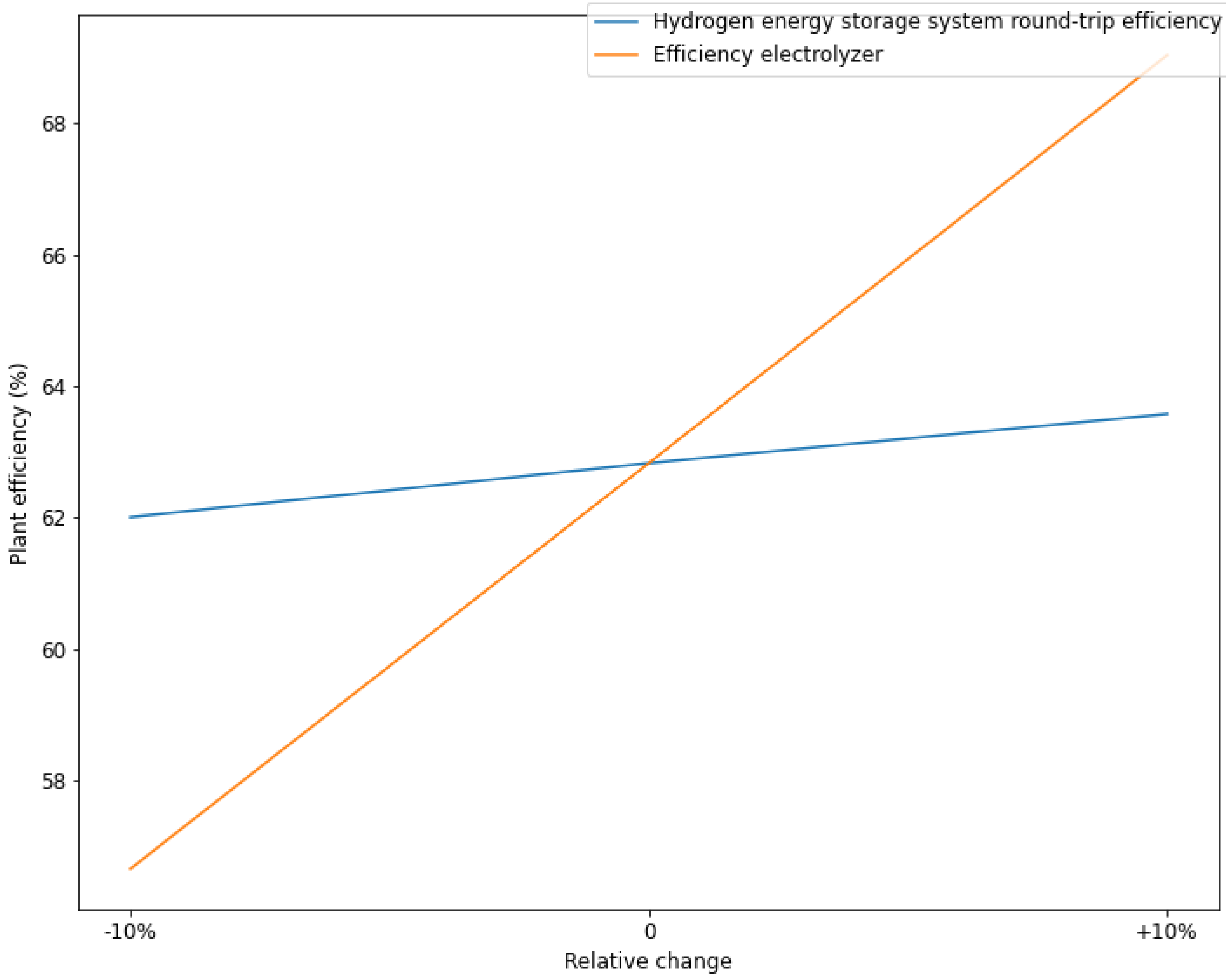

Figure 31: Sensitivity analysis of plant efficiency for scenarios with integrated HESS

Figure 31 depicts how the different input variables influence the *plant efficiency* of a wind-hydrogen plant with an integrated HESS. Similar to in Figure 30, the plant is mainly influenced by the *efficiency of the electrolyzer* and the *hydrogen energy storage system round-trip efficiency.*

5. Discussion

This section discusses the results as reported in chapter 4. In section 5.1 the key findings are highlighted and the research question is answered. Section 5.2 elaborates on the societal and scientific relevance of this study. Section 5.3 discusses the practical implications of the results for the renewable hydrogen policy of the EU. Finally, in section 5.4, the limitations of the study are discussed and suggestions are done for future research in section 5.5.

5.1 Performance of wind-hydrogen plants with energy storage systems

Results of this study show that the renewable hydrogen output of a hydrogen plant connected to a variable power source is lower than that of a hydrogen plant receiving a stable power supply from the grid. Additionally, the output of a hydrogen plant connected to a variable power source is much less consistent than that of a hydrogen plant connected to the grid. This can be problematic when supplying hydrogen to industry as many processes require or perform better when receiving a stable input of hydrogen.

The negative effects of connecting a hydrogen plant directly to a variable power source can be partly mitigated by integrating an energy storage system. An energy storage system can increase the hydrogen output rate of a wind-hydrogen plant by temporarily storing energy that cannot immediately be utilized by the electrolyzer in the plant. However, the hydrogen output rate would often still be lower than that of a hydrogen plant connected directly to the grid. The integration of an energy storage system in a wind-hydrogen plant also stabilizes the hydrogen output rate as energy generated during wind-peaks can be stored for times when there is a deficiency of wind energy available. This output would, in many cases, still be less stable than that of a hydrogen plant with a grid connection.

Besides partially mitigating the negative effects for a hydrogen of being directly connected to a variable power source, energy storage systems also introduce additional negative effects. The integration of an energy storage system causes a decrease in the efficiency of a wind-hydrogen plant. This decrease in efficiency is caused by the fact that energy is lost in the process of storing it and can therefore not be used for hydrogen production. Not only becomes the production of hydrogen in a wind-hydrogen plant with an integrated energy storage system less efficient, but it also becomes more expensive. This increase in costs is partly caused by the fact that more energy is needed to produce the same amount of hydrogen. Also, integrating an energy storage system increases the cost for a wind-hydrogen plant.

The following question has been posed to address the discovered knowledge gap:

"How does the integration of energy storage systems influence the performance of wind-hydrogen plants?"

As the performance of a wind-hydrogen plant has been defined as the average hydrogen output rate, standard deviation of the hydrogen output rate, plant efficiency and the levelized cost of hydrogen, this question can be answered based on the findings discussed above.

In short, the integration of an energy storage system increases hydrogen output and decreases the standard deviation of the hydrogen output. This can both be seen as an improvement in the performance. At the same time, the efficiency of a wind-hydrogen plant is decreased by the introduction of an energy storage system and the levelized cost of hydrogen is increased. These developments can be seen as negative for the performance of a wind-hydrogen plant.

The fact that the integration of an energy storage system in a wind-hydrogen plant has both positive and negative effects on its performance means there is a trade-off involved. This trade-off needs to be made per situation and depends on whether a higher and more stable output have priority over more efficient and cheaper hydrogen production.

5.1.1 Suitability of specific energy storage systems

Another trade-off can be identified when comparing different types of energy storage systems. Of all energy storage systems evaluated in this study, wind-hydrogen plants with LIBESS show the highest and most stable hydrogen production. At the same time, integrating LIBESS in a wind-hydrogen plant is relatively very expensive and makes for a high levelized cost of hydrogen. A cheaper and more efficient energy storage system is HESS. However, wind-hydrogen plants with HESS have a lower and less stable hydrogen output than those with LIBESS. This means that when optimizing the design of a wind-hydrogen plant, a choice has to be made between maximizing output and stability or maximizing efficiency and minimizing cost.

There are two main reasons LIBESS outperforms HESS in terms of size and stability of hydrogen production despite its lower round-trip efficiency. The first reason is its large energy (dis)charge capacity, allowing it to store a large amount of energy in a short amount of time. The second reason is that, as explained in section 4.8.3, HESS are also restricted by the maximum power consumption of the electrolyzer in their ability to store energy whereas LIBESS are not.

It should be noted that the difference in hydrogen production cost for wind-hydrogen plants with LIBESS and wind-hydrogen plants with other energy storage systems is so substantial, that it is unsure whether there are situations in which the use of LIBESS is feasible. When comparing the average levelized cost of hydrogen for wind-hydrogen plants with LIBESS to that of wind-hydrogen plants with HESS, that of wind-hydrogen plants with LIBESS is more than a hundred times as high.

The fact that wind-hydrogen plants with LIBESS integrated perform best in terms of volume and stability of hydrogen output is surprising as LIBESS is deemed unfit for seasonal energy storage in literature. The reason LIBESS was included in this study was to serve as a benchmark for energy storage systems that were deemed fit for seasonal energy storage, not because it was expected to perform well. Criteria for seasonal energy storage are a low self-discharge rate and a high energy density (Beaudin et al., 2010; Díaz-González at al., 2012; Lund et al., 2015). The fact that self-discharge is not considered in the used model could explain the fact that the results indicate that LIBESS performs so well. After all, LIBESS has a relatively high self-discharge rate while that of HESS, PHSS and CAESS is neglectable and that of FBESS is relatively low when compared to that of LIBESS (Rahman et al., 2020). If LIBESS were to be disqualified because of its high self-discharge rate, PHSS is the energy storage system resulting in the highest and most stable hydrogen output rate.

Besides their influence on the performance metrics as considered in this study, other, often qualitative, aspects of different energy storage systems are also relevant when comparing them. As described in section 2.2, the locations where PHSS and CAESS can be deployed are limited. When deployed on a large scale, PHSS needs a large water basin to operate and therefore requires a sizeable piece of land that is eligible to be flooded. This limits the locations where a wind-hydrogen plants with PHSS can be constructed. CAESS also requires a location with specific characteristics. Instead of a water basin, it needs an underground cavern to build up air pressure. The fact that PHSS and CAESS can only be deployed at specific locations may impact their useability in wind-hydrogen plants in a negative way. When the use of PHSS and CAESS restricts the construction of a wind-hydrogen plant to locations relatively far away from the users of the hydrogen it produces, more infrastructure will be required to deliver this hydrogen. This will ultimately drive up the cost.

A similar problem may arise for LIBESS when used on a large scale. When large LIBESS are constructed, additional circuitry is required to guarantee the safety and protection around them. This can form a hurdle when deployed at certain locations. For the same reason as PHSS and CAESS, this may drive up the costs of the infrastructure for delivery when integrated in a wind-hydrogen plant.

The fact that PHSS requires a large surface of land that can be flooded is not the only factor limiting its current useability in a wind-hydrogen plant. As mentioned in section 2.2, when build at a large scale, the construction time for PHSS can be relatively long. In the context of reaching the renewable hydrogen goals in the Fit for 55 this can be problematic. After all, these goals are formulated for 2030 and will thus require sufficient renewable hydrogen production capacity to be installed before then.

5.1.2 Design of wind-hydrogen plants

Besides insights in how the integration of different energy storage systems influences the performance of wind-hydrogen plants, insights in the influence of other design choices have also been gained. When designing a wind-hydrogen plant, it can be beneficial for the amount and stability of the hydrogen output to contract a higher amount of wind capacity. In the end this can also result in a lower levelized cost of hydrogen as it causes an increase in hydrogen output. A potential negative effect of larger wind capacity is a lower plant efficiency. When an energy storage system with a relatively low round-trip efficiency is installed, the plant efficiency can decrease as a large portion of the extra energy will be lost when stored.

Not only does the size of the wind park connected to the wind-hydrogen plant impact its performance, but the location of the wind park does also. Results show that wind-hydrogen plants connected to an offshore wind park produce more hydrogen on average at a more stable rate than wind-hydrogen plants connected to an onshore wind park. As offshore wind parks generate more energy on average than onshore wind parks, they might result in a lower plant efficiency when an energy storage system is in place.

5.2 Scientific and societal relevance

The results of this study contribute to the body of knowledge about hydrogen production and energy storage systems. While a broad body of literature exists on the topic of wind-hydrogen plants and on the topic of energy storage systems, the available literature on wind-hydrogen plants with integrated energy storage systems is very limited. Only one article on this topic was retrieved in the literature review performed. Some of the findings in this article by Guo & Sepanta (2021) are that the use of energy storage systems can improve the performance of a wind-hydrogen plant and that the sizing of energy storage system, wind park and electrolyzer affect the performance of a wind-hydrogen plants. Besides reconfirming these findings, the results in chapter 4 add to the body of knowledge on the topic of wind-hydrogen plants with energy storage systems. They provide insights in how the integration of different energy storage systems affect the performance of wind-hydrogen plants. Also, they compare different energy storage systems and their performance when being integrated in a wind-hydrogen plant.

The insights gained from this study are also societally relevant. With the insights gained, wind-hydrogen plants can be designed in a way that maximizes yield and stability of the output or in a way that maximizes efficiency and minimizes cost. All of this can be beneficial for the reduction of the use of fossil fuels by substituting them with renewable hydrogen. Ultimately this will lead to a decrease in greenhouse gas emissions and help overcome the grand challenge that climate change is. The gained insights can also be used by policy-makers evaluate policies on the production of renewable hydrogen. For the realization of the renewable hydrogen goals of the policy-makers within the European Commission, private companies will need to be stimulated to produce and use renewable hydrogen. To make this happen, adequate policies are required. To evaluate the influence of these policies, such as the temporal correlation requirement of RED II, on the production and use of renewable hydrogen, the insights from this study can be used. An example of a policy evaluation based on the results of this study is provided in section 5.3.

The relevance of modelling and simulation studies for the development of commercial renewable hydrogen production plants was also demonstrated during the internship connected to this study. As part of this internship, a series of simulation experiments have been performed with a similar model to that described in section 3.6. While using a similar model, the goal of the simulation experiments was different from that in this study. Instead of performing experiments to make generalizable claims, they were performed to gain insight in the performance of specific wind-hydrogen plats designs and to further optimize these designs. The outcomes of these experiments prove to be valuable when judging whether specific configurations of hydrogen plants could be suitable to meet the renewable hydrogen requirements of the client. Being able to define a set of viable configurations of wind-hydrogen plants early on helped to speed up the project and thereby also the development of new renewable hydrogen production capacity.

5.3 European Union hydrogen policy

Based on the results of this study, it can be evaluated how the temporal correlation requirement as defined in RED II by the European Commission would impact the performance of renewable hydrogen plants. Also, insights could be gained on whether these effects would be beneficial for reaching the renewable hydrogen goals as defined by the European Commission in the Fit for 55 package.

The temporal correlation requirement requires hydrogen to be generated with energy from a variable power source to be qualified as renewable. The results show that the production of hydrogen from a variable power source is lower and less stable than that hydrogen production from a continuous power source. Both these effects could be counterproductive for reaching the renewable hydrogen goals as stated in the Fit for 55 package. One of the defined goals is to produce 10 million tonnes renewable hydrogen by 2030. As hydrogen production powered by a variable source generates a lower yield, this goal will become harder to reach when temporal correlation is required. Another goal is for half of the hydrogen used in industry to be renewable. As a variable output of renewable hydrogen disadvantageous for many industrial processes, this goal also might become harder to reach if the requirement for temporal correlation is imposed. After all, the use of renewable hydrogen would become less attractive.

The negative effects of temporal correlation on reaching the renewable hydrogen goals in the Fit for 55 package can be mitigated by the integration of energy storage systems in wind-hydrogen plants. These energy storage systems cause an increase in size and stability of hydrogen output produced with energy from a variable source. However, the side effects of the integration of these energy storage systems could in turn also be counterproductive for reaching the renewable hydrogen goals of the Fit for 55 package.

The introduction of energy storage systems in renewable hydrogen plants also makes the production more expensive. This could make it less attractive for the industry to use renewable hydrogen instead and thereby hinder the goal for half of all hydrogen used by the industry to be renewable. Also, the fact that energy storage systems cause a decrease the efficiency of a wind-hydrogen plants can make it harder to reach the goal to produce 10 million tonnes of renewable hydrogen by 2030. An additional issue with the fact that hydrogen production becomes more costly when done in compliance with the temporal correlation requirement is that it affects the economic viability of hydrogen production. As stated in section 2.3, an increase in production cost of hydrogen can result in high barriers for new hydrogen producers to enter the market. This could also hinder the goal of the to produce 10 million tonnes of renewable hydrogen by 2030.

Not only is the temporal correlation requirement counterproductive for reaching the renewable hydrogen goals of the Fit for 55 package, it is also partially conflicting with the policy theory behind the RED II requirements for the production of RFNBOs. As mentioned in section 2.3, the general policy theory behind the proposal of these requirements is that when they are fulfilled, the contribution to the reduction of greenhouse gas emissions by the use of RFNBOs is ensured. However, as the temporal correlation requirement can make the production and use of RFNBOs less attractive, it may impact the greenhouse gas reduction by the use of RFNBOs in a negative way.

When assessing the policy theories behind the individual RED II requirements for the production of RFNBOs, it becomes clear that there is another conflict. The policy theory behind the additionality requirement is that it will serve as a mean to the end of stimulating the use of renewable energy. However, the additionality requirement is not the only one influencing the use of renewable energy. The temporal requirement can also influence the use of renewable energy as it makes the production of hydrogen with renewable energy less attractive. This shows that the current formulation of the RED II requirements fails to address the complexity that the different requirements may influence the goals of other requirements in unwanted ways.

As introducing a temporal correlation requirement can be counterproductive for reaching the renewable hydrogen goals of the Fit for 55 package, a policy recommendation can be made for the European Commission to explore different requirements to ensure hydrogen is produced in a renewable manner. This could create possibilities to let hydrogen producing parties purchase renewable energy on the spot market, outside of their PPAs. This purchased energy could then stabilize hydrogen production when the energy producing parties in their PPAs are not able to generate a sufficient amount of energy for a stable hydrogen production. To ensure this purchased energy is renewable, other Guarantee of Origin schemes as discussed by Velazquez Abad & Dodds (2020) could be considered.

When assessing the suitability of potential Guarantee of Origin schemes to replace the temporal correlation requirement, attention should be paid to how they influence the feasibility of the renewable hydrogen goals in the Fit for 55. Another important aspect to consider whether these schemes are in line with the general policy theory with the RED II requirements and how they influence the goals behind the other requirements. Lastly, it should address the challenges of developing an Guarantee of Origin scheme as listed in section 2.3.

When an alternative for the temporal correlation requirement is identified, it can be included in the newer version of the EU Renewable Energy Directive (RED III). This way it can be introduced in the negotiations with the European Parliament and ultimately be translated to legislation.

5.4 Limitations

When interpreting the results of this study, several limitations should be noted. As mentioned in section 3.9, various assumptions have been made to model the efficiency of an electrolyzer in a robust manner. The sensitivity analysis in section 4.8 shows that all the performance metrics considered are relatively sensitive to changes in the electrolyzer efficiency. This means that if the made assumptions are in any way not valid, it can have a large impact on the validity on the outcomes of this study.

A second limitation stems from the fact that self-discharge of energy storage systems is not accounted for in the model. Of all energy storage systems considered, LIBESS has the highest reported self-discharge rate (Rahman et al., 2020). This could be problematic as according to the model outcomes, wind-hydrogen plants with LIBESS have the highest and most stable hydrogen output. If the influence of including self-discharge in the model would be significant, LIBESS might not result in the highest and most stable hydrogen production. Similarly, the response time of the various energy storage systems is not accounted for in the constructed model. This can also affect the outcomes of the study.

Another limitation is based on the fact that a limited number of locations of wind parks have been considered. As shown in section 4.8, the maximum wind energy output has a significant influence on some of the performance metrics. Indirectly this means that these performance metrics are influenced significantly by the amount of wind energy available. As the amount of wind energy can vary greatly based on location, it is unsure whether the results of this study are generalizable for locations all over the world.

Lastly, as mentioned in section 3.9, the designs of the hydrogen plants considered in this study have not been optimized. Instead, a more exploratory approach has been taken. This makes that the performance of hydrogen plants in this study could be portrayed as relatively poor and can make the results of this study harder to compare with studies that do consider optimized hydrogen plant designs. Also, the reported performance of wind-hydrogen plants in this study may not always be representative of those that would be built in the real world as the design for these wind-hydrogen plants is expected to be optimized to some degree.

5.5 Further research

Reflecting on the results of this study, a number of suggestions can be done for further research. Some of these suggestions follow directly from the limitations of this study. For example, research could be done on the performance of a wind-hydrogen plant with an energy storage system in which only one specific electrolyzer is considered. This disqualifies the need for a generalizable model and thus allows for a model that captures the electrolyzer efficiency is a more realistic manner. A similar suggestion can be done for a study in which the self-discharge rate and response time of energy storage systems is considered when determining the performance of wind-hydrogen plants with energy storage systems. Also, a study could be performed where more different locations of wind parks is considered when looking at the performance of wind-hydrogen plants with energy storage systems.

Apart from suggestions that address the limitations of this study, suggestions based on different research scopes can also be made. Wind energy is only one of the different renewable sources that can be used to produce renewable hydrogen. A study looking into hydrogen plants powered by for example solar energy might yield different results. Also, research could be done focusing on other aspects of RED II than on the temporal correlation requirement. For example, one could look into the effects of geographical correlation on the availability and cost of energy to be used by renewable hydrogen plants. Lastly, a suggestion could be made to look into the effects of the integration of energy storage systems in production chains of other RFNBOs than hydrogen.

Suggestions for research that relate to the development of an alternative for the temporal correlation requirement can also be done. In this context, a number of potential alternatives could be evaluated in terms of how these would influence the feasibility of the renewable hydrogen goals of the Fit for 55 package. Additionally, research could be done that assesses potential alternatives for the temporal requirement in terms of how well they address the challenges in the development of a Guarantee of Origin scheme as discussed by Velazquez Abad & Dodds (2020).

6. Conclusion

In this study, the effect of the integration of energy storage systems on the performance of wind-hydrogen plant has been examined. The need for these storage systems could be introduced temporal correlation requirements for the production of renewable hydrogen as proposed by the European Commission. These requirements have been introduced to ensure the renewable origin of hydrogen. Simulation results of the study show that while the integration of energy storage systems enhances yield and stability of renewable hydrogen production from wind energy, it also causes a decrease in plant efficiency and an increase in hydrogen production costs. This means there is a trade-off involved between yield and stability on one side and efficiency and costs on the other side when deciding whether to integrate an energy storage system wind-hydrogen plant.

Of the different energy storage systems examined, lithium-ion batteries are most fit for increasing the yield and stability of a wind-hydrogen plant. However, the use of these batteries makes the production of hydrogen relatively expensive. The use of hydrogen energy storage systems results in the most efficient and cheapest renewable hydrogen production. This means that when deciding which energy storage system to integrate in a wind-hydrogen plant, a similar trade-off is at play between yield and stability on one side and efficiency and costs on the other side.

The findings of this study contribute to existing literature as is gives insight in the influence of energy storage systems on the performance of wind-hydrogen plants. Additionally, different energy storage systems have been compared in terms of how they influence this performance.

Limitations of this study stem from modelling choices that may impact the accuracy of the results. This is the case as the efficiency of electrolyzers has been considered static and the self-discharge rate and response time of energy storage systems have not been included in the model. Other limitations come from the fact that only a limited amount of wind data has been utilized when performing experiments. Also, the fact that the considered designs of wind-hydrogen plants were not optimized can give a distorted image of the performance of wind-hydrogen plants in general.

Suggestions for further research can be done based on the mentioned limitations. Studies can be performed in which the efficiency of the electrolyzer is modelled in a dynamic fashion, in which the self-discharge rate of energy storage systems is included and where a broader range of wind data is considered. Also, studies could be done that look into the use of other energy sources than wind or that evaluate the effects of other requirements for renewable hydrogen production than temporal correlation. Lastly, research could be performed to evaluate how alternative policies guaranteeing the renewable origin of hydrogen would impact the performance of wind-hydrogen plants.

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Appendix A: Overview of performance metrics

In table A1, various metrics used in literature to evaluate the performance of hydrogen plants powered with wind energy are listed. Metrics considering the performance of parts of the plant will are not considered to be used as these cannot be directly used to assess the performance of a wind-hydrogen plant as a whole. Besides the names of the metrics, a description will be given as well as the unit in which the metric can be expressed, the performance aspect the metric relates to and the literature where the metric is found. A metric is considered to review the performance of a wind-hydrogen plant in the economical aspect if it relates to the financial performance of a wind-hydrogen plant. If a metric relates specifically to the physical performance of a wind-hydrogen plant, it is considered to review the technical aspect of a wind-hydrogen plant.

Table A1: Performance metrics used in literature

Metric	Description	Aspect	Source
Net Present Cost (NPC)	"The total NPC cost refers the present value of all costs of the components over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime." (Chen et al., 2021)	Economical	Chen et al. (2021)
Levelized cost of hydrogen (LCOH)	The annualized cost of the whole system divided by the total amount of hydrogen supplied per year (Chen et al., 2021).	Economical	Chen et al. (2021), Olateju et al. (2014), Won et al. (2017), Khouya (2020), Olateju et al. (2016)
Netto energy consumed from the grid	"The assistance of the grid is controlled to guarantee the rated operation of the electrolyzer independently of the variations of the wind resource."	Economical	García Clúa et al. (2018)
Hydrogen output rate	Amount of hydrogen delivered in a certain timeframe	Technical	Guo & Sepanta (2021), Sopian et al. (2009)

Capital cost	Total capital cost for the hydrogen production operation over its lifespan	Economical	Won et al. (2017)
Annualized capital cost	Yearly capital cost for the hydrogen production operation	Economical	Won et al. (2017)
Operating cost	Yearly operating cost for the hydrogen production operation	Economical	Won et al. (2017)
Raw material cost	Yearly cost of the raw materials required for the hydrogen production operation	Economical	Won et al. (2017)
Byproduct credit	Yearly credit for the by products produced by the hydrogen production operation	Economical	Won et al. (2017)
Hydrogen selling price for NPV = 0	Hydrogen selling price required to keep the net present value of the hydrogen plant is zero	Economical	Bernal-Agustín & Dufo-López (2010)
Hydrogen selling price to recover investment	Hydrogen selling price required to recover the invested capital in the plant in a certain amount of time	Economical	Bernal-Agustín & Dufo-López (2010)
Efficiency	Amount of hydrogen produced from a certain amount of energy	Technical	Khouya (2020), Guo & Sepanta (2021)

Appendix B: Overview of model variables

Table B1: Model variables including type and unit

Symbol	Name	Type	Unit
$\mu_{H_2,t}$	Hydrogen output rate	Output	kg
$\mu_{H_2 prod,t}$	Hydrogen production rate	Intermediate	kg
$\mu_{H_2 SS\ in,t}$	Hydrogen energy storage system inflow	Intermediate	kg
$\mu_{H_2 SS\ out,t}$	Hydrogen energy storage system outflow	Intermediate	kg
$E_{elec,t}$	Energy consumption electrolyzer	Intermediate	MWh
η_{elec}	Efficiency electrolyzer	Input	(-)
E_{H_2}	Higher heating value hydrogen	Input	MWh/kg
$E_{wind,t}$	Wind energy	Intermediate	MWh
$E_{wind,max}$	Maximum wind energy output	Input	MWh
$E_{wind\ uti,t}$	Wind energy capacity utilization	Input	(-)
$E_{ss\ out,t}$	Energy storage system discharge	Intermediate	MWh
$E_{ss\ in,t}$	Energy storage system charge	Intermediate	MWh
$E_{elec,min}$	Minimum energy consumption electrolyzer	Intermediate	MWh
$R_{elec,min}$	Minimum energy consumption rate electrolyzer	Input	(-)
$E_{elec\ max,t}$	Maximum power consumption electrolyzer	Intermediate	MWh
$E_{elec,cap}$	Maximum rated power consumption electrolyzer	Input	MWh
$E_{elec,goal}$	Energy consumption goal electrolyzer	Intermediate	MWh
$E_{ss,t}$	Energy in storage system	Intermediate	MWh
$E_{ss,charge}$	Energy storage system (dis)charge capacity	Input	MWh
η_{ss}	Round trip efficiency energy storage system	Input	(-)
$\mu_{H_2,goal}$	Hydrogen output goal	Input	kg
$E_{ss,max}$	Energy storage system capacity	Input	MWh

$M_{H_sss,t}$	Hydrogen in hydrogen energy storage system	intermediate	kg
$\mu_{H_2ss,trans}$	Hydrogen energy storage system transport capacity	Input	kg
η_{H_2ss}	Hydrogen energy storage system round-trip efficiency	Input	(-)
$M_{H_sss,max}$	Hydrogen energy storage system capacity	Input	kg
η_{plant,T_p}	Plant efficiency	Output	(-)
$LCOH_{T_p}$	Levelized cost of hydrogen	Output	$/kg
I_i	Initial investment costs	Intermediate	$
I_t	Investment costs	Intermediate	$
O_t	Operational costs	Intermediate	$
E_t	Energy costs	Intermediate	$
i	Discount rate	Input	(-)
T_p	Plant lifetime	Input	years
$I_{MWh,el}$	Initial investment per MWh electrolyzer capacity	Input	$/MWh
$I_{MWh,ss}$	Initial investment per MWh energy storage system capacity	Input	$/MWh
$I_{MWh/t,ss}$	Initial investment per MWh energy (dis)charge capacity	Input	$/MWh
I_{kg,H_2ss}	Initial investment per kg hydrogen energy storage system capacity	Input	$/kg
$I_{kg/t,H_2ss}$	Initial investment per kg hydrogen energy storage system transport capacity	Input	$/kg
I_{el}	Electrolyzer investment	Intermediate	(-)
I_{ss}	Energy storage system investment	Intermediate	(-)
I_{H_2ss}	Hydrogen energy storage system investment	Intermediate	(-)
T_{el}	Electrolyzer lifetime	Input	years
T_{ss}	Energy storage system lifetime	Input	years
T_{H_2ss}	Hydrogen energy storage system lifetime	Input	years

R_r	Reinvestment rate		(-)
$O_{r,el}$	Operational expenses rate electrolyzer	Input	(-)
$O_{MWh/t,ss}$	Operational expenses per MWh energy (dis)charge capacity	Input	$/MWh
$O_{kg/t,H_2ss}$	Operational expenses per kg hydrogen transport capacity	Input	$/kg
$E_{wind,t}$	Excess wind energy	Intermediate	MWh
$S_{E,ex}$	Sales of excess wind energy	Intermediate	MWh
$P_{E,ex}$	Price of excess wind energy	Input	$/MWh
$LCOE$	Levelized cost of energy	Input	$/kg

Appendix C: Model input

Section C1 and C2 contain input values used for simulation experiments. Values marked with (a) have been based on the average of a range.

C1. Energy storage systems

PHSS

Table C1: Input values for scenarios with PHSS

Symbol	Name	Value	Source
$E_{ss,max}$	Energy storage system capacity	$50 \times \mu_{H_2,goal} \times E_{H_2}/100 \times \mu_{H_2,goal} \times E_{H_2}$	(-)
η_{ss}	Round trip efficiency energy storage system	65/80	Rahman et al. (2020)
$E_{ss,charge}$	Energy storage system (dis)charge capacity	$2 \times \mu_{H_2,goal} \times E_{H_2}$	Rahman et al. (2020)
$I_{MWh,ss}$	Initial investment per MWh energy storage capacity	70.5000 (a)	Rahman et al. (2020)
$I_{MWh/t,ss}$	Initial investment per MWh energy (dis)charge capacity	2.541.700 (a)	Rahman et al. (2020)
$O_{MWh/t,ss}$	Operational expenses per MWh energy (dis)charge capacity	6.000 (a)	Rahman et al. (2020)
T_{ss}	Energy storage system lifetime	45 (a)	Da Silva Lima et al. (2021).

CAESS

Table C2: Input values for scenarios with CAESS

Symbol	Name	Value	Source
$E_{ss,max}$	Energy storage system capacity	$50 \times \mu_{H_2,goal} \times E_{H_2}/100 \times \mu_{H_2,goal} \times E_{H_2}$	(-)
η_{ss}	Round trip efficiency energy storage system	41/75	Rahman et al. (2020)
$E_{ss,charge}$	Energy storage system (dis)charge capacity	$2 \times \mu_{H_2,goal} \times E_{H_2}$	Rahman et al. (2020)
$I_{MWh,ss}$	Initial investment per MWh energy storage capacity	117.000 (a) (aboveground)	Rahman et al. (2020)

$I_{MWh/t,ss}$	Initial investment per MWh energy (dis)charge capacity	930.500 (a) (aboveground)	Rahman et al. (2020)
$O_{MWh/t,ss}$	Operational expenses per MWh energy (dis)charge capacity	3.000 (a)	Rahman et al. (2020)
T_{ss}	Energy storage system lifetime	25 (a)	Da Silva Lima et al. (2021)

FBESS

Table C3: Input values for scenarios with FBESS

Symbol	Name	Value	Source
$E_{ss,max}$	Energy storage system capacity	$50 \times \mu_{H_2,goal} \times E_{H_2}/100 \times \mu_{H_2,goal} \times E_{H_2}$	(-)
η_{ss}	Round trip efficiency energy storage system	60/85	Rahman et al. (2020)
$E_{ss,charge}$	Energy storage system (dis)charge capacity	$\frac{E_{ss,max}}{12} / \frac{E_{ss,max}}{2}$	Rahman et al. (2020)
$I_{MWh,ss}$	Initial investment per MWh energy storage capacity	611.000 (a)	Rahman et al. (2020)
$I_{MWh/t,ss}$	Initial investment per MWh energy (dis)charge capacity	1.066.500 (a)	Rahman et al. (2020)
$O_{MWh/t,ss}$	Operational expenses per MWh energy (dis)charge capacity	27.500 (a)	Rahman et al. (2020)
T_{ss}	Energy storage system lifetime	13 (a)	Da Silva Lima et al. (2021)

LIBESS

Table C4: Input values for scenarios with LIBESS

Symbol	Name	Value	Source
$E_{ss,max}$	Energy storage system capacity	$50 \times \mu_{H_2,goal} \times E_{H_2}/100 \times \mu_{H_2,goal} \times E_{H_2}$	(-)
η_{ss}	Round trip efficiency energy storage system	65/88	Rahman et al. (2020)

$E_{ss,charge}$	Energy storage system (dis)charge capacity	$\frac{E_{ss,max}}{2}$ / $\frac{E_{ss,max}}{0{,}17}$	Rahman et al. (2020)
$I_{MWh,ss}$	Initial investment per MWh energy storage capacity	2.193.000 (a)	Rahman et al. (2020)
$I_{MWh/t,ss}$	Initial investment per MWh energy (dis)charge capacity	2.305.500 (a)	Rahman et al. (2020)
$O_{MWh/t,ss}$	Operational expenses per MWh energy (dis)charge capacity	61.000 (a)	Rahman et al. (2020)
T_{ss}	Energy storage system lifetime	13 (a)	Da Silva Lima et al. (2021)

HESS

Table C5: Input values for scenarios with HESS

Symbol	Name	Value	Source
$M_{H_s ss,max}$	Hydrogen storage system capacity	$50 \times \mu_{H_2,goal}$ / $100 \times \mu_{H_2,goal}$	(-)
$\eta_{H_2 ss}$	Hydrogen storage system efficiency	99	Christensen (2020)
$\mu_{H_2 ss,trans}$	Transport capacity hydrogen energy storage system	$2 \times \mu_{H_2,goal}$	(-)
$I_{kg,H_2 ss}$	Initial investment per kg hydrogen storage capacity	335 (a)	Rahman et al. (2020)
$I_{kg/t,H_2 ss}$	Initial investment per kg hydrogen transfer capacity	1064 (a)	Rahman et al. (2020)
$O_{kg/t,H_2 ss}$	Operational expenses per kg hydrogen transport capacity	170	Prenev et al. (2019)
$T_{H_2 ss}$	Hydrogen storage system lifetime	10	Prenev et al. (2019)

C2 Electrolyzers

AEL

Table C6: Input values for scenarios with AEL electrolyzer

Symbol	Name	Value	Source
$E_{elec,cap}$	Maximum rated power consumption electrolyzer	$1 \times \mu_{H_2,goal} \times E_{H_2}$ / $2 \times \mu_{H_2,goal} \times E_{H_2}$	(-)
η_{elec}	Efficiency electrolyzer	0,63 – 0,70	IEA (2019)
$R_{elec,min}$	Minimum energy consumption rate electrolyzer	0,2	Schnuelle (2020)
$I_{MWh,el}$	Initial investment per MW electrolyzer capacity	950.000 (a)	IEA (2019)
$O_{r,el}$	Operational expenses rate electrolyzer	0,02 (a)	Christensen (2020)
T_{el}	Electrolyzer lifetime	7	Christensen (2020)

PEM

Table C7: Input values for scenarios with PEM electrolyzer

Symbol	Name	Value	Source
$E_{elec,cap}$	Maximum rated power consumption electrolyzer	$1 \times \mu_{H_2,goal} \times E_{H_2}$ / $2 \times \mu_{H_2,goal} \times E_{H_2}$	(-)
η_{elec}	Efficiency electrolyzer	0,56 – 0,60	IEA (2019)
$R_{elec,min}$	Minimum energy consumption rate electrolyzer	0,05	Schnuelle (2020)
$I_{MWh,el}$	Initial investment per MWh electrolyzer capacity	1.450.000 (a)	IEA (2019)
$O_{r,el}$	Operational expenses rate electrolyzer	0,02 (a)	Christensen (2020)
T_{el}	Electrolyzer lifetime	9	Christensen (2020)

C3 Renewables.ninja input

Offshore windpark

Table C8: Renewables.ninja input for offshore windprofile

Input	**Value**
Latitude	52.292804010203575
Longitude	3.998981526056998
Year	2020
Dataset	Merra 2
Hub height	120
Turbine	Vestas 110 2000

Onshore windpark

Table C9: Renewables.ninja input for onshore windprofile

Input	**Value**
Latitude	52.12820550332259
Longitude	4.477582035270807
Year	2020
Dataset	Merra 2
Hub height	120
Turbine	Vestas 110 2000

Appendix D: Validation input values

Production model

Table D1: Input values for production model validation

Input variable	Value
Hydrogen output goal	0,005
Maximum wind energy output	0,01
Efficiency electrolyzer	0,83
Minimum energy consumption electrolyzer	0,05
Maximum energy consumption electrolyzer	0,000237
Energy storage system (dis)charge capacity	0,0146
Energy storage system capacity	0,0119
Round trip efficiency energy storage system	0,8

Renewables.ninja

Table D2: Input values Renewables.ninja for model validation

Input	Value
Latitude	38.2788
Longitude	47.4834
Year	2019
Dataset	Merra 2
Hub height	150
Turbine	DewindD6 1000

Appendix E: Sensitivity analysis

E1 Sensitivity analysis base scenarios

Table E1: Base case input values sensitivity analysis

Input	PHSS, CAESS, FBESS or LIBESS	HESS
Hydrogen output goal	1000	1000
Maximum wind energy output	118.2	118.2
Plant lifetime	15	15
Energy storage system capacity	1970.0	0
Round trip efficiency energy storage system	0.65	0
Energy storage system (dis)charge capacity	78.8	0
Initial investment per MWh energy storage syst...	70500	0
Initial investment per MWh energy (dis)charge ...	2541700	0
Operational expenses per MWh energy (dis)charg...	6000.0	0
Energy storage system lifetime	45	0
Hydrogen energy storage system capacity	0	50000.0
Hydrogen energy storage system round-trip effi...	0	0.99
Hydrogen energy storage system transport capacity	0	2000
Initial investment per kg hydrogen energy stor...	0	335.0
Initial investment per kg hydrogen energy stor...	0	1064.0

Operational expenses per kg hydrogen transport...	0	170.0
Hydrogen energy storage system lifetime	0	10
Maximum rated power consumption electrolyzer	78.8	78.8
Efficiency electrolyzer	0.63	0.63
Minimum energy consumption rate electrolyzer	0.2	0.2
Initial investment per MWh electrolyzer capacity	950000.0	950000.0
Operational expenses rate electrolyzer	0.02	0.02
Electrolyzer lifetime	7	7
Levelized cost of energy	99.0	99.0
Higher heating value hydrogen	0.0394	0.0394
Reinvestment rate	0.5	0.5
Discount rate	0.15	0.15
Price of excess wind energy	74.25	74.25

E2 Sensitivity analysis results

Scenarios with integrated PHSS, CAESS, FBESS or LIBESS

Table E2: Sensitivity analysis outcomes for scenarios with PHSS, CAESS, FBESS or LIBESS

Input variable	**Change input value (%)**	**Change average hydrogen output rate (%)**	**Change standard deviation hydrogen output rate (%)**	**Change plant efficiency (%)**	**Change LCOH (%)**
Hydrogen output goal	10	6,8445	35,6694	0,3653	-4,5091
Hydrogen output goal	-10	-8,0263	-31,9917	-0,2309	6,2258
Maximum wind energy output	10	1,6983	-18,7482	-0,0135	0,0684
Maximum wind energy output	-10	-2,8347	24,0366	0,2062	0,8329
Plant lifetime	10	0	0	0	-2,2257
Plant lifetime	-10	0	0	0	0,7382
Energy storage system capacity	10	0,4279	-4,0198	-0,2049	1,4683
Energy storage system capacity	-10	-0,5143	5,0212	0,2126	-1,418

Round trip efficiency energy storage system	10	0,3065	-3,0685	1,4351	0,2247
Round trip efficiency energy storage system	-10	-0,3392	3,6212	-1,6364	-0,278
Energy storage system (dis)charge capacity	10	0	0	0	2,7016
Energy storage system (dis)charge capacity	-10	0	0	0	-2,7016
Initial investment per MWh energy storage syst...	10	0	0	0	1,8484
Initial investment per MWh energy storage syst...	-10	0	0	0	-1,8484
Initial investment per MWh energy (dis)charge ...	10	0	0	0	2,6655
Initial investment per MWh energy (dis)charge ...	-10	0	0	0	-2,6655
Operational expenses per MWh energy (dis)charg...	10	0	0	0	0,036
Operational expenses per MWh energy (dis)charg...	-10	0	0	0	-0,036
Energy storage system lifetime	10	0	0	0	0
Energy storage system lifetime	-10	0	0	0	0
Maximum rated power consumption electrolyzer	10	-0,0619	1,454	-0,0036	1,4125
Maximum rated power consumption electrolyzer	-10	0,0708	-1,7115	0,0041	-1,4168
Efficiency electrolyzer	10	2,0352	-22,3827	9,7568	-4,0325
Efficiency electrolyzer	-10	-3,2127	25,8592	-9,6236	5,6329
Minimum energy consumption rate electrolyzer	10	-0,0619	1,454	-0,0036	0,0436
Minimum energy consumption rate electrolyzer	-10	0,0708	-1,7115	0,0041	-0,0498
Initial investment per MWh electrolyzer capacity	10	0	0	0	1,368
Initial investment per MWh electrolyzer capacity	-10	0	0	0	-1,368
Operational expenses rate electrolyzer	10	0	0	0	0,1141
Operational expenses rate electrolyzer	-10	0	0	0	-0,1141
Electrolyzer lifetime	10	0	0	0	-0,9483
Electrolyzer lifetime	-10	0	0	0	0
Levelized cost of energy	10	0	0	0	5,1987
Levelized cost of energy	-10	0	0	0	-5,1987
Higher heating value hydrogen	10	-2,8686	23,3359	0,3653	5,04
Higher heating value hydrogen	-10	2,193	-24,4352	-0,2309	-4,3968
Reinvestment rate	10	0	0	0	0,2577
Reinvestment rate	-10	0	0	0	-0,2577

Discount rate	10	0	0	0	3,7823
Discount rate	-10	0	0	0	-3,6845
Price of excess wind energy	10	0	0	0	-1,1167
Price of excess wind energy	-10	0	0	0	1,1167

Scenarios with integrated HESS

Table E3: Sensitivity analysis outcomes for scenarios with PHSS, CAESS, FBESS or LIBESS

Input variable	**Change input value (%)**	**Change average hydrogen output rate (%)**	**Change standard deviation hydrogen output rate (%)**	**Change plant efficiency (%)**	**Change LCOH (%)**
Hydrogen output goal	10	4,3744	51,6629	0,1822	-2,1852
Hydrogen output goal	-10	-7,405	-45,3545	-0,1787	4,0857
Maximum wind energy output	10	1,547	-17,7292	-0,0545	1,4151
Maximum wind energy output	-10	-2,3241	20,4344	0,0766	-1,0836
Plant lifetime	10	0	0	0	-0,9954
Plant lifetime	-10	0	0	0	-0,5591
Hydrogen energy storage system capacity	10	0,2249	-1,9988	-0,0614	0,3382
Hydrogen energy storage system capacity	-10	-0,2709	2,8216	0,0622	-0,3171
Hydrogen energy storage system round-trip effi...	10	0,5318	-5,1816	1,1914	-0,8533
Hydrogen energy storage system round-trip effi...	-10	-0,6119	5,6661	-1,3092	0,9713
Hydrogen energy storage system transport capacity	10	0	0	0	0,0969
Hydrogen energy storage system transport capacity	-10	0	0	0	-0,0969
Initial investment per kg hydrogen energy stor...	10	0	0	0	0,4206
Initial investment per kg hydrogen energy stor...	-10	0	0	0	-0,4206
Initial investment per kg hydrogen energy stor...	10	0	0	0	0,0534
Initial investment per kg hydrogen energy stor...	-10	0	0	0	-0,0534
Operational expenses per kg hydrogen transport...	10	0	0	0	0,0435
Operational expenses per kg hydrogen transport...	-10	0	0	0	-0,0435

Hydrogen energy storage system lifetime	10	0	0	0	-0,068
Hydrogen energy storage system lifetime	-10	0	0	0	0,0782
Maximum rated power consumption electrolyzer	10	1,2939	-14,3423	-0,034	1,6465
Maximum rated power consumption electrolyzer	-10	-3,483	28,2966	0,1855	-0,6694
Efficiency electrolyzer	10	2,5326	-32,3029	9,8873	-5,7358
Efficiency electrolyzer	-10	-5,8725	41,4873	-9,8311	8,5724
Minimum energy consumption rate electrolyzer	10	-0,1666	2,6871	0,0119	0,0774
Minimum energy consumption rate electrolyzer	-10	0,152	-2,5153	-0,002	-0,0748
Initial investment per MWh electrolyzer capacity	10	0	0	0	2,2971
Initial investment per MWh electrolyzer capacity	-10	0	0	0	-2,2971
Operational expenses rate electrolyzer	10	0	0	0	0,1915
Operational expenses rate electrolyzer	-10	0	0	0	-0,1915
Electrolyzer lifetime	10	0	0	0	-1,5923
Electrolyzer lifetime	-10	0	0	0	0
Levelized cost of energy	10	0	0	0	8,7294
Levelized cost of energy	-10	0	0	0	-8,7294
Higher heating value hydrogen	10	-5,0601	37,6465	0,1816	7,5665
Higher heating value hydrogen	-10	2,6362	-34,1077	-0,1126	-6,2357
Reinvestment rate	10	0	0	0	0,4848
Reinvestment rate	-10	0	0	0	-0,4848
Discount rate	10	0	0	0	1,2554
Discount rate	-10	0	0	0	-1,2101
Price of excess wind energy	10	0	0	0	-1,544
Price of excess wind energy	-10	0	0	0	1,544