An energy efficiency study on the Ocean Battery together with hydrogen conversion

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Abstract

The energy transition towards renewable energy is one of the main challenges towards a greener planet. However, due to the intermittency of renewable energy, part of the energy production needs to be stored for later use. One of the inventions that can be used is the Ocean Battery, a hydro pumped storage system designed by Ocean Grazer B.V. The Ocean Battery is mainly used for short term storage; a hydrogen production with a subsequent conversion to methane or methanol has the potential to add over-seasonal storage. However, the interactions between the Ocean Battery and a hydrogen production have not yet been assessed. This thesis aims to show the added value of the Ocean Battery on the energy efficiency of an offshore hydrogen production. Next to this, it aims to show the energy efficiency of the transportation to shore of the produced energy. To achieve this, a simulation model was made in Simulink using technical input data found in literature. The simulation model allowed to analyse and compare different scenarios. The results showed that the Ocean Battery has a short term influence on the hydrogen output of the electrolyzers. It was also established that in the current methane and methanol production and transportation through pipelines, CO2 capture from air is by far the most energy consuming.

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1 Introduction

Renewable energy is one of the main challenges towards a greener planet. With the Paris agreement of 2016, 196 nations expressed their goal to limit global warming below 2 degrees Celsius compared to pre-industrial levels (UNFCCC, 2016). To reach this limitation of global warming, global greenhouse gasses need to be reduced. Renewable energy from wind or solar energy is an already existing possibilities to produce green energy (Sawin et al., 2016).

However, besides the production of renewable energy, also the storage of this energy is of importance. One of the possibilities to store renewable energy is in the Ocean Battery (OB), which is developed by the Ocean Grazer B.V. The Ocean Grazer company is currently working on commercializing the OB. They completed the first steps in their 'Go to Market Strategy' (Ocean Grazer (1), 2021). These were testing the OB in the lab as well as testing a working prototype in Groningen Seaports. The next step in their marketing strategy is to demonstrate a full-scale operational model.

The OB is a pumped hydro storage system that stores energy beneath the surface of a waterbody. The OB consists of two separate reservoirs, a pressurizing reservoir and a depressurizing reservoir. In this system, the pressurizing reservoir has a deformable wall, and the depressurizing reservoir has a rigid wall (Prins et al.,2019). This can also be seen in figure 1 below.

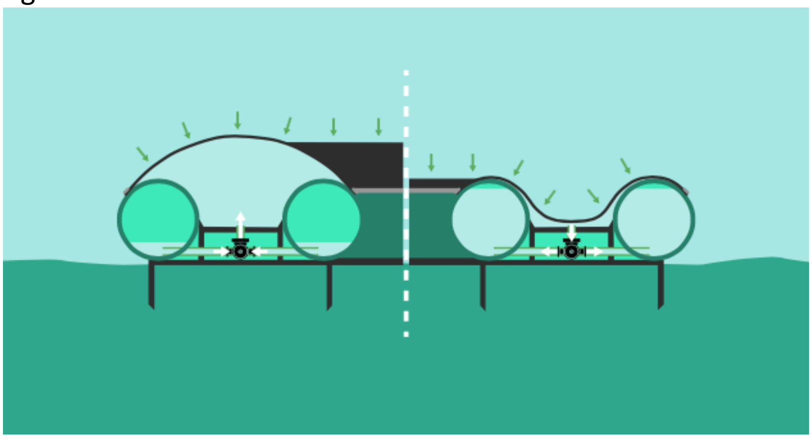

Figure 1 A schematic overview of the Ocean Battery, on the left side the charging of the battery, and on the right side the discharging of the Ocean Battery is displayed (Ocean Grazer, 2021).

There are two main processes which take place in the OB, the charging and the discharging. During the charging, water is pumped from the depressurizing reservoir into the pressurizing reservoir. This process can also be seen on the left side of figure 1. During this process, electricity is converted to potential energy. When this potential energy is needed, the OB can be discharged. During this process, the water in the pressurizing reservoir is released and is converted back to electricity (Prins et al.,2019).

As Ocean Grazer B.V. wants to commercialize the OB, market research needs to be done to discover opportunities for a feasible implementation of the OB. One of these opportunities could be to implement the OB together with some form of hydrogen conversion. Hydrogen is a clean energy carrier similar to electricity. Hydrogen can be used in hydrogen fuel cells; these cells convert the chemical energy of hydrogen to clean and efficient electricity (Zohuri, 2019). The Ocean Battery already solves current problems involving the intermittency of renewable energies (Schenk et al., 2012). Adding a hydrogen conversion to the supply chain could simplify the transport of the produced energy, as well as enabling the energy producer to store the green energy over-seasonal (Niermann et al., 2021). To find an efficient implementation of the OB to a hydrogen production, multiple possibilities need to be explored. This can be done by developing multiple system designs for the implementation of the Ocean Battery together with hydrogen (Konda et al., 2012) (Bolat and Thiel, 2014).

This research is on applying the OB together with a hydrogen conversion. Chapter 2 will focus on the analysis of the problem faced when applying the OB together with a hydrogen conversion. After this, in chapter 3 the system in which the research takes place will be described. Chapter 4 details the research design of the research. The literature which is needed for this research will be discussed in chapter 5. Next, in chapter 6 the assumptions needed to develop the model will be discussed, as well as the implementation of the model itself. After this, the results which are retrieved from the model are discussed in chapter 7. Last, in chapter 8 and 9 the discussion and subsequently the conclusion is discussed.

2 Problem Analysis

The problem that arises with commercializing the OB is that it is still unclear for Ocean Grazer B.V. how and in which energy supply chains the OB will fit. The CTO of Ocean Grazer B.V. is Marijn van Rooij; thus he is involved in all the technical aspects of the company. Van Rooij is the problem owner in this research. As research has already shown that it would be possible to implement a hydrogen conversion together with renewable energy sources (Andrews et al., 2012) (Schenk et al., 2012); the problem owner wants to know if it enhances the energy efficiency to use the OB in a hydrogen production system. This would help the Ocean Grazer company to predict future implementations of the OB in an energy supply chain.

2.1 Stakeholder analysis

Next to the problem owner, there are several other stakeholders. The stakeholders are divided into internal and external stakeholders.

2.1.1 Internal stakeholders

The first internal stakeholder in this research is Prof. Dr. Antonis Vakis. He is the co-founder and scientific advisor of the Ocean Grazer research group. He is mainly interested in the technical aspects of the Ocean Battery. However, he is interested in this research, as the research will show the energy efficiency of implementing the Ocean Battery together with a hydrogen conversion.

Next, Wout Prins is the last internal stakeholder. He is the founder of the Ocean Grazer. Just as Van Rooij, he wants to commercialize the Ocean Grazer; his main interest is therefore also to find out whether the OB can have a positive influence on the energy efficiency of hydrogen production.

2.1.2 External stakeholders

Next to the internal stakeholders, there are also several external stakeholders. These are mostly parties that are positioned in the renewable energy supply chain. Possible stakeholders are grid owners, owners of abandoned offshore rigs, government institutions, companies that produce hydrogen, but also the eventual customers of the hydrogen. For these stakeholders, the way of transporting and the form in which the hydrogen is transported to shore is of most interest.

2.2 Problem Statement

Now the stakeholders and their interests have been defined, a problem statement can be formulated. The following problem statements were defined:

It is not clear if the OB has added value to the energy efficiency of a hydrogen production with a renewable energy input.
And
It is not clear what the most energy efficient transportation form and state is for offshore produced hydrogen.

3 System description
This chapter will first elaborate on the overall system in which this research takes place. After this, the subsystems within the energy supply chain will be discussed and the scope will be defined.

3.1 Overall system
The system in which this research is placed is in the renewable energy sector. In this sector, the Ocean Battery and the hydrogen conversion are placed in between the renewable energy sources and the energy user. The renewable energy source in this system is offshore produced wind energy. Offshore wind energy is chosen because offshore wind farms are expected to become a large energy source globally (Perveen, Kishor and Mohanty, 2014). The wind energy source is then connected to the Ocean Battery and the hydrogen conversion.

To see what the added value of the OB is to the efficiency of a hydrogen conversion, two possible options can be defined. These options can be found in Figure 2 below.

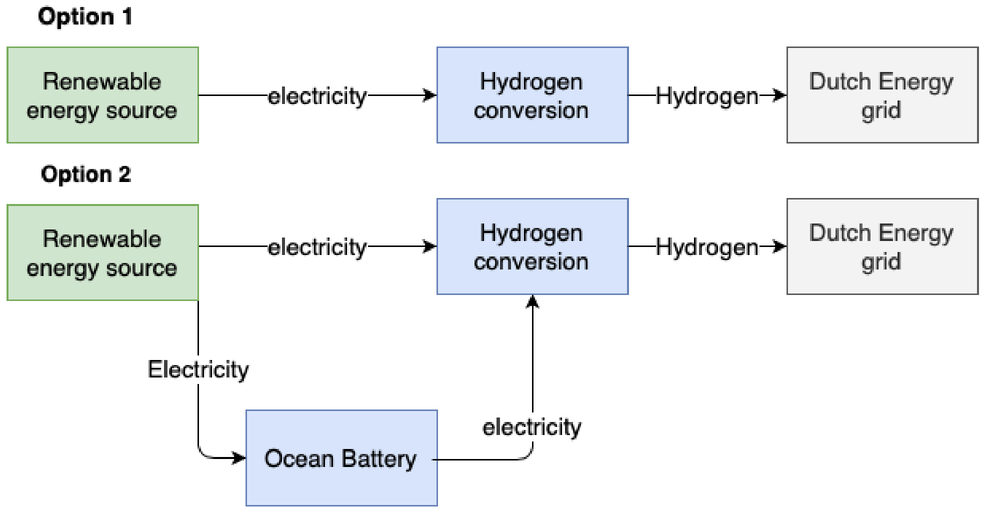

Figure 2 system description to show the added value of the OB to a hydrogen conversion

In option 1, the OB is not taken into account, and in option 2 it is. These two options will be compared to see whether the OB has a positive influence on the hydrogen production process. In both options, the hydrogen is produced offshore, and therefore will need to be transported to shore after production.

3.2 The Ocean Battery
For the system of this research, the working of the OB will not be taken into account. Only the ratio of the energy input and output is taken into account; this is the round trip efficiency of the OB. The round trip efficiency is considered a constant which is given. The rest of the OB will be considered a black box.

3.3 Hydrogen conversion
To produce hydrogen in a 'green' way, no fossil fuels need to be used in the production process; therefore, the most suitable process to produce hydrogen is through electrolysis of water. This is the reversed process of burning hydrogen to produce water (Zohuri, 2019).

During this process, electricity is used to separate oxygen and hydrogen atoms. The equation for the electrolysis process is:

$$2H_2O(l) \rightarrow 2H_2(g) + O_2\,(g)$$

The electricity required in this process could either come directly from the renewable energy source or come from the OB. For the system which will be taken into account, it is of most importance to define the different technical processes of the production of hydrogen, and to see if it needs a steady input of electricity.

3.4 Energy transport

As the OB and hydrogen conversion are located offshore, the energy produced needs to be transported. First, the electricity needs to be transported to the OB and the hydrogen conversion, and after this the hydrogen to shore.

3.4.1 Electricity transport

Firstly, the energy transportation of the electricity will be elaborated on. Electricity is transported from the renewable energy source to the OB and to the hydrogen production site. To transport the electricity, cables need to be utilized. However, in these export cables power losses occur. The power losses that occur are mainly active and reactive power losses (Chabane et al., 2018).

3.4.2 Hydrogen transport

Secondly, the hydrogen transportation will be discussed. A first study of literature shows three transportation methods for hydrogen. The first possibility is to compress the hydrogen in gaseous form (GH_2). Hydrogen in this gaseous form can be transported through pipelines or by trucks (Reuß et al., 2017). The second possibility to transport the hydrogen is by first converting the hydrogen to liquid hydrogen (LH_2). In a liquefaction process, the hydrogen is cooled to below 21 K (Krasae-in et al., 2010). The liquid hydrogen is currently transported by trucks and could in the future also be transported by ship and rail transportation (Reuß et al., 2017). The last storage and transport form for hydrogen which will be discussed is by storing hydrogen in a Liquid Organic Hydrogen Carrier (LOHC). In this form, a LOHC is loaded with hydrogen during production and discharged when the hydrogen is needed. The most suitable LOHCs should be liquid at ambient conditions and show similar properties to crude oil-based liquids (Niermann et al., 2021). The main reason the LOHC should look and behave like crude oil-based liquids is to be able to utilize the existing oil network.

3.5 Scope

The scope of this research will firstly focus on the energetic efficiency for hydrogen production with or without an OB. In this system the round trip efficiency of the OB will be considered a given constant. Next to this, the scope of the research will also focus on the most energy efficient hydrogen transportation from the production site offshore to shore. The scope of this research will therefore only stay on the energetic side of these two sub-problems and will not take into account costs of any kind. The scope can be found in Figure 4.

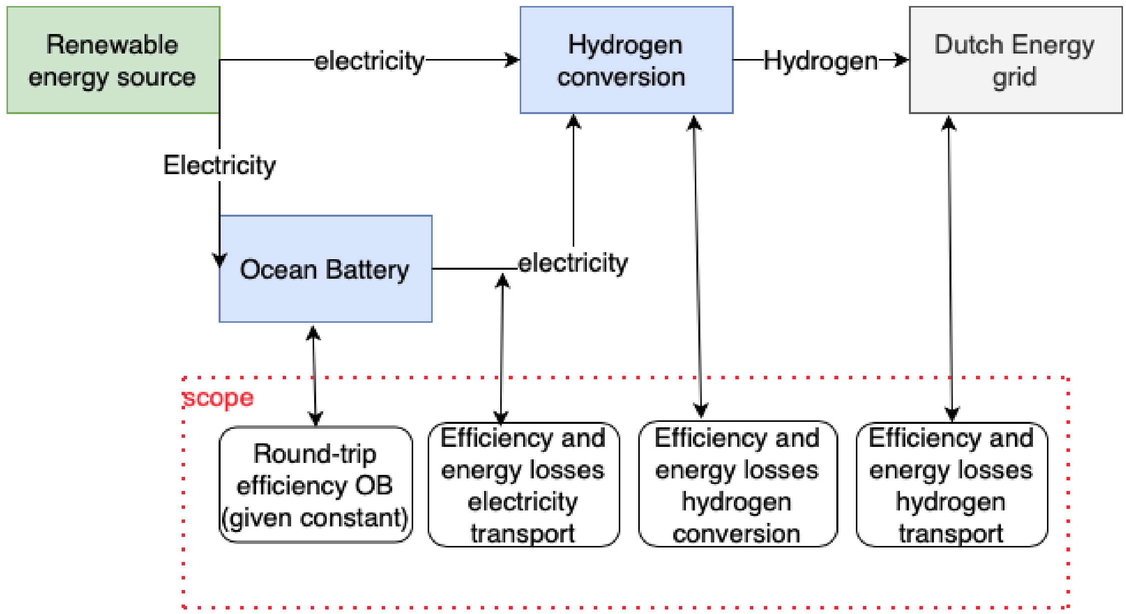

Figure 3 Scope

3.6 Goal statement

The research objective can be constructed according to the problem statement and the stakeholder analysis. In order to conduct a good research, a S.M.A.R.T. goal can be defined according to the paper (Bjerke and Renger, 2017).

The final goal can be described as follows:
Deliver a model which shows what value the OB has on the energy efficiency of the offshore production of hydrogen and what is the most energy efficient way hydrogen can be transported to shore, all before June 4th.

3.7 Research Questions

Now that the research goal has been defined, the research questions can be formulated. There is one central research question to be answered. The central research question has multiple sub-questions, which are as follows:

How to model an energy supply chain incorporating a hydrogen production and the OB in which a comparison can be made between different system designs?

Sub questions:

1. What is an appropriate modelling approach for comparing energy efficiencies?
2. What are the relevant inputs, outputs and controls for the separate subsystems?
3. What is the energy efficiency, or the energy losses, of the subsystems?
4. How can these subsystems be modelled appropriately?
5. What will be the critical outputs on which the different designs will be compared?
6. How can the outcomes of the model be validated?

4 Research Design

This chapter will elaborate on the research methods that will be used. For this research, the engineering cycle of Wieringa will be used (Wieringa, 2012). This cycle can be found in Figure 5 below.

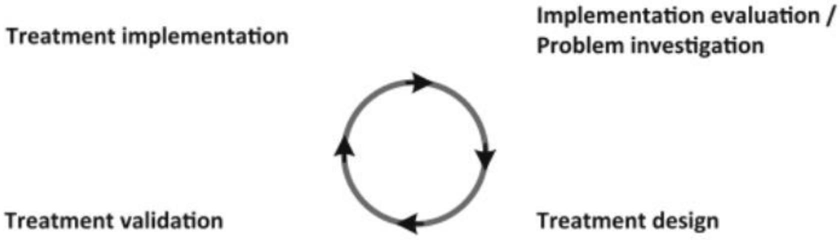

Figure 4 The engineering cycle from Wieringa (Wieringa, 2012)

This is the most suitable cycle for this research because the final model cannot be implemented in a real-life situation; therefore, the different cycles of Van Aken are not suitable. In chapter 2 and 3 of this RDP, part of the problem investigation has already been done. The rest of the investigation, the design and the validation need to be given in the rest of the research.

The final deliverable will be a model which will be used to assess the energy efficiency of different scenarios. This could be done by developing an optimization model for each scenario, starting with the simplest base case. However, the alternatives have not yet been well enough defined to develop this optimization model. It is therefore more convenient to develop a simulation model. The model will be derived by first gaining the information which is needed on the hydrogen conversion, efficiency of the OB and the efficiency of the transportation of energy. For the research on the OB, the Ocean Grazer company and research group can be consulted. For the information on the hydrogen conversion and transportation, literature research will need to be done and calculations will be needed. When all the needed data is known, iterations will be made to investigate possible system designs.

There are some limitations to this research, as this research will only focus on the energy efficiency of the subsystems, as well as for the system as a whole. However, it does not look at any costs which need to be made to establish and maintain the system. This could be reason for future research, if the results proof to be positive.

4.1 Validation

The ideal validation for this research would be to implement the final information model in a real-life situation and to compare this to the model outcome. However, this will not be possible for this research at this time. Therefore, the final validation will be done by comparing the model which is derived with existing literature to see whether the model is a correct representation of the incorporation of the OB together with a hydrogen conversion in a renewable energy supply chain.

5 Literature research
As was mentioned in the research design, information is needed on the hydrogen production, the transport of the energy and on the OB. In order to get this information, literature has been analysed. This chapter elaborates on the technologies used in the energy system and identifies variables and inputs for the model.

5.1 Hydrogen production
Firstly, information is needed on the hydrogen production process. For the production of hydrogen, electrolysis is used. The equation for the electrolysis process is shown below:

$$2H_2O(l) \rightarrow 2H_2(g) + \ O_2\ (g)$$

To determine the energy that can be distracted when hydrogen completely combusts with oxygen, the lower or higher heating value (LHV or HHV) can be used.

For the electrolysis of water electricity is needed. This electricity needs to be transported from the (renewable) energy source towards the production site of hydrogen. For this transport cables are needed; as the production site is located offshore, submarine cables are used. The losses in these cables are about 3.7% over a length of 1000 km (Ardelean and Minnebo, 2015).

Besides electricity, seawater is needed in the electrolysis process; however, it cannot be directly used for electrolysis as it does not have the desired purity. Therefore, a desalination technology is needed. Reverse osmosis is the most commonly used technology as a desalination water treatment (Meier, 2014). In reverse osmosis seawater is pressurized against a semipermeable membrane; this membrane lets water pass through, but retains salt (Elimelech and Phillip, 2011). The energy needed for this has been calculated in a case study and is 2.374 kWh/m3; this is pretty close to the energy reported in similar industrial applications, which is 2.54 kWh/m3 (Karabelas et al., 2018). The theoretical water use in an electrolyzer is 1 litre of water per 1.24 [Nm3] of hydrogen; however, the actual water consumption is 25% higher (Barbir, 2005).

For the electrolysis of water an electrolyzer is needed. Possible electrolyzers are an Alkaline electrolyzer, a PEM electrolyzer and a Solid Oxide Electrolyzer Cell (SOEC) (Goeppert et al., 2014). For this research, it is important what the effect of the intermittent power supply is on the hydrogen production. Therefore, important features of the electrolyzers are the load range, the start-up time, the energy efficiency and the duration at which the production process can continue.

5.1.1 Alkaline electrolyzer
The first electrolyzer technology which will be discussed is the Alkaline electrolyzer. Alkaline electrolysis is the most mature technology of the three water electrolysis processes. Alkaline electrolyzers have a reported load range between 20 and 100% of the design capacity (Götz et al., 2016). However, Lehner et al. (2014) reported that operating an alkaline electrolyzer in the lower half of its load range results in significantly lower gas purity and increasingly reduced system efficiencies; this part of the load range is called the lower partial load range. An alkaline electrolyzer shows a lower partial load range in the first 30-40% of the nominal load (In Lee et al., 2019) (Lehner et al., 2014). Adding to this, In Lee et al. (2019) stated that:

when operating in the lower partial load range, the hydrogen concentration rapidly increases to the critical point. For this reason, the electrolyzer should not operate in this load range. Another problem with Alkaline electrolyzers is that they have an extensive start up time, which ranges from 30-60 minutes (Götz et al., 2016) (Goeppert et al., 2014). This could be a problem if the electrolyzer needs to stop often due to the intermittency of the input.

An example of a commercialized alkaline electrolyzer is the McLyzer by McPhy. This electrolyzer cell has a nominal hydrogen flow rate of 800 Nm3/h H2; at this flow rate the rated power used is 4MW. This is with an efficiency of about 71%. The energy consumption at this nominal hydrogen flow rate is 4.5 kWh/Nm3. (McPhy, 2021) Keeping in mind the load range and lower partial load range for an alkaline electrolyzer which were discussed before, the minimum load for this 4 MW electrolyzer would be 2.08 MW. With this information, and the information on the load range and lower partial load range of an alkaline electrolyzer, the output in Nm3 of hydrogen can be calculated.

5.1.2 PEM

The next electrolyzer technology that will be discussed is the PEM electrolyzer. PEM electrolyzers are relatively new compared to the alkaline electrolyzers. Just as alkaline electrolyzers, PEM electrolyzers are available commercially (Götz et al., 2016) (Goeppert et al., 2014). The main advantages of PEM electrolyzers compared to alkaline electrolyzers are that they have a faster start time and a broader load range. However, a PEM electrolyzer has a lower efficiency (Esmaili et al., 2015). Next to this, a PEM electrolyzer is capable of producing hydrogen purities of 99.99+% over the load range of 1-100% (Lehner et al., 2014). This is significantly better compared to the alkaline electrolyzer.

In Mainz located in Germany, tests have been done with one of the largest Power-to-Gas plants, which utilizes a PEM. This PEM electrolyzer can operate continuously at a rated power input of 4MW with an efficiency of 64% (Kopp et al., 2017).

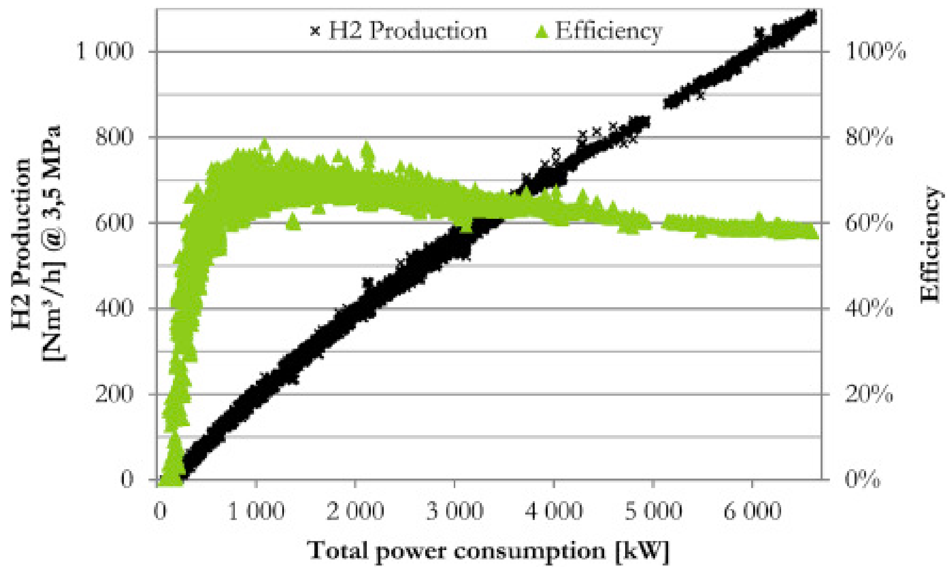

figure 5 Efficiency curve PEM electrolyzer (Kopp et al., 2017)

In figure 5 the efficiency curve and the hydrogen production in Nm2/h can be seen for the PEM electrolyzer. The efficiency and power consumption include the cooling, purification and compression of the produced hydrogen (Buttler and Spliethoff, 2018). The electrolyzer can work at peak power (6000 kW) for 15 minutes, after this period the electrolyzer needs to be shut down for 15 minutes (Kopp et al., 2017). Due to an eventual lower output in hydrogen, this is undesirable; therefore, producing hydrogen at peak power should be prevented. To do this a maximum input of 4 MW should be used.

5.1.3 SOECs

The last electrolysis technology that will be discussed is a SOEC. SOECs are used in a reversible Solid Oxide Cell (rSOC). rSOC designs have a large potential to produce clean electricity. This is mainly because rSOC designs have a high chemical-to-electrical conversion efficiency, operate at higher temperatures and due to this, have a fast electrochemical reaction rate (Sadeghi et al., 2021). The roundtrip efficiency of a rSOC is close to 80% (Venkataraman and Aravind, 2019). A big difference between the Alkaline and PEM electrolyzers and a rSOC is that the rSOC can operate in both directions. Due to this, it has an operation range of -100 to 100%. (Buttler and Spliethoff, 2018)

The large downside to a SOEC is that they are not yet available commercially; next to this, the SOEC has only been tested on a large scale in programs like Aspen plus (Venkataraman and Aravind, 2019). For this reason, it should not be forgotten that the technique is not yet available and will probably not be available for real-life implementation in the near future. However, it is discussed in this literature research due to the large potential the SOEC electrolyzers have.

In table 5.1 the most important features of the three electrolyzers are stated.

Table 5.1 characteristics of the three electrolysis technologies

	Alkaline	PEM	SOEC
Current density	0.25-0.45 A cm-2 (Buttler and Spliethoff, 2018)	1.0-2.0 A cm-2 (Buttler and Spliethoff, 2018)	1.0 A cm-2 (Venkataraman and Aravind, 2019)
Specific energy consumption	4.2-4.8 kWh/Nm3 (Buttler and Spliethoff, 2018)	4.4-5.0 kWh/Nm3 (Buttler and Spliethoff, 2018)	3 kWh/Nm3 (Buttler and Spliethoff, 2018)
Efficiency	71% (Buttler and Spliethoff, 2018) 73% (Meier, 2014)	63% (Esmaili et al., 2015) and (Meier, 2014)	80% (Venkataraman and Aravind, 2019) 66% (Meier, 2014)
Cell temp. in Celsius	40-90 (Götz et al., 2016)	20-100 (Götz et al., 2016)	700-900 (Buttler and Spliethoff, 2018), 800 (Venkataraman and Aravind, 2019)
Cold start time	Minutes-hours (Götz et al., 2016)	Seconds-minutes (Götz et al., 2016)	Hours (Buttler and Spliethoff, 2018)
Warm start up-time	1-5 min (Buttler and Spliethoff, 2018)	< 10 s (Buttler and Spliethoff, 2018)	15 min (Buttler and Spliethoff, 2018)
Load range	20%-100% (Buttler and Spliethoff, 2018)	1%-100% (Buttler and Spliethoff, 2018)	-100%-100% (Buttler and Spliethoff, 2018)
Lifetime (hour)	<90.000	<20.000	-
Hydrogen production per stack (Nm3h-1)	<1400 (David et al.,2019)	<400 (David et al.,2019)	<10 (David et al.,2019)

5.2 Transportation/storing

Because of the low volumetric density of hydrogen, it requires either compression to 350 to 700 bars or liquefaction to -235C. Due to this the storage and consequently the transport of hydrogen needs a lot of energy (Goeppert et al., 2014). Next to this, the storage, transport and distribution of hydrogen also raise safety concerns (Varone et al., 2015).

For this reason, other storing possibilities are needed. The most promising technologies that can be used for this, are Power-to-Gas (PtG) and Power-to-Liquid (PtL) (Buttler and Spliethoff, 2018). In the PtL process, typically Fischer-Tropsch (F-T) synthesis is used to produce liquid fuels; where in the PtL process, CO2 methanation (also known as a Sabatier reaction) is mostly used to produce methane (Zhang et al., 2019). In the next paragraphs, the energy efficiencies of these processes will be discussed.

5.2.1 Power-to-Gas (PtG)

The first possibility to store and transport the renewable electric energy is to utilize a PtG technology. In this technology, renewable electric energy is stored as methane via electrolysis and methanation. The end product, CH4, can be easily used in many existing gas facilities, including the existing gas grid and existing gas storages. CH4 is better known as substitute natural gas (SNG). (Götz et al., 2016)

For the methanation of hydrogen, the Sabatier principle can be used. When the Sabatier principle is used, CO2 and hydrogen are injected in a reactor for methanation; this principle has been used in the Audi project: e gas, which started in 2012. This plant has a reported output of 6 MW SNG (Iskov and Rasmussen, 2013). The Sabatier reaction can be seen below:

$$CO_2(g) + 4H_2(g) \rightleftharpoons CH_4(g) + 2H_2O(g)$$

Several other reactions also take place during methanation of hydrogen (Götz et al., 2016) (Schaaf et al., 2014); all reactions taking place can be seen below:

$$CO_2(g) + 4H_2(g) \rightleftharpoons CH_4(g) + 2H_2O(g)$$
$$CO(g) + 3H_2(g) \rightleftharpoons CH_4(g) + H_2O(g)$$
$$CO_2(g) + H_2(g) \rightleftharpoons CO(g) + H_2O(g)$$
$$2CO(g) \rightleftharpoons C(s) + CO_2(g)$$

The methanation process takes place in a methanation reactor. As can also be seen in figure 5 below, the efficiency of a methanation reactor at 20 bar is 78% (Götz et al., 2016). This is in line with the efficiency for a methanation reactor reported by Sterner (2009), which is between 75-85%.

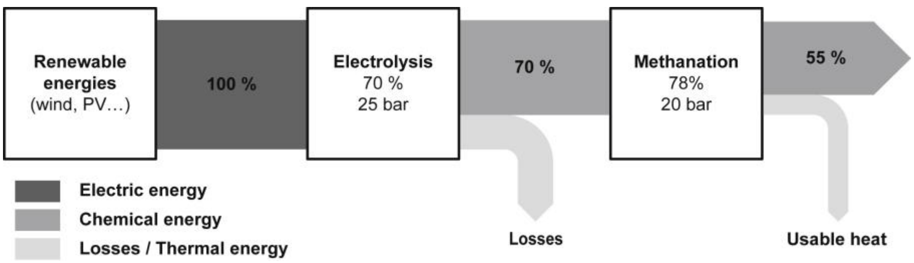

figure 6 Efficiency methanation reactor (Götz et al., 2016)

In the literature that was found, the formula which is used to calculate the efficiencies of the system are not explained. Frank et al. (2018) described a systematic method to calculate the efficiency of a PtG system. Therefore, this formula for the efficiency of the methanation process will be used; the formula can be found below in equations (1)-(3).

$$\eta = \frac{\dot{E}_{out}}{\dot{E}_{in}} \quad (1)$$

$$\dot{E}_{out} = \dot{E}_{ch,out} = \dot{m}_{CH_4} \times H_{h,CH_4} \quad (2)$$

$$\dot{E}_{in} = \dot{E}_{ch,in} = \dot{m}_{H_2} \times H_{h,H_2} \quad (3)$$

For the ingoing and outgoing energy flow of the methanation reactor, the chemical energy of the hydrogen and methane is used. The formulas for these can be found in equation (2) and (3). The mass flow is in kg/h and can be calculated from the production rate of the electrolyzer, which is in Nm3/h. The exact calculation to do this can be found in appendix 1. The HHV of methane is 55.536 MJ/kg and for hydrogen this is 141.72 MJ/kg (McAllister, Chen and Fenandez-Pello, 2011).

5.2.2 Power-to-Liquid (PtL)

The second possibility to store and transport the produced energy, is as a liquid; this can be done by using the PtL technology. In a PtL process, typically a Fischer-Tropsch synthesis is used to generate long-chain hydrocarbons (Zhang et al., 2019). One of the most common PtL processes is the production of methanol.

The reaction for methanol synthesis is exothermic. Methanol is produced in two steps, these steps can be found below (Esmaili et al., 2015).

$$CO_2 + H_2 \rightarrow CO + H_2O$$

$$CO + 2H_2 \rightarrow CH_3OH$$

The overall reaction for the production of methanol is:

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

Methanol is produced in a methanol plant. A methanol plant has a reported efficiency of 84% (Detz et al., 2018). Detz et al. (2018) do not state how this efficiency is calculated. However, König et al. (2015) do give a formula for the efficiency of a methanol plant. This formula will be used in the rest of this research. The formula can be found in equation (4).

$$\eta = \frac{\dot{m}_{SF} \times LHV_{SF}}{\dot{m}_{H_2} \times LHV_{H_2}} \quad (4)$$

If the efficiency and mass flow of hydrogen are known, the mass flow of synthetic fuel can be determined. The synthetic fuel in this case in methanol. The LHV for methanol is 19.915 MJ/kg and for hydrogen this is 119.96 MJ/kg (McAllister, Chen and Fenandez-Pello, 2011). The mass flow is in kg/h and can be calculated from the production rate of the electrolyzer, which is in Nm3/h. The exact calculation to do this can be found in appendix 1.

5.2.3 CO2 capture

For both the PtG and PtL, CO2 is needed in the production process. Literature lists four main possible sources of CO2. These are: CO2 from fossil power plants, CO2 from biomass, CO2 from industrial processes and CO2 from air (Schiebahn et al., 2015). Firstly, the CO2 from fossil power plants and from industrial processes will be discussed. This CO2 is not from a natural source, but is from the burning of fossil fuels. Additionally, this CO2 needs transportation from the production site to the power plant. For these reasons, these CO2 sources are not renewable and will not result in the production of green methane. Next, the CO2 which can be extracted from biomass will be discussed. The production of CO2 from biomass is considered green; however, the production capacity is limited and therefore not applicable in a large plant (Schiebahn et al., 2015). The last CO2 source is the capture of CO2 from air. When renewable electricity is used in this process, the captured CO2 is considered green. For these reasons, CO2 captured from air will be used in the rest of this research.

In the process of capturing CO2 from air, it needs to be concentrated from about 400 ppm to an almost pure form (House et al., 2011). House et al. (2011) report that the energy that is needed to extract CO2 from air ranges from 500-800 KJ/mol CO2, which corresponds to 3000-5000 kWh/t CO2. For the production of 1 kg methane, 2.744 kg of CO2 is needed. Next, for the production of 1 kg methanol, 2,37 kg of CO2 is needed. With this information and the energy consumption per kg CO2, the needed energy can be calculated.

5.2.4 Transport through pipelines

After the conversion to either methane or methanol, the product needs to be transported to shore. In this paragraph the energy needed for the transportation of methanol and methane will be discussed. For the transport of both the produced methane and methanol, pipelines are an option. The energy demand for pumping a fluid through a pipeline is much influenced by the properties of the fluid, such as the viscosity (Müller, Fabisch and Arlt, 2014). For the energy demand for pumping a gas through a pipeline, important features are the pipeline diameter and the length of the total pipeline (Kee et al., 2020).

Firstly, for the transportation of the produced methane through pipelines, compression is needed. The energy needed for this compression is dependent on the desired (input and output) pressure, the pipeline diameter and the length of the pipeline (Kee et al., 2020). Kee et al. (2020) report an energy demand of 25.32 MW for 360 $\frac{ton}{h}$ of methane over a period of 20 hours. This corresponds with an energy demand of 3.5167 $\frac{kWh}{t_{Methane} \times 150\ km}$.

Secondly, for the transportation of methanol through pipelines, a pump is needed. The energy which is needed for the pump is 4.13$\frac{MJ}{t_{Methanol} \times 100\ km}$, this corresponds to 1.1472 $\frac{kWh}{t_{Methanol} \times 100\ km}$. (Müller, Fabisch and Arlt, 2014). This is for a pipeline with an inner diameter of 1.4 meter and with a pump efficiency of 80%. Müller, Fabisch and Arlt (2014) state that for an undamaged pipeline, the overall efficiency of methanol going in and out of the pipeline is 99.99%.

5.3 Efficiency of the OB

The last important part of the system which needs to be discussed in this literature review is the efficiency of the OB. As the working of the OB is not included in this research, the only information that is needed is on the energy efficiency of the OB. This can be seen in figure 7.

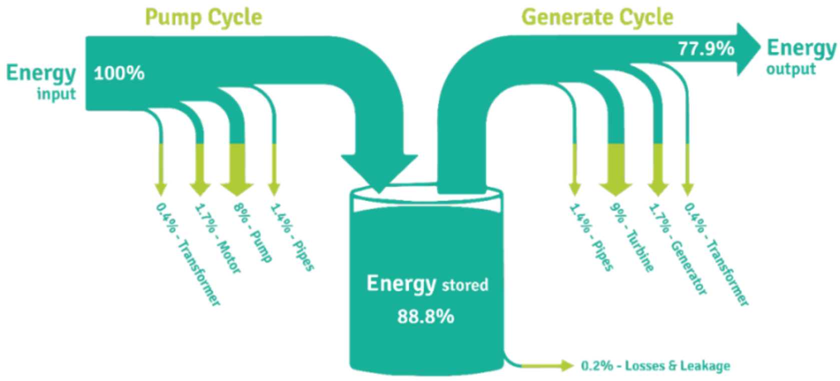

figure 7 Flow scheme of the losses in the OB (Van Rooij, 2020)

As can be seen in the flow scheme of figure 7, the losses during the charging of the OB are 11.2% and for discharging the losses are 12.3% (Van Rooij, 2020). These losses correspond to the theoretical efficiency of the OB.

6 Model

This chapter elaborates on the model which is made in Simulink. Firstly, the assumptions and input parameters are discussed. After this, the model in Simulink is elaborated on.

6.1 Assumptions

In order to make the model in Simulink, assumptions needed to be made concerning technical parameters found in literature or retrieved from technical data from manufacturers. In the following paragraphs the assumptions for every individual subsystem will be discussed.

6.1.1 Renewable energy input

First, for the input of the model, data is used from a windfarm located in Germany; this dataset has been gotten from Wout. It is not precisely known how many wind turbines are in the data set. However, the maximum and minimum output of the dataset are 1043 MW and 0 MW. The assumption made is that this input is from 11 MW wind turbines (Vattenfall, 2021), and that the input for the system is scaled down to 3 wind turbines. The input data can be seen in figure 8 below.

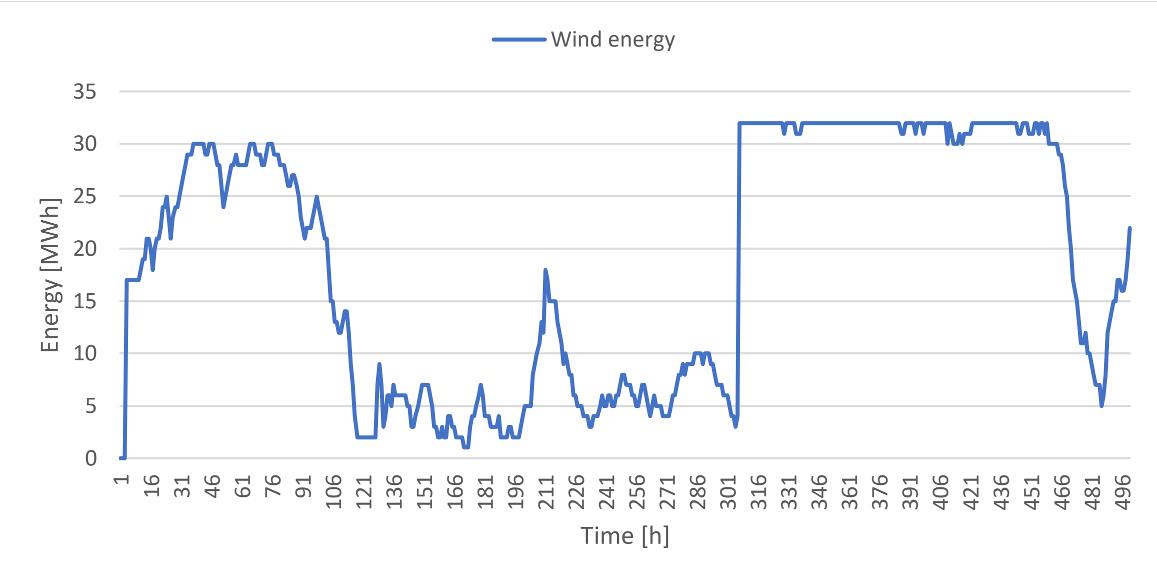

figure 8 Wind energy input for the model in MWh.

The wind energy is transported to the OB and the electrolyzers via cables. Based on platforms in the North Sea, the distance between the platforms and the wind parks is about 5 km (Jepma and Schot, 2017).

6.1.2 OB

Second, it is assumed that all the OBs in the system act as one battery. The individual OBs are not modelled individually. If energy is extracted from the OB to be used in the rest of the system, it is not specified from which OB this energy is coming. Next to this, it is also not specified which OB is charged if there is a surplus of input energy. This is probably not the case in a real life application; however, this is sufficient to model the effect of the OB on the production of hydrogen.

6.1.3 Electrolyzers

Next, there are also some assumptions for the electrolyzers used in the model. In the model only the PEM and alkaline electrolyzers are included. This is mainly because the SOEC does not yet have a real life application. For both the PEM and alkaline electrolyzer, it is assumed that all the produced hydrogen goes to the methane or methanol production site; therefore, there is not intermediate hydrogen storage necessary. Furthermore, the electrolyzers only produce hydrogen in their load range.

For the alkaline electrolyzer it is assumed that next to its load range, it also does not produce hydrogen in its lower partial load range. This is because the efficiencies in the lower partial load range get very low, and the hydrogen concentration goes to the critical point rapidly (In Lee et al., 2019). The hydrogen output is based on the energy consumption of the alkaline electrolyzer, which is 4.5 kWh/Nm3 (McPhy, 2021). An exact efficiency curve for the alkaline electrolyzer, like the one for the PEM electrolyzer, could not be found in literature. However, it cannot be simply assumed that the energy consumption of the alkaline electrolyzer is 4.5 kWh/Nm3. For this reason, the assumption is made that the alkaline electrolyzer starts at 50% of its eventual efficiency, and that this efficiency goes up linearly towards 100% of its efficiency. As was concluded in the literature research, the optimal efficiency of the alkaline electrolyzer is 71%. This efficiency corresponds to the energy consumption of 4.5 kWh/Nm3.

The PEM electrolyzer could go to an overproduction of 150% of its load range; however, this can only be done for 15 minutes. After these 15 minutes, the electrolyzer will need to cool down for 15 minutes, otherwise it breaks down (Kopp et al., 2017). For this reason, it is assumed that next to its normal load range, the PEM electrolyzer does not overproduce hydrogen.

6.1.4 Water desalination

Furthermore, during the reverse osmosis process, it is assumed that all the seawater that is needed is available. Energy for pumping the water towards the production site is not taken into account. Next, the desalination process takes place parallel to the hydrogen production. In real life, first the reverse osmosis would need to be done, after which it is used in the electrolyzer. However, for this research it does not matter that this happens in parallel, as this does not affect how much energy is needed.

6.1.5 PtG and PtL

Next, for the PtG and PtL it is assumed that all the hydrogen can be converted to either methane or methanol. For both the PtG and PtL, the formulas for the efficiency in combination with the efficiency found in literature are used to determine the output. A problem that occurred during literature research is that there was no efficiency found together with the formula used to calculate this efficiency. However, a general formula was found for the efficiency formula. Due to this, it is assumed that all the efficiencies that have been found were calculated with this general formula.

6.1.6 CO2 capture

After this, it is assumed that all the CO2 that is needed for the PtG and PtL processes can be captured from the air. However, the system does check if there is enough electricity available to do so.

6.1.7 Pipeline transport

Last, for the transport of the produced methane and methanol, it assumed that the complete output from the production site can be transported to shore. The distance which the methane and methanol have to be transported to shore differs and can be altered in the model. For the model, distances based on platforms in the North Sea have been used. These distances vary from 121 km to 213 km (Jepma and Schot, 2017). Next to this, it also assumed that the energy needed for the transportation which was found in literature is fairly constant and does not change.

6.2 Input parameters

Now all the assumptions have been made, the input variables for the model can be defined. The most important input variables can be seen below in table 6.1.

Table 6.1 most important input parameters for the model

Subsystem	Parameter	Symbol	Value	Source
Electricity transport	Efficiency electrical cables over 5 km	$\eta_{electrical}$	0.999 [-]	(Ardelean and Minnebo, 2015)
OB	Efficiency OB	η_{OB}	0.9 [-]	(Van Rooij, 2020)
	Number of OBs in the system	N_{OB}	2 [-]	-
	Storage capacity 1 OB	E_{OB_max}	8 [MW]	(Van Rooij, 2020)
Electrolyzer	Maximum capacity electrolyzer	E_{el_max}	4 [MW]	(McPhy, 2021) and (Kopp et al., 2017)
	Energy needed for reverse osmosis	$E_{desalination}$	0.0000025654 [MW / Nm3 H2]	(Karabelas et al., 2018) and (Barbir, 2005)
	Number of electrolyzers in the system	N_{el}	2 [-]	-
	Delay PEM due to start up time	D_{PEM}	0.01667 [hour]	(Götz et al., 2016)

	Delay Alkaline due to start up time	$D_{Alkaline}$	0.5 [hour]	(Götz et al., 2016)
	Minimum load alkaline electrolyzer	$E_{\min\_alkaline}$	2.08 [MW]	(In Lee et al., 2019), (Lehner et al, 2014) and (Götz et al., 2016)
	Minimum load PEM electrolyzer	$E_{\min\_PEM}$	0.04 [MW]	(Lehner et al., 2014) and (Kopp et al., 2017)
PtG and PtL	Efficiency PtG	η_{PtG}	0.84 [-]	(Götz et al., 2016).
	Efficiency PtL	η_{PtL}	0.79 [-]	(Detz et al., 2018)
	Energy needed for CO2 capture for methanol	$E_{CO2\_cap\_methanol}$	0.00548 [MW/kg CH3OH]	(House et al., 2011)
	Energy needed for CO2 capture for methane	$E_{CO2\_cap\_methane}$	0.010976 [MW/kg CH4]	(House et al., 2011)
Transport	Energy needed for transport methane through pipelines	$E_{transport\_methane}$	0.000000023 [MW/kg CH4 x distance in m]	(Kee et al., 2020)
	Energy needed for transport methanol through pipelines	$E_{transport\_methanol}$	0.000000011 [MW/kg CH3OH x distance in m]	(Müller, Fabisch and Arlt, 2014)

6.3 Application in Simulink

The parameters mentioned in table 6.1 are the input for the simulation model which is made in Simulink. The overall model can be seen in figure 9 below.

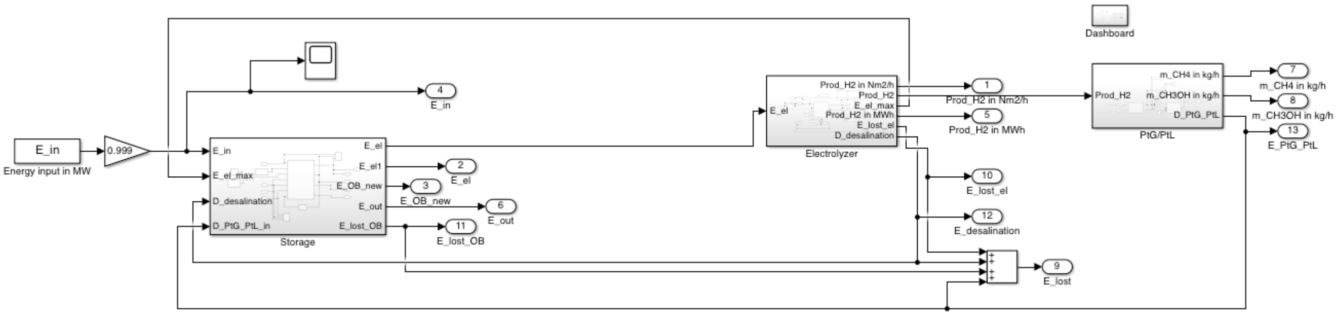

figure 9 Simulink model of the overall energy system

The energy flows from the left, at the energy input, to the right. Just as would happen on a real energy platform. However, the model checks at the start how much energy is needed for the reverse osmosis, the CO2 capture and the transport to shore. When the energy demand is available in the input energy, the total production step is implemented at once. A problem that was encountered with the model, is that Simulink cannot cope with algebraic loops. It was therefore necessary to implement delays before the signals for the energy demand are fed back into the start of the model. Due to this the energy demand lacks behind one timestep, which in this model corresponds to one hour.

6.3.1 Electricity storage/transport

Next, the model checks if the input energy is lower or higher than the maximum energy that can go into the electrolyzer. Next to this, the model also checks if there is enough energy for the reverse osmosis and to transform and transport the hydrogen. This is due to the fact that all the processes are completed in one timestep. The model for the storage and transport of the input energy can be seen in figure 10.

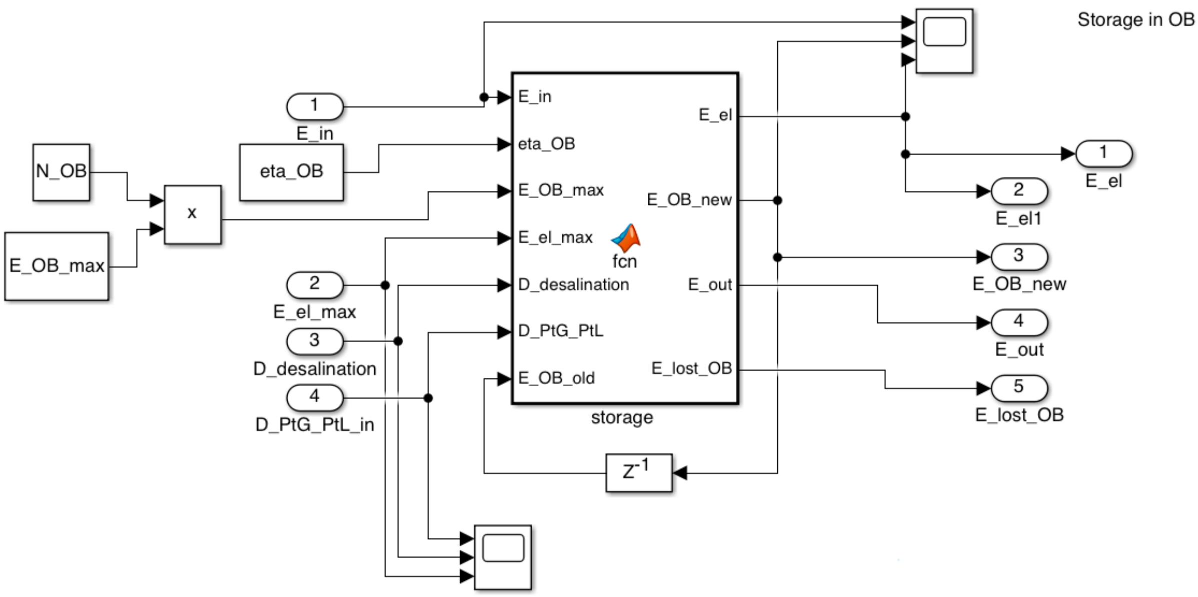

figure 10 Model for storage in the OB and transport of energy to the electrolyzer

If the input energy is not high enough to satisfy the energy demand, the system checks if there is energy left in the OB to be discharged. If the input energy is higher than the energy demand, it is checked if there is storage left in the OB to be charged. As mentioned before, Simulink cannot handle algebraic loops; for this reason, a time delay of one timestep (which corresponds to one hour) is used. Doing so, the energy output for the new energy in the OB of the MATLAB function block becomes the input in the next timestep for the old energy in the OB. Due to this the energy in the OB is one timestep behind on the actual value.

6.3.2 Electrolyzers

The energy output from the electricity storage/transport subsystem is the input for the electrolyzer subsystem. In this subsystem, the model checks if the energy input is higher/equal or lower than the minimum load which is needed for the electrolyzer. If it is higher/equal, hydrogen will be produced. The output of this system is in Nm3/h. The model for the electrolyzer model can be seen below in figure 11.

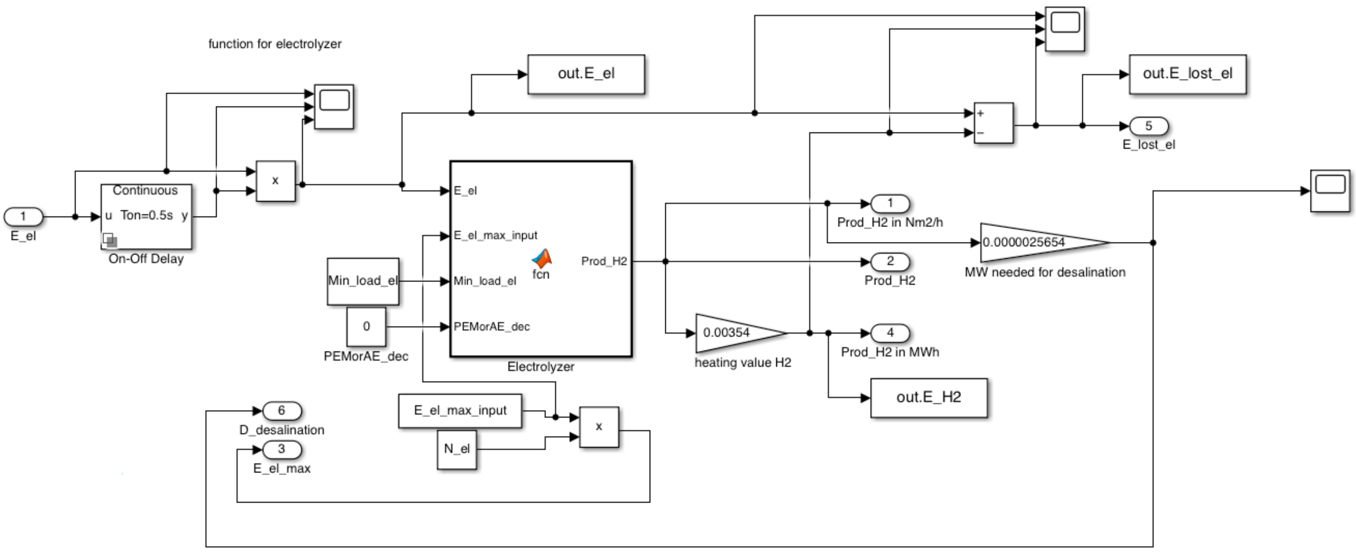

figure 11 Simulink model for the electrolyzer

There are two separate functions for the output in hydrogen for a PEM electrolyzer and an alkaline electrolyzer. The output for the PEM electrolyzer is based on the output graph in figure 5. The output of the alkaline electrolyzer is based on the energy consumption per normal cubic meter of produced hydrogen. The output in hydrogen is also converted to MWh using the higher heating value. This is done to be able to compare the energy flowing into the electrolyzer in MWh and the output in hydrogen in MWh.

6.3.3 PtG and PtL processes and transport to shore

After this, the hydrogen flows to the PtG and PtL process. In these processes, the energy efficiency equations together with the LHVs and HHVs are used to determine the output in either methane of methanol. The Simulink model for this can be seen in figure 12.

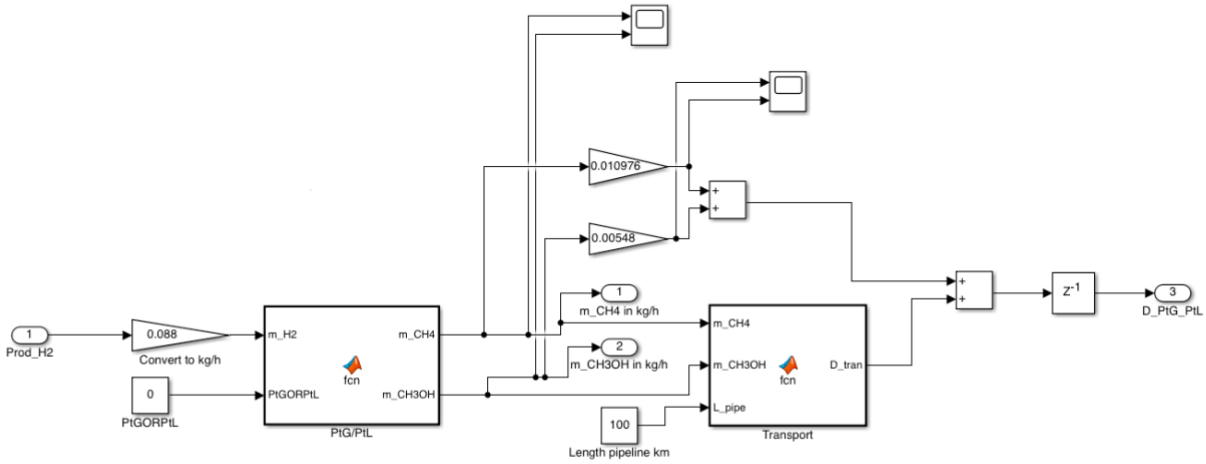

figure 12 Simulink model for the PtG and PtL process. Next to this, this part of the model also includes the transport of methane and methanol to shore.

The produced methane and methanol are also converted to MWh in order to compare the output to the input; this is done using the LHVs of methane and methanol. The LHV of methane is 0.0139 MWh/kg, for methanol this is 0.00554 MWh/kg. The produced methane or methanol then flows to the transport function. In this function it is calculated how much electrical energy is needed for the transport of methane or methanol over a given distance. This can be done because it is assumed that there are no losses of methane and methanol in the pipelines.

6.3.4 Dashboard

In order to make the model more user friendly, a dashboard is made. This dashboard is connected to the different variables in the model. The dashboard can be seen in figure 13. With the first slider a choice is made whether the alkaline or PEM function is used. Furthermore, with the second slider it is chosen if methane or methanol is produced. Next to this, the numerical values can be altered in the edit boxes.

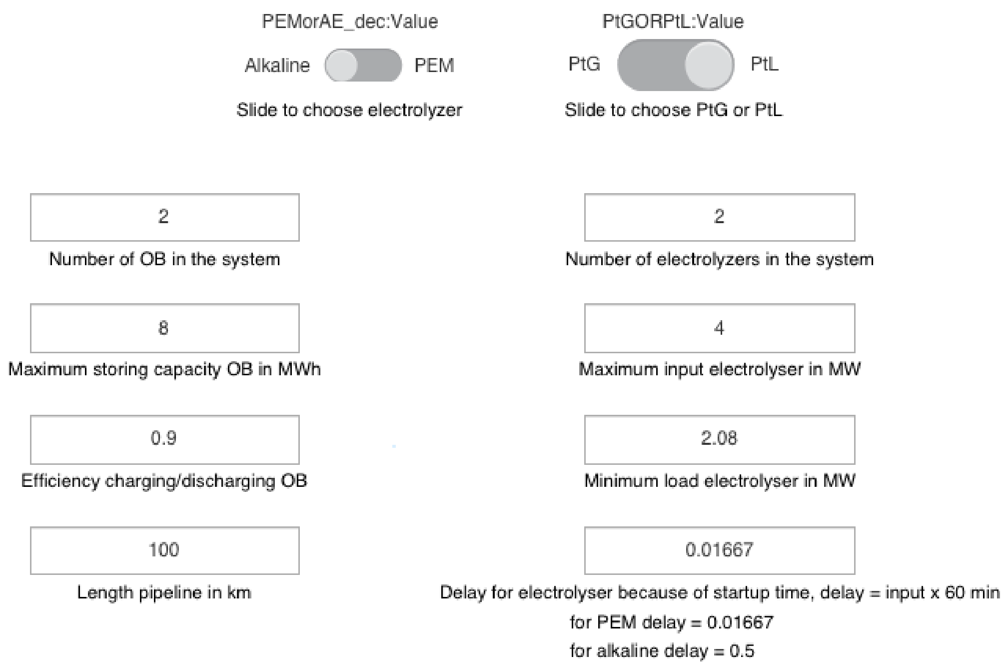

figure 13 Dashboard used as user interface for the model

7 Results

The model discussed in chapter 6 can be run with a lot of different configurations. In order to explain the difference between the different configurations, this study focuses on several scenarios. The main choices which need to be made in the model are the following: whether there are OBs in the system, the type and number of electrolyzers which are used and lastly the conversion technology that is used (PtG or PtL). This leads to eight scenarios, which are displayed in Table 7.1.

Table 7.1 Input variables for the different scenarios.

Scenario		N_{OB} [-]	$E_{OB,max}$ [MWh]	$N_{el,alkaline}$ [-]	$N_{el,PEM}$ [-]	$l_{Pipeline}$ [km]	PtG or PtL
1.1	Alkaline	2	8	2	0	121	PtG
1.2	Alkaline	2	8	2	0	121	PtL
2.1	PEM	2	8	0	2	121	PtG
2.2	PEM	2	8	0	2	121	PtL
3.1	No OB, Alkaline	0	8	2	0	121	PtG
3.2	No OB, Alkaline	0	8	2	0	121	PtL
4.1	No OB, PEM	0	8	0	2	121	PtG
4.2	No OB, PEM	0	8	0	2	121	PtL

As can be seen in Table 7.1, the length of the pipeline is not varied. This is because the simulations show that the energy needed to transport the methane or methanol is very small compared to other energy consumers.

7.1 Scenarios 1.1 and 1.2 – Alkaline

The first two scenarios use an alkaline electrolyzer. The exact input data for the model can be found in Table 7.1. In Scenario 1.1 a PtG process is simulated, with methane as the final product. Figure 14 shows the change of the energy that is stored in the OB, and also the energy which is transported to the electrolyzer, the hydrogen production and the methane which is produced.

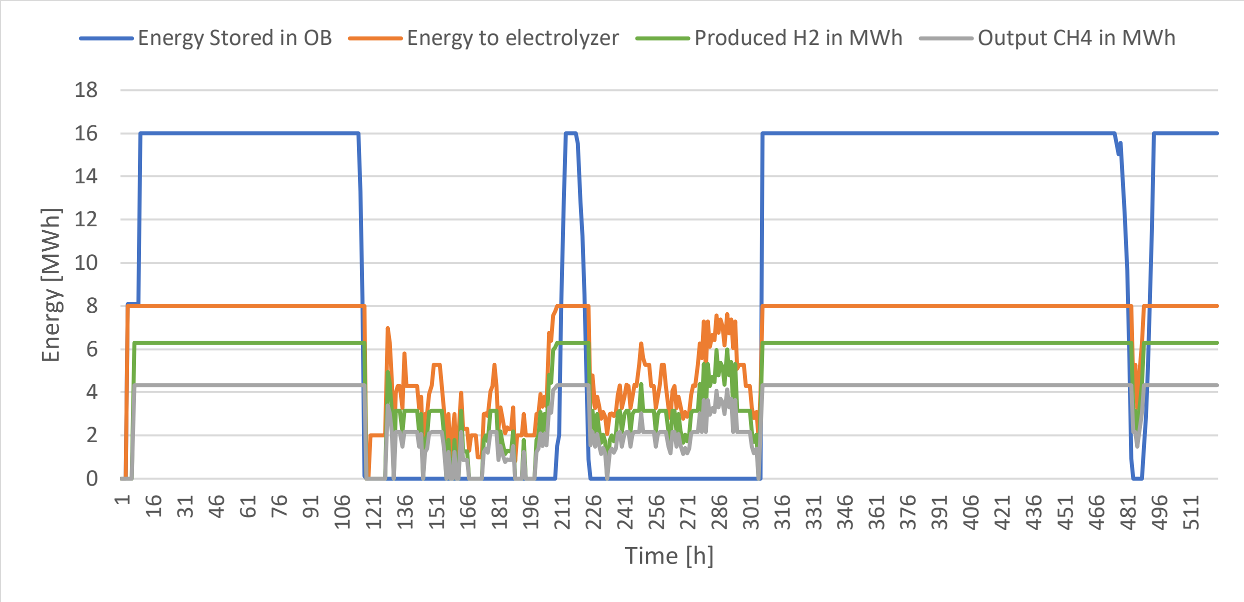

figure 14 Data for scenario 1.1 on the energy stored in the OB, transported to the electrolyzer and the produced hydrogen

The figure shows that the OBs behave as expected; energy is stored when the wind energy is higher than what the electrolyzer can handle and this energy is discharged when the input energy drops below the maximum input for the electrolyzer. However, at the beginning there is a small dip in the charging of the OB at 8 MWh. This dip is due to the delay in the energy demand from the CO2 capture, electrolyzer and the PtG/PtL conversion and transportation. Besides the charging of the OB, the figure clearly shows the lower partial load range of the alkaline electrolyzer, as there is no production of hydrogen below an energy input of 2.08 MW into the electrolyzer.

There is a difference of little less than 4 MW between the energy input of the electrolyzer and the energetic output of methane. This is due to losses in the production processes of hydrogen and methane. The system has a total methane production of 1764.9 MWh over a period of 525 hours. Besides the energy losses in these production processes, there are also losses in the OB and energy is needed for CO2 capture, desalination and transport through pipelines. These energies can be found in figure 15 below.

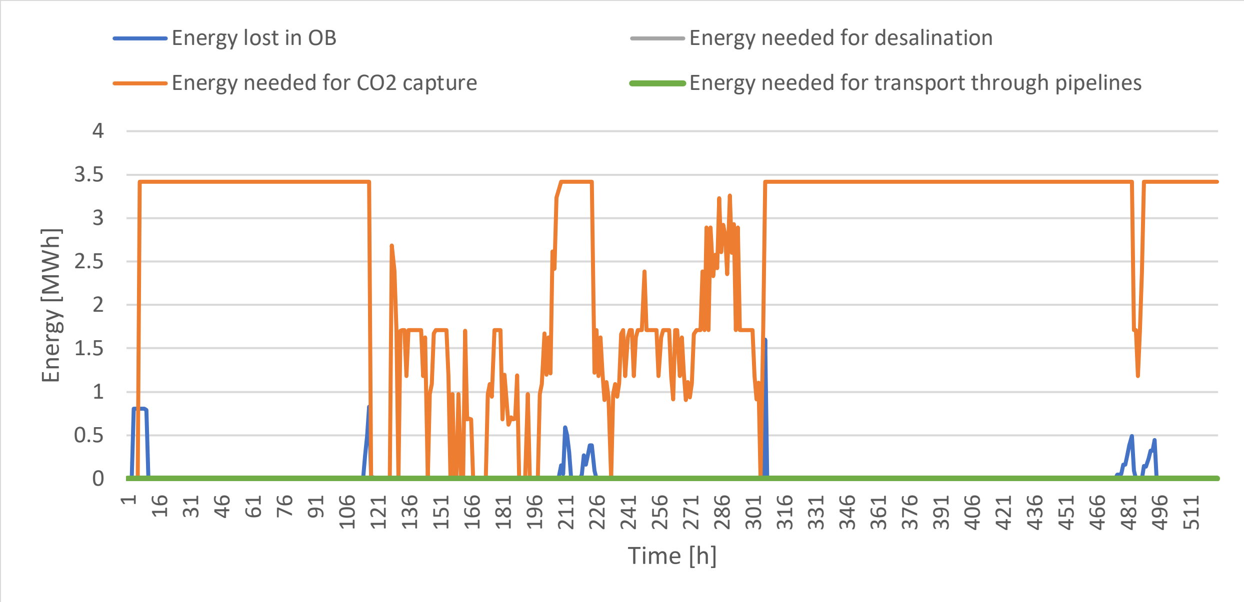

figure 15 Energy lost and needed in scenario 1.1

Most of the energy is needed for the capture of CO2. Besides this, the charging and discharging of the OB can clearly be seen in the blue peaks which represent the energy losses in the OB. Lastly, the energy for the desalination of the seawater and for the transport through pipelines are much lower compared to the energy needed for CO2 capture.

The second scenario which will be discussed is scenario 1.2. This scenario was modelled to see what the difference is between the energy efficiency of the PtG and PtL process in combination with an alkaline electrolyzer and the OB. The development of the energies in the OB and to the electrolyzer in this scenario are similar to the energies in scenario 1.1; therefore, a similar figure as in Figure 14 is produced. Only a minimal decrease is seen in the energy in the OB and in the supply energy towards the electrolyzer. This results in a very small decrease in the hydrogen production and consequently also in the output of methanol. This is due to a higher energy consumption for CO2 capture, as more CO2 is needed in the production process for methanol compared to methane; figure 16 shows that the energy needed is almost 1 MWh higher compared to that in the production process of methane.

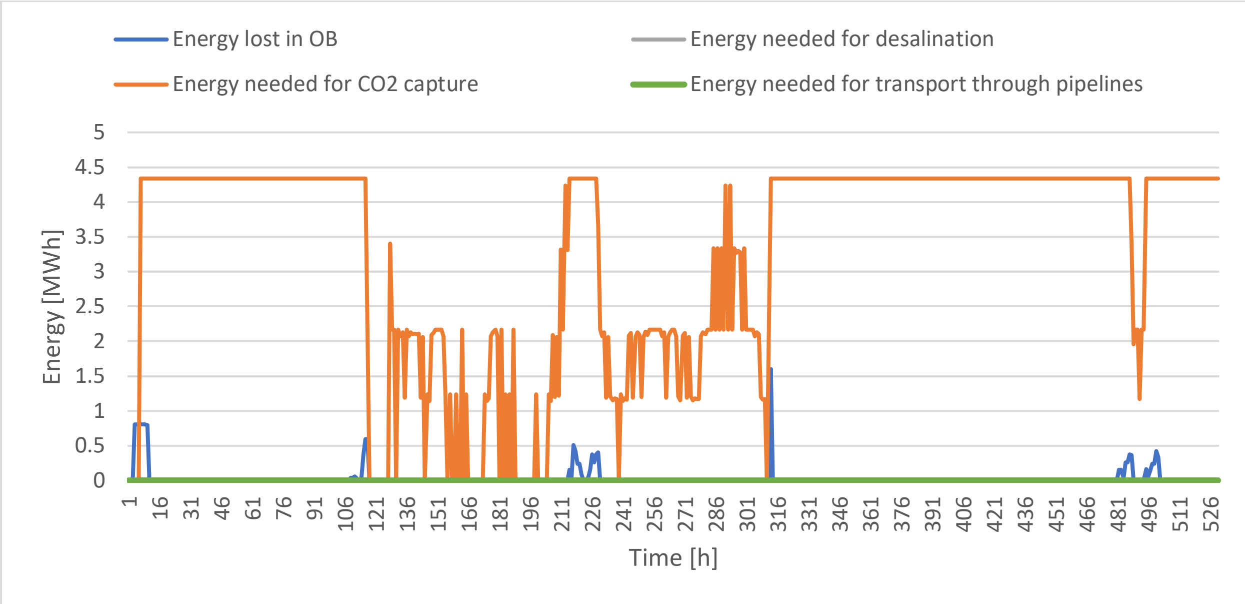

figure 16 Energy lost and needed in scenario 1.2

7.2 Scenario 2.1 and 2.2 – PEM

In the third and fourth scenario a PEM electrolyzer is implemented instead of an alkaline electrolyzer. Scenario 2.1 and scenario 2.2 are compared to each other to see the difference between PtG and PtL in a system with a PEM electrolyzer. Figure 17 shows the energies for the configuration for scenario 2.1. The main difference between this configuration and the first two configurations with the alkaline electrolyzer, is that this output shows no sign of lower partial load range for the electrolyzer; which is as expected, as literature states a very small lower partial load range (Lehner et al., 2014) (Kopp et al., 2017).

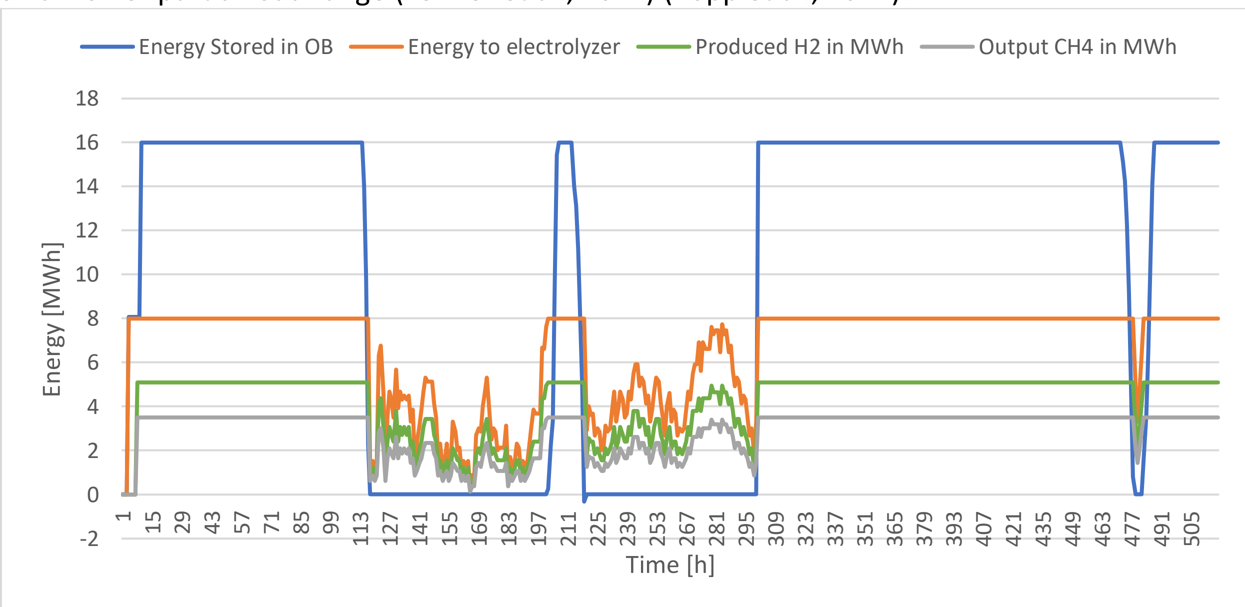

figure 17 Data for scenario 2.1 on the energy stored in the OB, transported to the electrolyzer and the produced hydrogen

Besides the lower partial load range, the energy lost in the production of hydrogen and methane is higher compared to the first two conversions. This is the result of the efficiency of the PEM electrolyzer, which is lower compared to alkaline electrolyzer. Another effect of the lower efficiency of the PEM electrolyzer is that the steady state production of hydrogen from the PEM electrolyzer is lower compared to the steady state production of the alkaline electrolyzer. A result of this can be seen in Figure 18. This figure shows that the needed for CO2 capture is lower compared to scenario 1.1; the maximum energy needed for CO2 capture in scenario 1.1 was 3.42 MWh, and for scenario 2.1 this is 2.77 MWh. The rest of the energy developments are similar compared to scenario 1.1 and 1.2.

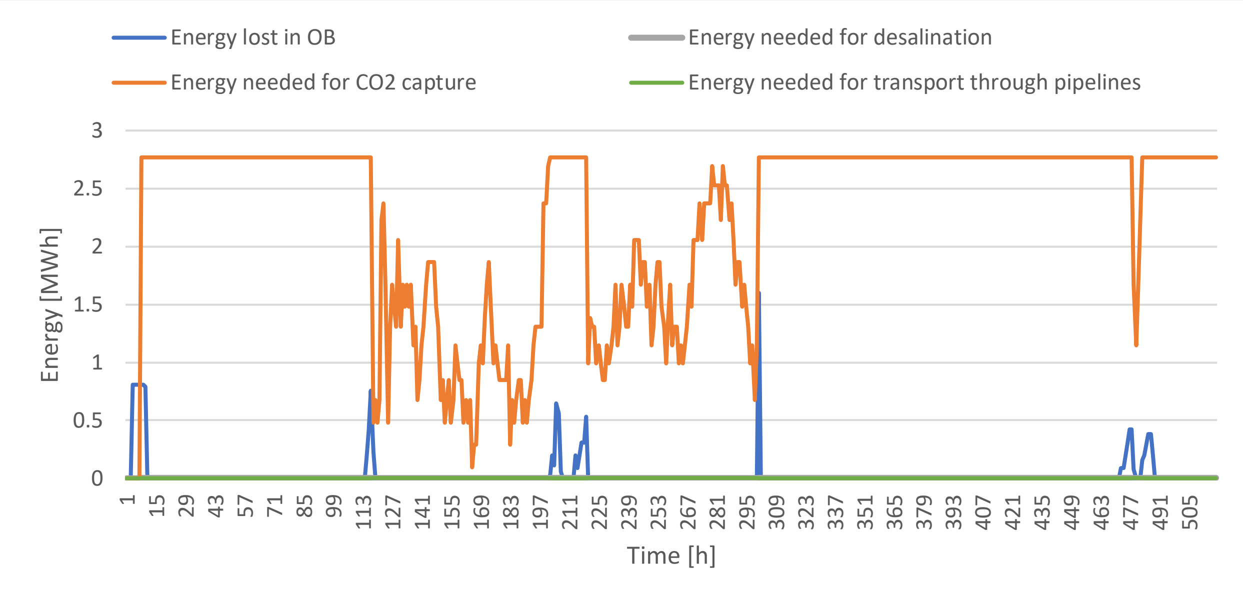

figure 18 Energy lost and needed in scenario 2.1

When comparing scenario 2.1 to scenario 2.2 the same results as in section 7.2 on the alkaline electrolyzer arise. This is logical as only the electrolyzers have been changed in the system. Less energy is available for the electrolyzer and OB due to a higher demand in energy for the CO2 capture system; this energy demand rises from a maximum of 2.77 MWh in scenario 2.1 to a maximum of 3.52 MWh in scenario 2.2.

7.3 Scenario 3.1 and 3.2 - No OB, Alkaline

In the next two scenarios the same systems are used as in scenarios 1.1 and 1.2; however, in these scenarios there is not intermediate storage in an OB. For the scenarios without an OB, the main point of interest is the difference in electricity flowing to the electrolyzer compared to the systems with an OB.

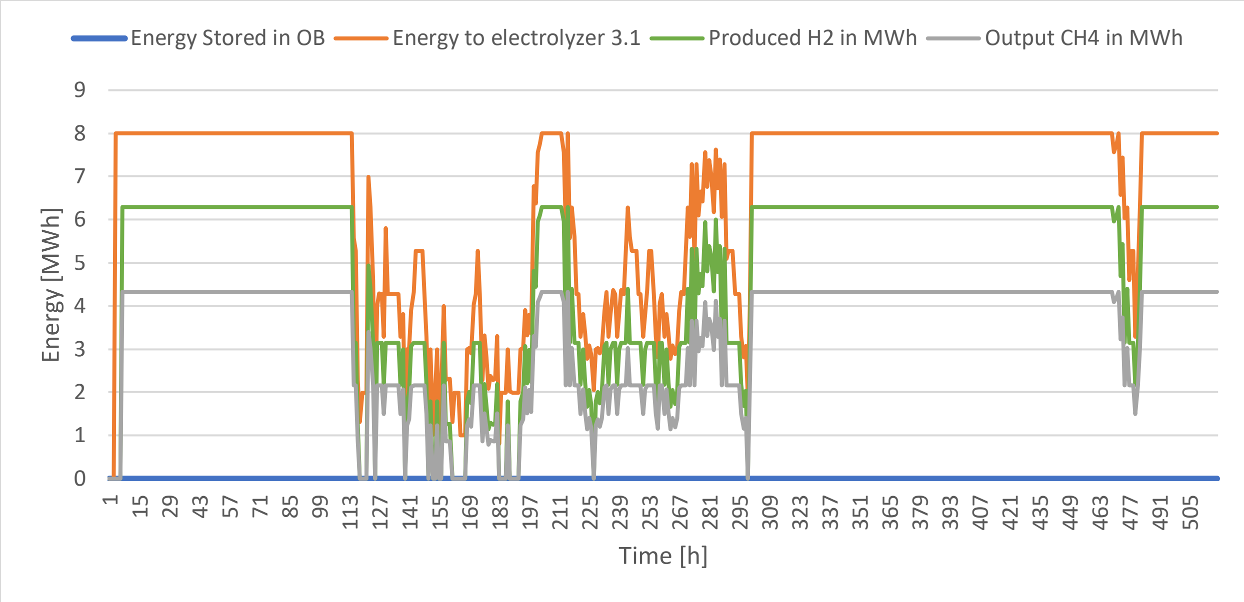

figure 19 Data for scenario 3.1 on the energy stored in the OB, transported to the electrolyzer and the produced hydrogen

It is hard to exactly compare the energies from scenario 1.1, 1.2, 3.1 and 3.2 just from the graphs; for this reason, the numerical simulation output is summarized in table 7.2 for all 8 scenarios.

As can be seen in Table 7.2, the energy to the electrolyzer in scenario 1.1 is 37.22 MWh higher compared to that in scenario 3.1.; this is somewhat similar to the difference between scenario 1.2 and 3.2., which is 33.6 MWh. This is the energy that is first stored in the OB and is discharged to the electrolyzer when the wind energy input gets lower.

7.4 Scenario 4.1 and 4.2 - No OB, PEM

In these last two scenarios there are two PEMs and again no OBs. As can be seen in figure 20, just like in scenario 3.1 there is no OB to be charged. The main two differences between this scenario and scenario 3.1 is that there is hydrogen production over the total load range and the efficiency of the electrolyzer is lower. The energy development for scenario 4.2 is slightly lower in some parts compared to scenario 4.1.

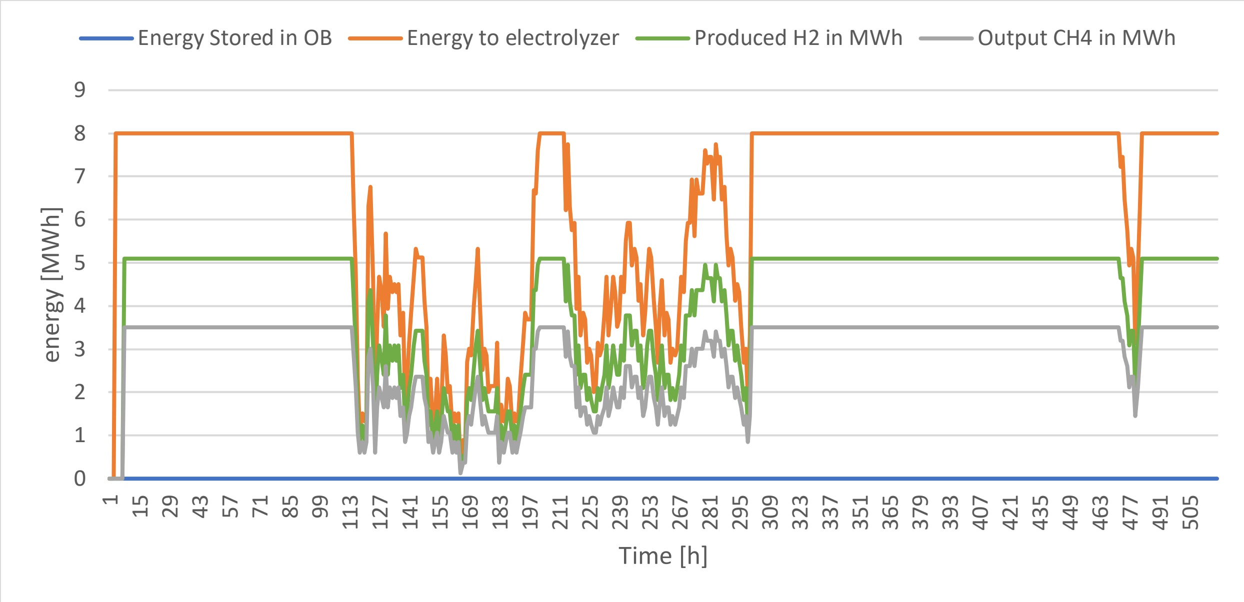

figure 20 Data for scenario 4.1 on the energy stored in the OB, transported to the electrolyzer and the produced hydrogen

To effectively compare scenarios 4.1 and 4.2 to scenarios 2.1 and 2.2, their values can be found below in Table 7.2. The energy going to the electrolyzer in scenario 2.1 is 32.49 MWh higher compared to that in scenario 4.1. In scenario 2.2 this is 42.22 MWh higher. The effect of this can be seen in the produced hydrogen and subsequently in the production of methane and methanol.

Table 7.2 Numerical simulation output for all scenarios

Scenario	**1.1**	**1.2**	**2.1**	**2.2**	**3.1**	**3.2**	**4.1**	**4.2**
Energy to electrolyzer [MWh]	3426.36	3384.79	3415.69	3376.39	3389.14	3351.19	3383.20	3334.17
Produced H2 [MWh]	2566.09	2521.86	2171.11	2136.93	2531.79	2491.29	2151.42	2115.43
Produced CH4 [MWh]	1764.98	0	1493.23	0	1741.98	0	1479.42	0
Produced CH3OH [MWh]	0	1757.30	0	1489.07	0	1736.00	0	1474.08
Energy lost in OB [MWh]	15.36	15.48	15.27	15.35	0	0	0	0
Energy needed CO2 capture [MWh]	1393.63	1738.26	1179.12	1472.94	1375.54	1717.20	1168.43	1717.20
Energy needed desalination [MWh]	1.86	1.82	1.57	1.55	1.84	1.81	1.56	1.81
Energy transport [MWh]	0.35	0.42	0.30	0.36	0.35	0.42	0.30	0.42

8 Discussion

In this research a simulation model was created in which the energy system is modelled for a renewable energy system. The system included a wind energy input, hydrogen conversion and intermediate storage in the OB, as well as the transport to shore, through pipelines. Due to the limited time and the many different aspects in the system, the model is not all inclusive and several assumptions were made. The study gave some interesting findings, with important implications for the added value of the OB and on the eventual transportation of the energy. These findings are discussed in the following paragraphs. As this study is just a start on the research of the added value of the OB to a hydrogen production, it would be interesting to implement future research. Thus, at the end of this chapter some additional opportunities for future research are discussed.

Firstly, it was found that the OB increases the energy flow towards the electrolyzer on the short term. No large differences were found between the added value of the OB to the alkaline or the PEM electrolyzer. However, due to the large difference in lower partial load range of the electrolyzers it would be logical to see a difference in the added value of the OB. This could be because the energy input that is used, is the total energy for one hour. It would therefore be interesting in future research to use a much smaller timestep to see if the added value of the OB changes. Adding to this, for the renewable energy input only wind energy is taken into account. In real life, solar and wave energy are other possible energy sources. It would be interesting to see what the effect of another energy source is on the energy system. Furthermore, the energy losses in the electricity cables from the wind turbine towards the OB and electrolyzer are considered as a constant factor that increases linearly. This is probably not the case and could be investigated.

Next, the energy losses occurring in the energy transport between the OB, the electrolyzer and the PtG/PtL conversion are not included in the model. Nevertheless, losses do occur in these parts of the energy system and it would be interesting to see if this changes the overall performance of the energy system. Furthermore, the hydrogen production of the alkaline electrolyzer is most likely not modelled according to its real life performance. This was not possible because an efficiency curve similar to the one for the PEM electrolyzer was not found. This is possibly due to the very limited partial load of the alkaline electrolyzer. Nevertheless, adding real data to the hydrogen output function for the alkaline electrolyzer would result in a better comparison with the PEM electrolyzer.

Another interesting finding was on the methane and methanol production; it was found that the most energy consuming part of this process is the capture of CO2 from air. This consuming method was chosen as this ensures for completely renewable hydrogen. However, as this energy demand is even higher than the energy losses of the actual production process of methane and methanol, it could be wise to search for other CO2 sources. Another limitation on the CO2 capture technology is that the amount of CO2 needed for methane and methanol production is based on the theoretical reaction forces. It is therefore likely that more CO2 is needed for the actual production processes, which results in a higher energy demand.

Next, the simulation assumed a methane and methanol conversion based on the efficiency formulas found in literature. However, it is not sure if these formulas correspond to the formulas used for the efficiency values for the methane and methanol reactors considering the formulas and the efficiency values were found in different sources. Another aspect that is not taken into account is that the efficiency formula for the PtG conversion uses the higher heating values; on the contrary, the efficiency formula for the PtL conversion uses lower heating values. It is not clear why this is the case but substituting the higher heating values with the lower heating values does not result in the same output. For these reasons, a more in depth research on PtG and PtL would improve a future implementation of the simulation model. Additionally, the energy needed for the transport of methane and methanol is treated as a constant per kilometre in the model. This is probably not true in a real life situation.

Besides the previously listed opportunities for future research which resulted from current limitations of the model, three additional cases for future research can be specified. Firstly, a connection to the grid can be added to the simulation model. In the current model the excess energy does not go anywhere, this would not be realistic in a real life situation. Thus, it would be interesting to see what happens to the energies in the system if the system should also account for the energy demand of the grid. Secondly, there was no time to see what the effect of disturbances in the system would have. Disturbances could occur due to breakdowns or maintenance in the OB, electrolyzer or PtG/PtL reactor. Adding this would make the model more useful for analysing real situations. The last, nonetheless an important opportunity for future research is the financial aspect of the modelled energy system. This factor is not taken into account at all but should not be discarded in analysing different configurations of the system.

9 Conclusion

In this research, an offshore renewable energy system which includes an OB, a hydrogen conversion and an energy transportation method was investigated. The goal of the research was to develop a model that shows the value of the OB on hydrogen production, as well as to show what the most energy efficient transportation form and state is for the produced energy. This was done by first conducting a literature study to determine the most important technical parameters and functions that were needed in the model. In the system, the wind energy is transported to either the OB or the electrolyzer. For the OB the energy efficiency during charging and discharging was obtained from the Ocean Grazer company. It was found that for the electrolyzer, the most important parameters are the load range, the start-up time, the energy efficiency and the duration at which the production process can continue. For the alkaline electrolyzer, the output was based on the energy demand of the electrolyzer; for the PEM electrolyzer, an efficiency curve including the hydrogen output was found. The produced hydrogen is the input for the next sub-system, which is the PtG and PtL reactor. The output of the PtG and PtL reactor can be calculated based on the efficiency formulas. Besides hydrogen, CO2 is the other main input for the reactor; the required CO2 is captured directly from the air. Finally, the methane or methanol needs to be transported to shore; the energy needed for this is retrieved from the input energy.

Next, the technical parameters and functions were translated into a realistic simulation model in Simulink. Not all parameters could be directly modelled into the system, for this reason, several assumptions needed to be made. To be able to analyse the possible configurations of the model, eight different designs were compared. The comparison was twofold; firstly, the designs were compared on the energy flowing to the electrolyzer and the subsequent hydrogen production. Secondly, the designs were compared on the energy demand for CO2 capture, desalination and the transport.

The results of the simulation show that the OB has a short term influence on the energy output of the electrolyzers. This has a larger effect on the alkaline electrolyzer then on the PEM electrolyzer. The model also shows that in the PtG and PtL systems, the main energy consumption is related with the CO2 capture. Therefore, when CO2 is directly captured from air, PtG is currently the more energy efficient system.

Overall, this research shows that there is potential for the OB in the energy supply chain with a hydrogen production. However, there is still work left in the development and optimization of the simulation model.

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Appendix 1

Convert gas state from Nm^3/h to kg/h:

The ideal gas law demonstrates that:
$PV = n \times R \times T$ in which $n = m/M$

n	mole number
m	Mass or mass flow [kg/h]
V	Volume or volumetric flow [m3/h]
M	Molecular weight of the gas [kg/kgmol]
P	Pressure = 100 kPa (in normal conditions according to SI definition)
T	Temperature = 0 ℃ or 273.15 K (in normal conditions according to SI definition)
R	Gas constant = 8.314 $[Pa \times m^3 \times mol^{-1} \times K^{-1}]$

$PV = (m/M) \times R \times T$ or $m\left(\frac{kg}{h}\right) = \frac{P \times V \times M}{R \times T}$

At normal conditions:

$m\left(\frac{kg}{h}\right) = M \times 100 \times \frac{V\left(\frac{Nm^3}{h}\right)}{(8.314 \times 273.15)}$ or

$m\left(\frac{kg}{h}\right) = 0.044\ M \times V\left(\frac{Nm^3}{h}\right)$

For hydrogen the molecular weight is 2 [kg/kgmol]