North Sea Energy
Offshore Energy Islands

Deliverable D3.8

As part of Topsector Energy:
TKI Offshore Wind & TKI New Gas

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Table of Content

1. Executive Summary

Aim of the North Sea Energy program is to create value from synergies of the current and new energy system functions offshore. One of the options to combine these options that gained attention recently is the development of offshore energy islands. Energy islands were firstly proposed to centralize electrical transmission of wind parks far offshore. However, more and more, people try to see if there are other potential use functions for such offshore islands that could improve the business case of such islands on the one hand, and mitigate some of the challenges that are expected for offshore wind and related electrical grid development on the long term (>2030) on the other hand.

In the current study, we shed some light on the dynamics of the business case of multi-functional energy islands. The aim is to identify the main trends for key parameters influencing the techno-economics of offshore energy islands with combined electrical transmission as well as hydrogen production. We did not specify a location, but we set up various scenarios of energy islands with variations in e.g. connected wind capacity, rate of hydrogen conversion, distance to shore, etcetera. Next to that, we addressed environmental and legal aspects of offshore energy islands and give an outlook towards which use functions other than electrical transmission and hydrogen production could improve the business case of offshore energy islands.

Three island variants have been studied with 2, 5 and 20 GW of offshore wind capacity connected. For these variants we analysed what the Net Present Value would be when bringing wind energy to shore as electrons and hydrogen. We assumed that either 30% or 70% of the electricity collected at the island is converted to hydrogen. A reference scenario with 100% electricity transport to shore is used to benchmark the outcomes.

The reference scenarios with 100% electron transport show the best NPV for all island variants. However, under the assumption that green hydrogen has a significant role to play in our future energy system we see evidence for a tipping point that favors offshore production of hydrogen on energy islands over onshore production under specific conditions.
In general, we observed that the offshore production is favourable over onshore production for smaller island scenarios (2, 5 GW of connected wind capacity) at larger conversion rates (70%) for the conditions that we assumed. This is in accordance with studies of the North Sea Wind Power Hub[i].
We found that the hydrogen production facility is the important driver for the cost of the island. The CAPEX of island construction is relatively minor to the price of the electrolysers. This opens the floor for potential strengthening of the business case of islands by adding potentially interesting other use functions, as creating extra space for those on the island turned out not to be the main cost driver. In general, we foresee other ways to make offshore islands smarter. On example is to explore opportunities for stacking of the hydrogen production facility to reduce the spatial claim of the electrolyser stacks.

Next to improving the project business case by adding use functions it is also needed to explore the societal and energy system value of energy islands further. This assessment has not been included so far, but could potentially improve the business case. An example of this is the potential advantages that arise from energy islands for the mitigation of e.g. grid congestion. However, monetization of this social value of offshore energy islands is not straightforward and therefore needs to be addressed in the future.

Finally, we do see that techno-economics solely do not determine whether offshore energy islands will be successful. Regulatory aspects are important as well. The government has recently announced that they are working on a policy framework concerning the construction of artificial islands in the Dutch part of the North Sea. Besides that, we also see that determination of the ecological and environmental effects of offshore energy islands is not straightforward which results in a delicate balance between positive and negative effects. We foresee that successful implementation of offshore energy islands may only work if we find a way for nature-inclusive design.
The development of offshore energy island for electrical transmission and hydrogen production is thus not straightforward, but we see that there are opportunities for successful implementation. As dynamics of the business case are strongly site-specific, feasibility of specific projects will determine if, when and under what conditions an offshore energy island could be successful.

2. Context & Scope

Aim of the North Sea Energy program is to try to create value from synergies of the current and new energy system functions offshore. One of the options to combine these options that gained attention recently is the development of offshore energy islands. The reason to study energy islands is two-fold; it might be an interesting option from a techno-economic perspective to centralize the collection of offshore wind, as well as bringing certain energy functions like e.g. production of hydrogen to the offshore. As space is limited on (existing) platform structures, there might be a need to go to islands in case capacities grow. Production on platforms is taken into account in deliverable D3.2-3.6. Secondly, not only techno-economics drive the potential move to the offshore. For example spatial, safety and environmental considerations may favour offshore activities over onshore activities for specific cases. To better understand when all these considerations point towards offshore activity on energy islands, there is a need to study the dynamics of such energy systems.

Energy islands were firstly proposed to centralize electrical transmission of wind parks far offshore. However, more and more, people try to see if there are other potential use functions for such offshore islands that could improve the business case of such islands on the one hand, and relieve some of the challenges that are expected for electrical grid development on the long term (>2030) on the other hand. Offshore production of hydrogen on such islands is currently studied intensively, e.g. by the North Sea Wind Power Hub[ii] by a consortium of TenneT NL and TenneT Germany, Energinet, Gasunie and the Port of Rotterdam, and by the IJVER island consortium[iii] of Offshore Service Facilities. Both initiatives consider one or more multi-functional island with both electrical transmission and hydrogen production. These islands have specific locations with a specific business case.
Side-specific studies can introduce some first-order estimations of trends in the business case and boundary conditions for successful implementation of energy islands. However, gaining inside in these major trends has not been the main focus of previous study and therefore generic insight in the dynamics of offshore energy islands is still lacking. This is however vital to address the general applicability of energy islands and to make sure that smart location selection can be applied.

In the current study, we would like to shed some light on the general dynamics of the business case of multi-functional energy islands. For that reason we do not specify a location, but we set up various scenarios of energy islands with variations in e.g. connected wind capacity, rate of hydrogen conversion, distance to shore, etc. Aim is to identify the main value drivers and techno-economic challenges influencing the techno-economics of offshore energy islands with combined electrical transmission as well as hydrogen production (Chapter 3). We executed a sensitivity analysis to several key parameters to better understand the business case for energy islands. However, we did not only look at techno-economics. As we have seen in earlier phases of the North Sea Energy program, legal and environmental considerations can be as important for successful implementation of system integration options. For that reason a first-order legal (Chapter 6) and environmental (Chapter 5) analysis have been executed to gain some insights in how these considerations (including potential challenges) may influence this implementation. Finally, we do believe that there might be other use functions that could strengthen the business case for offshore islands even further. Therefore, we added a qualitative assessment based on expert opinion that addresses the potential of various other use functions (Chapter 4). Chapter 7 provides a synthesis of the outcomes of the previous chapters, summarizing the main conclusions and recommendations that result from this study.

This study was developed in close collaboration between various research institutes and industry partners: TNO, New Energy Coalition, Rijksuniversteit Groningen, RoyalHaskoningDHV, Bilfinger Tebodin, DEME Group and Boskalis Subsea Cables. This collaboration enabled us to bring together applied research insights together with the industry perspective, leading to inclusion of the latest knowledge and available technology into the work stream.

3. Techno-economic analysis of electrical transmission and hydrogen production on offshore energy islands

In this chapter, the considerations and results for techno-economic analysis of multi-functional energy islands (wind transmission combined with hydrogen production) will be described. In the first paragraph we sketch the sixteen scenarios that were used to address the main trends in techno-economics for an offshore energy island. After that, several dedicated subparts of the business case will be discussed:

(i) The design and cost of hydrogen production installations on the island
(ii) The design and cost of the electrical transmission system on the island
(iii) The resulting design and costs of the island construction

These three parts will be combined in the last paragraph of this chapter into the techno-economics of the complete offshore energy islands showing the Net Present Value and Levelized Cost Of Energy for the various scenarios.

3.1. Scenarios

A set of scenarios was established to address the techno-economics of transmission of wind energy and hydrogen production on energy islands. Three main island scenarios have been set-up based on the amount of connected offshore wind capacity:

- Scenario 1; 2 GW of offshore wind connected
- Scenario 2; 5 GW of offshore wind connected
- Scenario 3; 20 GW of offshore wind connected

For these scenarios, no specific location has been chosen as the aim of this study is to identify the influence of various parameters on the business case of offshore energy islands, and not to establish a business case for a certain location. However, for the three island scenarios a distance to shore is determined as this influences some of the island costs. The islands are located respectively at 60, 150 and 300 km from shore. Similarly, a timing has been set for each island, assuming that larger islands will be build further away in the future. Therefore a respective timing of 2030, 2030 and 2040 have been chosen. The earliest timing of 2030 has been chosen for two reasons: (i) as no energy islands are expected to be built before 2030[iv], and (ii) as the chosen electrolyser type (PEM) is not expected to be available at competitive prices before 2030 at the required scale (see next section for argumentation). For each scenario an applicable transport current and voltage level has been identified in correspondence with external sources.

To address the most important trends in techno-economics of an offshore island, various scenarios have been set up with variation in:

a. Location of conversion (offshore versus onshore)
b. Conversion rate from electricity to hydrogen (30% and 70%)

A reference scenario was set up for each scenario where 100% of the energy is transported to shore as electricity. The choice for 30% and 70% is arbitrary and aims to show how the conversion influences large-scale trends in the business case. We do not claim that either of the options should be considered as an optimum conversion rate.

These variations lead to a total of 16 scenarios including the reference scenarios. Table 1 shows an overview of the main scenarios with their main characteristics. Assumptions for the specific CAPEX and OPEX calculations will be addressed in the dedicated sections.

Table 1 Overview of scenarios that were used for techno-economic analysis of multifunctional energy islands

Scenario	Capacity (GW)	Distance (km)	Timing (yr)	Conversion rate (electrons/H_2)	Location H_2 production	AC/DC	Voltage (kV)
1a	2	60	2030	70/30	Offshore	AC	220
1b	2	60	2030	70/30	Onshore	AC	220
1c	2	60	2030	30/70	Offshore	AC	220
1d	2	60	2030	30/70	Onshore	AC	220
1ref	2	60	2030	100/0	N.A.	AC	220
2a	5	150	2030	70/30	Offshore	DC	525
2b	5	150	2030	70/30	Onshore	DC	525
2c	5	150	2030	30/70	Offshore	DC	525
2d	5	150	2030	30/70	Onshore	DC	525
2ref	5	150	2030	100/0	N.A.	DC	525
3a	20	300	2040	70/30	Offshore	DC	525
3b	20	300	2040	70/30	Onshore	DC	525
3c	20	300	2040	30/70	Offshore	DC	525
3d	20	300	2040	30/70	Onshore	DC	525
3ref	20	300	2040	100/0	N.A.	DC	525

3.2. Description of functions, facilities and installations

In this paragraph the various functions, facilities and installations are described that will be considered as part of the multi-functional offshore energy island. This includes all considerations that were made to come to the techno-economic analysis of this island.

3.2.1. Electrical design

The “war of currents” (alternating current (AC) versus direct current (DC)) goes back to the 1880s. The AC market has been mostly developed since then and is the most used current for transport of energy. The demand for larger currents over longer distances is growing and the limitations of AC are also becoming visible. The loss of power is increasing over large distances, which makes AC less viable, reaching the limitations of the technique. Much is known about the AC market. Both on a technical level and on production and cost price level.

We see that within the island scenarios there is a demand for a higher current. The recently increased roll-out of HVDC projects across Europe, notably in the offshore environment, underlines the need for improving the reliability and availability of HVDC cables and systems. Because the application of DC subsea cables is relatively limited so far worldwide, external information has been obtained for this through desk research on existing 525kV lines (like Viking) and external experts. In this way, developments in the DC field have been added to create a most complete image.

This study has resulted in different scenarios based on the year of execution of the energy island. Figure 1 shows an overview of the cable designs for the three main scenarios. The total generation of energy has been taken into account, in combination with expected future developments regarding cable technology.
TNO has developed a dedicated offshore energy transport model to make a cost-optimization on cable costs given a certain technology, distance and volume of energy. The model optimizes the cross-section and the number of (parallel) cables.
The first scenarios have been discussed with relevant external sources. The outcome of the described scenarios below are based on standardization philosophy of the Dutch TSO (TenneT 2017)[v]. Note that the costs of the infield cables (66 kV) are not taken into account as these are part of the wind park.

3.2.1.1. Scenario 1: 2GW 2030 60km

For the island scenario of 2 GW the infield voltage has been set to 66 kV. The limiting distance for 66 kV AC power is around 30km[1]. We assumed that in case of a 2 GW power hub the windfarm will be located within a range of 30 kilometers from the island. In this case an additional connection platform between the windfarm and the island is not needed. Substations usually regulate voltage flows to the grid, but can be placed on the island itself in this case. The export cable scenario is based on the standardized 700MW 220 kV concept (TenneT 2017).

3.2.1.2. Scenario 2: 5GW 2030 150 km

For the island scenario of 5 GW the infield voltage has been set to 66 kV. We assumed that in case of a 5 GW power hub the multiple windfarms will be located within a range of 30km from the island. In this case an additional connection platform between the windfarm and the island is not needed. More interesting in this case are the future developments of voltages for export cables. In this case a tipping point is addressed for AC or DC power. The expected developments for power scenarios by the time of executing are expected for 400KV for AC and 525KV for DC (EUROPACABLE 2019)[vi]. Based on expert-input from external sources a development to 525 kV DC seems more viable (due to standardization) than 400 kV AC power by the time of 2030.

3.2.1.3. Scenario 3: 20GW 2040 300km

The last scenario is based on a timeframe of 2040, with a total amount of energy of 20GW,and a distance of 300km from shore. Because of the high amount of energy it is plausible that not all the energy will be generated within a range of 30km of the island. In this case it is assumed that half of the energy will be generated within 30km of the island and the other half will be generated outside the 30km range. In this case we have assumed two substations to channel half of the wind energy (10GW) to the energy island. These substations step up the incoming voltage level of a windfarm (66kV) to an alternating current of 220 kV, which transports the energy from a windfarm to the island. In this case half of the energy is channeled via the standardized 220 kV concept to the island, and the other half via 66 kV. The generated energy will come in on to the island in two different voltage levels. On the island the energy is getting transformed to meet the requirements of the export transmissions to shore or to meet the requirements of the electrolyser package.

[1] discussions with relevant external sources

2 GW transmission system island to shore		
220 kV HVAC transmission - 60km		
Island **66kV - 220kV** Transformer costs (step-up) Switch gear costs Installation costs	HVAC cable costs (procurement) cable laying and losses reactive power compensation costs	**Onshore substation** **220kV - 380kV** Transformer costs (step-up) Switch gear costs Installation costs

5 GW transmission system island to shore		
525 kV HVDC transmission - 150km		
Island **66kV - 525kV** Transformer costs Converter costs (AC-DC) Installation costs	HVAC cable costs (procurement) cable laying and losses reactive power compensation costs	**Onshore substation** **525kV - 380kV** Transformer costs Converter costs (DC-AC) Installation costs

20 GW transmission system island to shore				
Collection system to island		Transmission system island to shore		
220 kV AC collection - 30 km		525 kV DC transmission - 300 km		
Platform **66 kV-220 kV** Transformer costs Switchgear costs Platform costs Installation costs	HVAC cable costs (procurement) HVAC cable laying costs HVAC cable losses Reactive power compensation costs	**Island** **220 kV AC - 525 kV DC** Transformer costs (Converter costs (AC/DC)) Installation costs	HVDC cable costs (porcurement) HVDC cable laying costs HVDC cable losses	**Onshore Substation** **525 kV - 380 kV** Transformer costs Converter costs (DC/AC) Installation costs

Figure 1 Overview of electric system components for techno-economic analysis

3.2.2. Hydrogen production facility

In this paragraph we describe the necessary elements of the hydrogen production facility and considerations and assumptions for this production facility.

3.2.2.1. Proton Exchange Membrane Electrolysers

For this study, we have chosen to work with Proton Exchange Membrane electrolysers. For an energy island, transport of raw materials as well as footprint should be as low as possible. A PEM electrolyser has an advantage over e.g. alkaline electrolysers in terms of raw material usage as well as it has smaller footprint. Thereby, the PEM electrolyser has a response time in seconds, whereas an alkaline electrolyser requires minutes for startup.[vii] For that reason, it is foreseen that the PEM electrolysers will dominate the electrolysis market after 2030 with strong intermittent energy sources as a feed-in. Figure 2 shows a typical flow diagram for a PEM electrolyser unit.

3.2.2.2. Electrolyser efficiency

The efficiency of an electrolyser is defined as the ratio of the higher heating value of hydrogen (HHV) to energy consumed by the electrolyte per kg of hydrogen. At present, typical electrolysis efficiency ranges between 70 and 75% (HHV)[viii]. The efficiency of electrolysis is expected to increase in future. This projection is based on many factors such as current density, electricity costs, capital costs, etc. In this case study, the efficiency is maintained at 72% for the 2 GW and 5 GW island scenarios (Scenario 1 and 2, timing 2030), a typical value that is predominantly found in the electrolysis market now. The efficiency calculations for 2040 and beyond (Scenario 3, timing 2040) are calculated for higher efficiency (85%) since efficiency is likely to increase in future[ix].

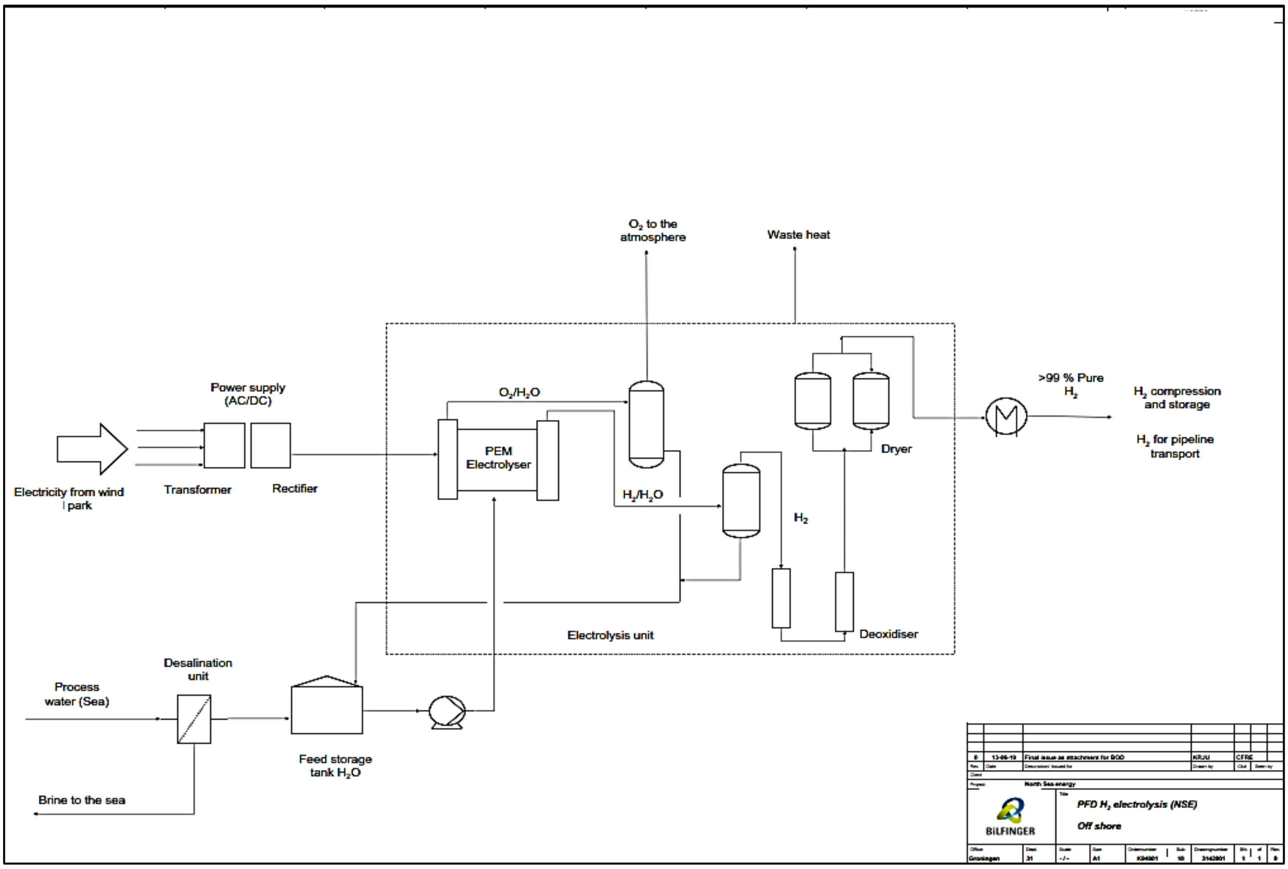

Figure 2 Typical process flow diagram (PFD) for a PEM electrolysis unit

3.2.2.3. High-voltage transformers (incl. rectifiers)

The hydrogen production process needs low-voltage direct current. Wind turbines typically supply high-voltage alternating current; therefore, the high voltage has to be transformed. This will be done in two steps, for example 220 kV → 66 kV → 400 V. The 220 kV/ 66kV conversion shall be on a separate part of the island and the 66 kV/400V including high power rectifier shall be located close to the electrolyser units. Table 2 shows the transformer numbers for each scenario.

Table 2 Number of transformers required for each scenario.

Scenarios	Wind Capa-city (GW)	H2 conversion rate (%)	Capacity electrolyser (GW)	Number of Transformers (400MW 220/66kV)	Number of Transformers (25MW 66kV/400V)	Number of Transformers (50MW 66kV/1000V)	Number of rectifiers
Scenario 1b	2	30%	0,6	2	27		27
Scenario 1d	2	70%	1,4	4	62		62
Scenario 2b	5	30%	1,5	4	66		66
Scenario 2d	5	70%	3,5	10	155		155
Scenario 3b	20	30%	6	17		134	134
Scenario 3d	20	70%	14	40		311	311

3.2.2.4. Desalination

A specific component that is imperative for electrolysis is the availability of demineralised water. Figure 3 shows the demand for demineralized water in the various scenarios.

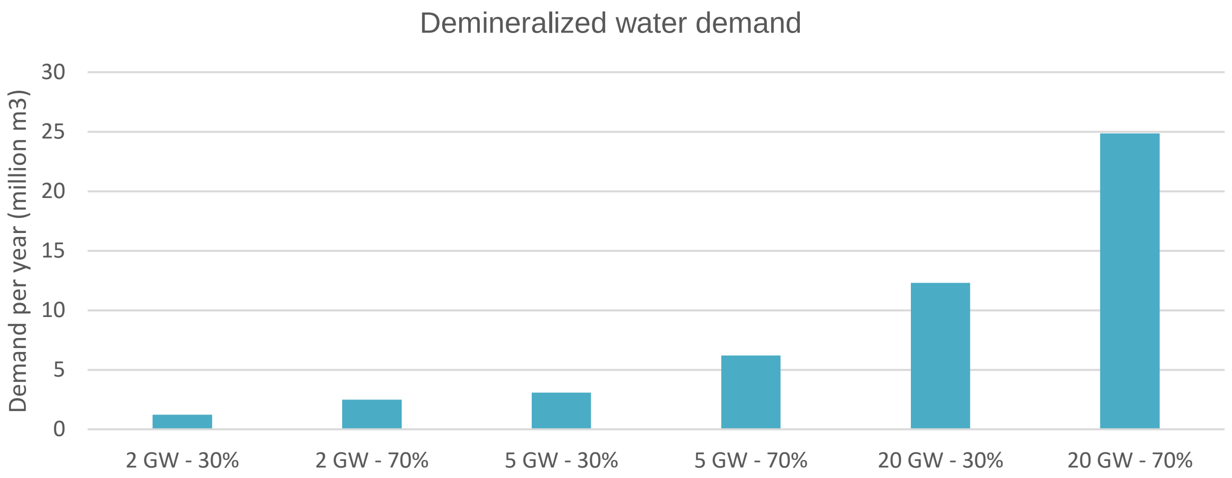

Figure 3 Demand for demineralized water

On the bases of full load, some 2 to 25 million m³ of demi water would be required per year[2]. This can be produced from sea water, but that requires a demineralisation unit. An extensive description of considerations regarding desalination can be found in Appendix D. Figure 4 shows the expected CAPEX of the desalination unit for the various scenarios.

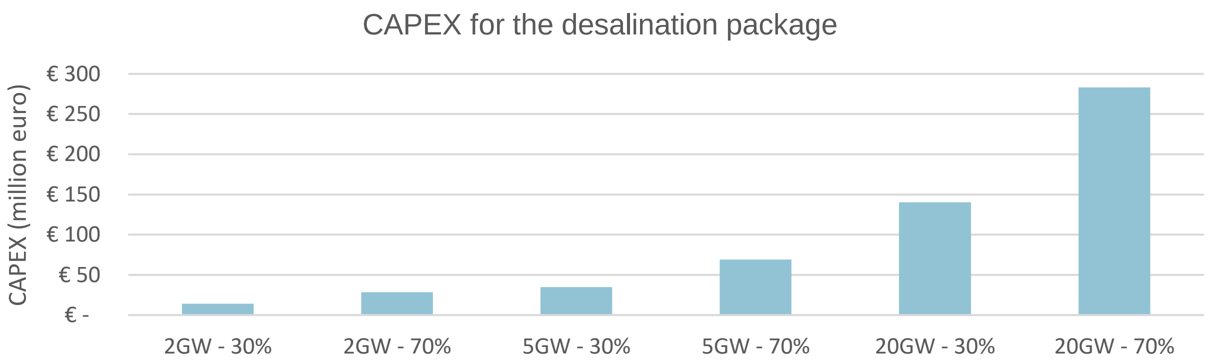

Figure 4 CAPEX desalination package for the various island scenarios

3.2.2.5. Deoxidizers & dryers

The electrolyser system, apart from cell stack and feed water demineralizer, includes a hydrogen scrubber, deoxidizer and drying unit. Saturated hydrogen gas is fed into the gas scrubber system, which purifies the produced hydrogen. Residual oxygen in hydrogen gas is removed using deoxidizer unit followed by drying in twin tower dryer.

[2] The power requirement for the desalination unit was set at 0,004 kW per liter per hour, which equals 2,99 kWh/m³.

3.2.2.6. Compression & boosting

High pressure hydrogen compression is a prerequisite for the transport of hydrogen to shore. Because of its lower molecular weight and viscosity, hydrogen flows move 2–2.5 times faster than natural gas in a pipeline under the same conditions of pipe diameter and pressure drop. However, because of the lower heating value of hydrogen, a hydrogen pipeline carries about 30%–40% less energy than a natural gas pipeline. That is why hydrogen pipelines need to operate at higher pressures to supply the same amount of energy, or need to have a larger diameter (Ball, 2009)[x]. Assuming that at the upstream end in each scenario (the production location) a PEM electrolyser will split the water molecules using offshore wind power to produce the hydrogen, output pressure at the pipe inlet will be in the order of 30 barg. It is expected that due to technological innovation this may increase towards 60 barg (Hinicio, 2017)[xi]. New developments are being carried out to advance on the High-Pressure Electrolysis (HPE), which is based in the PEM electrolysis, but with the difference that the compressed hydrogen output is around 120 to 200 bar at 70 ºC.

In each offshore scenario the hydrogen is compressed to satisfy the required downstream receiving pressures of 30 barg at shore. The input pressure varies between all of the scenarios as it is determined by a pressure drop calculation tool. The pressure drop calculation tool is used to determine the size of the pipeline and the design or inlet pressure of the pipeline. A number of limitations were set to this tool (See Table 3) At shore, the hydrogen is compressed (via a booster) to 68 barg. An additional booster is assumed to increase the pressure from 30 to 68 barg making it comparable to the pressure on the existing gas grid. Combining the criteria set in the table below with the volume of hydrogen produced, an optimisation between pipeline diameter and input pressure is calculated. When the flow rate is too high, the pressure drops below 0, which can be corrected by using a larger internal diameter.

Table 3 Model input for pressure drop calculation

Model input pressure drop calculation	Value
Output pressure (onshore)	30 bar
Admissible surface roughness new pipeline	0.05 mm
Temperature (at inlet)	10 deg. C
Molecular weight	2.016 g/mol
Dynamic viscosity	0.0000086 Pa.s
Velocity	Between 10 and 20 m/s.
Mass flow rate	Variable input (depending on the scenario) (kg/h)
Distance	Variable input (depending on the scenario) (m)
(Internal) Diameter	Variable output (depending on the scenario) (m)
Pressure (at inlet)	Variable output (depending on the scenario) (bar)

The CAPEX of compression is determined on the base of compression power required for the various scenarios. Appendix D shows some additional background on how the compression cost where determined. The result are displayed in Figure 5. Capital cost of about €2000/kW[3] are assumed, operational expenses of 8% of the initial CAPEX and in additional varying electricity cost based on compression power.

We compared our outcomes with quotes from vendors, that yielded that we may be on the optimistic side when it comes to CAPEX of compression. On the other had, as we consider scenarios that are up to 20 years in the future, we think that this falls in the uncertainty range.

[3] Based on (Jean Andre, 2014) while assuming an exchange rate of 1.20 EUR/USD (2017)

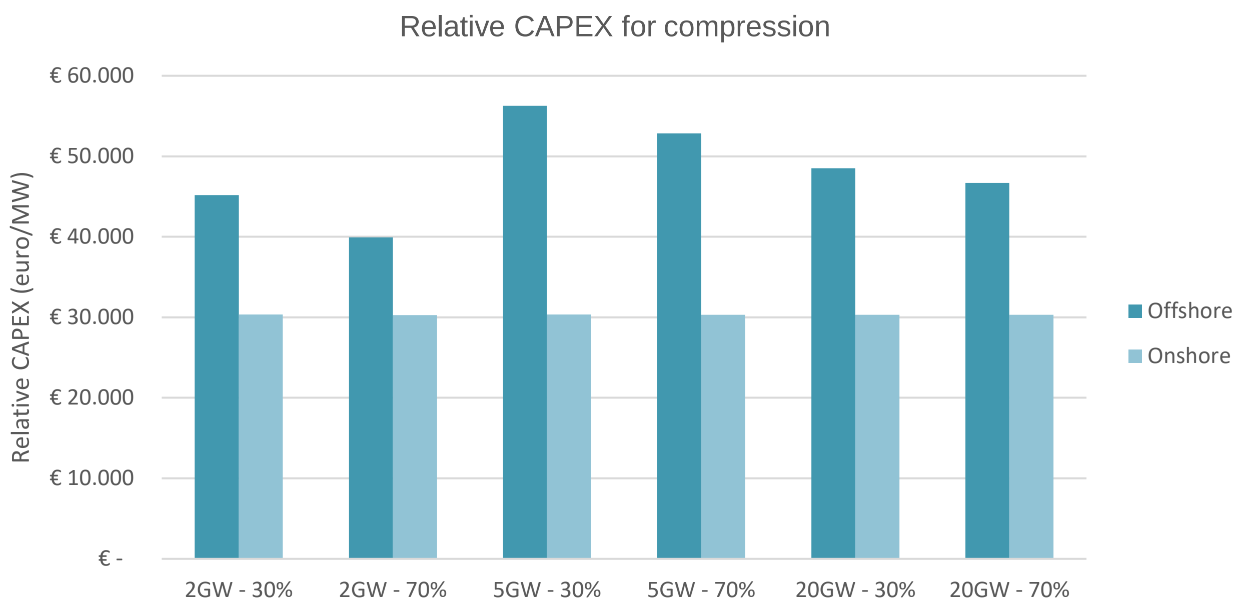

Figure 5 Relative CAPEX of compression in €/MW installed hydrogen capacity

3.2.3. Hydrogen transport pipelines

Pipeline transport of hydrogen can take multiple forms. In the most cost-optimal situation, the existing pipeline infrastructure can be used to transport pure hydrogen to shore. In the least cost-optimal situation a new dedicated hydrogen pipeline should be installed. Since the exact location of the island, and thus the proximity of existing pipelines is unknown, new, dedicated hydrogen pipelines are taken as a base for calculation. The pressure drop calculation tool (developed as part of WP 3.4[4]) is used to determine the size of the pipeline and the design or inlet pressure of the pipeline. The output pressure of the pipeline is set at 30 bar (similar to the output pressure of the onshore electrolysers), and the diameter of the pipeline is set such that the velocity of hydrogen transport does not exceed 20m/s. The pipeline outer diameters ranges between 10 inch (2GW 30%) and two pipelines of 36 inch (20GW 70%).

The methodology used to construct associated costs follows the series of estimations made by EBN and Gasunie in their report 'Transport en opslag van CO_2 in Nederland' (EBN & Gasunie 2018)[xii] and is extensively discussed in Deliverable 3.2 to 3.6. It states that on average, besides the pipeline material, two major factors are crucial for pipeline investments costs: the diameter and the distance to be covered (see Figure 6).
The CAPEX of pipelines with different diameters is shown in Figure 6 below. It is important to mention that there are more costs related to the installation of pipelines which are not taken into account in this study due to undefined locations. To such costs belong e.g. pre-installation surveys and tests as well as the CAPEX of crossings. To apply these cost data for hydrogen pipelines minimal adjustment to the formula are required. It is expected that special seals to minimize hydrogen leakages will require special labour (H2-specific welds) therefore more expensive labour, some 25%. Another concern with hydrogen is that pipes resisting hydrogen embrittlement will cost more than ordinary pipe (some 50%). Since, the existing right of ways will be used, a top-up cost factor of only 13% will be assumed that is expected to cover all additional investment cost for hydrogen pipelines.

[4] This tool is developed by Hint and available upon request to NSE3 consortium members

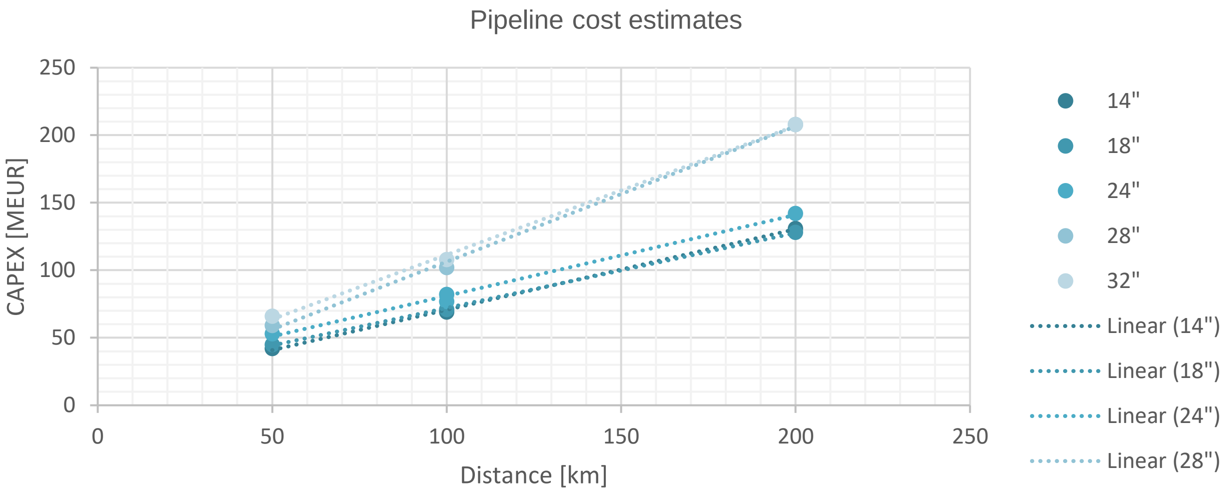

Figure 6 Pipeline cost estimates as a function of diameter and length (author's figure, based on EBN & Gasunie (2018)[xiii])

Figure 7 gives an overview of the pipeline costs for the various scenarios. Other factors that can have a prominent impact on the cost of laying new pipelines include: submarine obstacles (such as other pipes and cables), but also super-sea obstacles, such as platforms or wind farms. All this may require that crossings need to be implemented. As this study does not focus on a specific location within the North Sea, it is not possible to assess how many and what type of crossings should be considered when concrete locations will be studied. Such costs obviously must be taken into consideration in greater detail if a specific location would be chosen. We compared these costs to the results of the H-vision project[xiv]. This yielded that costs for larger diameter pipelines (> 18 inch) may be on the optimistic side.

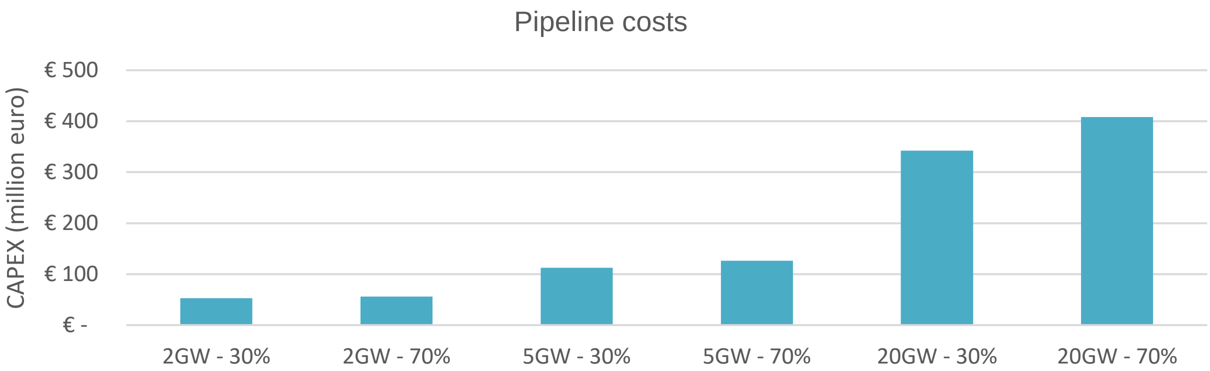

Figure 7 Pipeline costs for the various scenarios

3.2.4. End-of-life costs

It is very unlikely that the island will be removed if the end-of the technical lifetime of the installed windfarm/hydrogen conversion is realised. The lifetime of the island is expected to be longer than of the installed equipment. Although, it is hard to monetize the future value of an island, it is very likely that the island will be re-used for the next-generation wind turbines/electrolysers. The value is conservatively set to zero, though it can be expected to be positive since it exceeds the lifetime of the analysed energy system. Moreover, from a juridical and ecological stand point it is unclear whether removal of a sandy island will be necessary/favourable. Though, cost reservations should be made if more clarity will be provided from a juridical point regarding ownership and operational responsibility with respect to the removal of energy islands.

3.2.5. Other island functions

To enable the development of various use functions at an offshore energy island, several generic use functions are needed, e.g. living areas, a helicopter landing zone, a harbour with relevant bunkering opportunities, etc. In this study, areal space for these activities is included in the island construction plan (see also plot plans in Appendix A). However, we have chosen not to take the costs of these activities into account in the techno-economic analyses. This is because we expect these costs to be minor compared to the electrical and hydrogen installation costs, and (ii) because these costs will be present for each type of island and are therefore not interesting for comparison reasons.

3.3. Hydrogen production & processing installation costs

This chapter describes the costs of the hydrogen production facility for the various scenarios. The objective of the ballpark CAPEX figures is to consider the economic feasibility of hydrogen production and installation both offshore and onshore. The ballpark figures were realized using the methodologies and tools from Bilfinger Tebodin. Based on the different capacities (GW) of hydrogen production, total CAPEX was estimated for the various scenarios.

Price ranges are consistent for all components. However, there is a major uncertainty in the electrolyser cost. According to Schmidt et al (2016)[xv], the price range for PEM electrolysers in 2020 varies from 1000 -1950 euros/kW. For 2030, it is predicted PEM will cost 850 -1650 euros/kW. This is due to technology dominance and production scale up of PEM stacks which could result in 8-24% cost reduction (Bartel et al. (2010)[xvi]). Recent communication with two leading suppliers indicated a much lower price range from 700 – 1000 euros/kW in 2030. This leads to a strong spread ball park figure range for the whole system. These varying costs were taken into account and moderated towards a more realistically ranged scenario.
We assumed base case prices of the electrolyser to be 700 euro/kW and 400 euro/kW in respectively 2030 (Scenario 1 & 2) and 2040 (Scenario 3). These numbers were determined in collaboration with TNO experts. The lifetime of the electrolyser stack was assumed to be 7 years for all scenarios. The lifetime of all other components was estimated at 20 years. In all scenarios (offshore and onshore), the major cost component is the PEM electrolyser. For the offshore, an offset factor of 25% is used to compensate for transportation and installation of all equipment and materials to the offshore location. We estimated this factor based on Bilfinger Tebodin expert opinion.

Ballpark figures for equipment have been obtained through Bilfinger Tebodin database or through budget quotes from two vendors. For balance of plant, building and infrastructure the prices were based on the provided lay-out. We used this lay-out to determine general material take off (MTO) and priced this accordingly with Tebodin database. Indirect costs like engineering construction services are taken as a percentage of direct costs and range between 1 and 2%. Contingency is included as this study is in prefeasibility phase. The contingency percentage for offshore is set at 25%, whereas it is 20% onshore. Hence the accuracy of the ball park figure is +/- 50%. Figure 8 shows the ballpark CAPEX figures for the various scenarios for both onshore and offshore. A detailed break-down of these ballpark figures can be found in Appendix J.

This cost estimate shows the influence of costs of the electrolyser packages to the total investment of the energy Island, even though no large-scale offshore hydrogen production facilities exist today. The results from cost estimates has to be considered in detail when an offshore hydrogen production facility is considered to be developed. This study only examines the feasibility of hydrogen production with technological simplicity, as there is a need for further research on technological challenges such as design of auxiliary systems, desalination, electrical equipment etc.

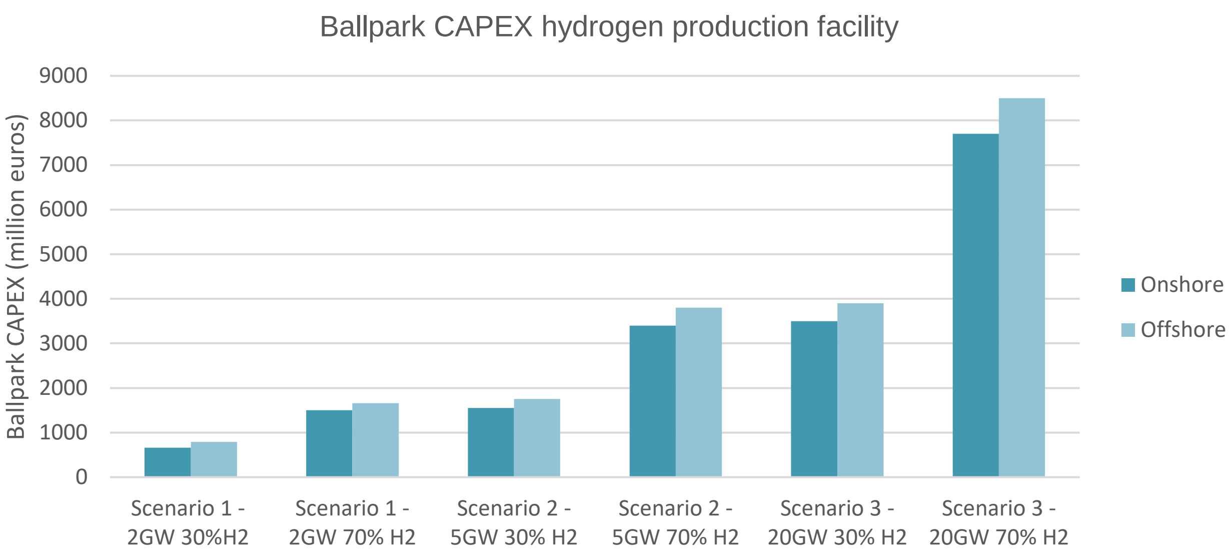

Figure 8 Ballpark CAPEX installation design. The uncertainty in the CAPEX figures is +/-50%.

3.4. Electrical design plan and costs

3.4.1. Electrical design costs model

TNO has developed a dedicated offshore energy transport model for calculating electric infrastructure costs. This sections describes this model in short. Appendix I gives an extensive description of the equations. The electric infrastructure costs are calculated based on a technical design relevant for a typical power transmission system for the Netherlands. For both HVAC & HVDC power transmission systems, sub-components such as cables, inductors, transformers, offshore platform, etcetera were identified. For each sub-component, costing data were sourced from public & proprietary sources available in the Eefarm database[5]. The costing data was fitted to a linear or quadratic polynomial and included within the offshore energy transport model as cost functions.

HVAC transmission system considers a cable voltage of 220 kV, 100% reactive power compensation (50% at each cable end), 1 transformer per cable and transformer rating of 125% of the active power transmitted. 8 standard cable c/s sizes (IDs) were included in the model. A thinner cable is rated to transmit less power than a thicker cable. Cable size is chosen programmatically to be just sufficient to transmit desired active power. If one cable is insufficient, then additional cables are considered in parallel until all desired active power can be transmitted. All parallel cables are assumed to be of same c/s size.

HVDC transmission system considers a cable voltage of 320 kV & 525 kV, bi-polar (or similar) configuration requiring a cable-pair, pair of rectifiers per cable-pair. Similar to the HVAC transmission system, 8 standard cable c/s sizes (IDs) are included, with parallel cables added if necessary to transmit desired power levels.

For both the transmissions systems, cable costs include a fixed cable laying cost (per km). For HVAC cable, the laying cost was applied for a single cable whereas for HVDC cable, the laying cost was applied for a cable-pair. Apart from the cable costs, the offshore platform (including transformers/rectifiers) and onshore substation costs are also calculated.

[5] TNO & TU Delft developed the Eefarm program for the electrical and economic evaluation of different electrical layouts & concepts for offshore wind farms

3.4.2. CAPEX of electrical transmission

Using the offshore energy transport model as described in the previous paragraph, we determined the CAPEX for electrical transmission on the island for the various scenarios. In the 20 GW case some 10GW of 220kV collection system is required as the wind turbines are located outside the 66kV area range of 30-40km. Preferably, this energy will be stepped-up further on the energy island (to 525kV DC) and transported to shore. Figure 9 shows the CAPEX distribution over the various items for the electrical infrastructure per MW of installed cable capacity.

The outcomes clearly illustrate the economics of scale of electric transmission, as it indicates a decrease in M€/MW of cable installed as the capacity of the cable increases. Another effect that becomes clear is the increase of cost going from 2GW, to 5GW and 20GW respectively. Noteworthy is that, from the electric perspective, 5GW island constructions may lead to lower transport cost for electricity in comparison to the 20GW islands cases. This is largely in line with the findings of the North Sea Power Hub[6]. Though we cannot exclude distance to play a factor here (since many variables are dependent on distance), the need for having an collection system upstream affects the electric transport costs of the 20GW case negatively.

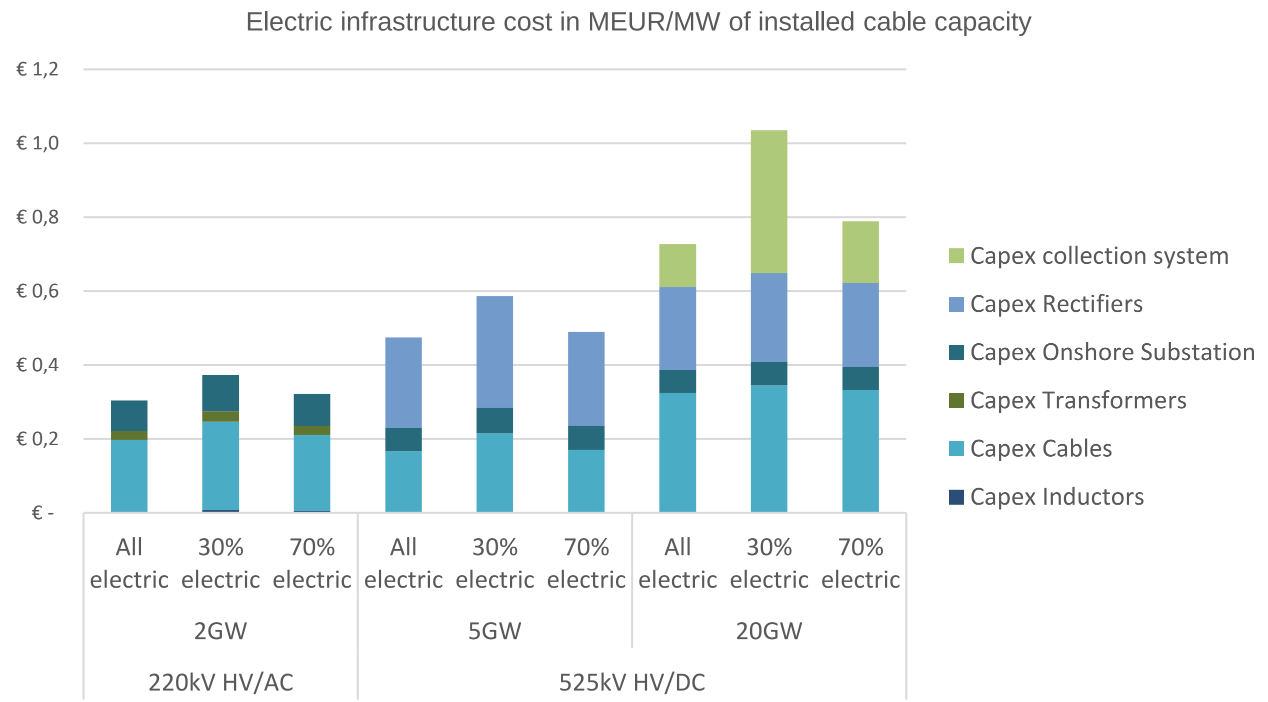

Figure 9 CAPEX costs electric infrastructure per MW of transmission capacity

[6] Outcome of reflection session with relevant external sources was that an additional collection system would be required if one comes at island sizes of 10-15GW.

3.5. Design considerations and costs of constructing an offshore energy island

3.5.1. Installation and services design for a multi-functional energy island

This chapter describes the design considerations and related estimations of cost of constructing an offshore energy island. We constructed island plot plans for the various scenarios. Figure 10 shows a typical plot plan for Scenario 2b. This scenario considers the connection 5 GW of wind with 30% hydrogen conversion. Plot plans for all scenarios can be found in Appendix A. Appendix B describes the methods for construction and accompanying figures demonstrating the various phases.

The areas are divided into several functions of the island. At the left side of the plot plan are mostly the facilities for an island (e.g. Heliport, Refueling, bunker, (fresh) water and waste station, living quarters, quay and port) positioned. The sizes of these facilities are based on or an extrapolation of Quick-scan Eiland in Zee[xvii]. On the right side, the installation for hydrogen production is placed. The dimensions of the island are determined by each individual area. Appendix A shows a break-down in spatial claim for each different function on the island and the island plots for the different scenarios .

3.5.1.1. Relation between areas

The relations between the individual areas has been set up as follows. Because the port and the quays are on the left side the refueling, bunker, (fresh) water and waste station is connected to the port for storage or disposal of several products from/to ships. The laydown area and the warehouse is also connected to the port/quays for lifting and laydown maintenance-parts, food products, etc. from/to the ships. The heliport, living quarters, control room and offices are as close as possible for safety and ergonomic reasons. To escape from the island by helicopters the rendezvous is close to the living quarters, control room and offices. To provide the hydrogen production units with demineralized water, the desalination area is positioned as close as possible to the hydrogen production units to minimize the distance of the upstream part. This also applies for the HV AC/DC-part to feed the needed voltage to the hydrogen production units. The HV AC/DC includes also an area for the direct current voltage to shore. The output of the hydrogen production units will continue to the compressor area. The compressor area includes the things described before and the start of the pipeline to shore.

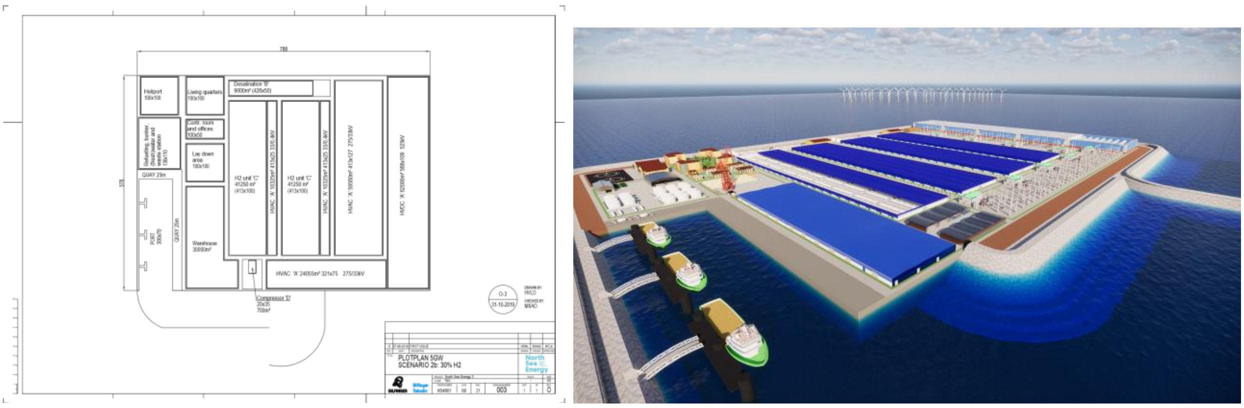

Figure 10 a) A typical energy island plot plan. This specific plot plan is for Scenario 2b - 5 GW 30% hydrogen conversion. b) a 3D impression of the 5GW-70% hydrogen conversion scenario.

3.5.1.2. Onshore hydrogen production installation

Areas like port, quays, refueling, bunker, (fresh) water and waste station, heliport and living quarters will not be included in the scenario for onshore hydrogen production. The laydown area and the warehouse can be smaller with respect to a faster and easier delivery of maintenance-parts, less food products, etc. because of available infrastructure onshore. The rest of the areas will approximately the same for onshore as for offshore.

In each of the 6 cases, the height of the island (at +8 m LAT), the size of the harbour (300 x 70 m) and the length of the breakwaters (800 m) have been chosen the same as in the *Quick-scan Eiland in Zee* since this can be independent from the rest of the layout of the island.[7]

3.5.2. Methods for CAPEX and OPEX estimation

In this paragraph, the method to come to a rough budget estimate for each of the six islands is discussed. Furthermore a bandwidth on this estimate was determined.

The budget estimate is based on the Quick-scan Eiland in Zee on which DEME and BOSKALIS have determined a correction factor and a bandwidth.

The budget of the islands is depending on the following factors:

- Size of the island
- Distance of the island to the coast
- Location of the island (East-West positioning) and corresponding wave climate
- Boundary conditions for the design of the island
- Design of the island

The influence of the above factors on the budget estimations will be briefly described in the paragraphs below.

3.5.2.1. Size of the island

As described before, 6 islands are considered with a different connected wind capacity hydrogen production capacity. The height of the island (+8 m LAT), the size of the harbour (300 x 70 m) and the length of the breakwaters (800 m) have been chosen the same as in the Quick-scan Eiland in Zee. These elements are the same for all 6 islands. The total size of the different islands, the corresponding sand volume that is required and the length of the revetments is determined from the island plot plans. The plots plans can be found in Appendix A.

3.5.2.2. Distance to the coast

The distance to the coast has an influence on the construction depth of the island, which has its influence on the volumes and unit prices of certain parts of the island.

Following scenarios are considered:

- Location A: Island at 50 km from the coast (bathymetry between -20 m and -25 m LAT)
- Location B: Island at 100 km from the coast (bathymetry between -25 m and -35 m LAT)
- Location C: Island at >300 km from the coast (bathymetry between -18 m and -24 m LAT)

For location A & C, the construction depth in the *Quick-scan Eiland in Zee* equal to -23 m LAT has been considered. For location B, a construction depth at -30 m LAT is considered.

The distance from the coast also has an influence on logistics. This influence can have both a positive as a negative effect on price, depending on where the logistics is coming from. Therefore, the influence of logistics on the rough budget estimate was neglected.

3.5.2.3. Location of the island and corresponding wave climate

The location of the island is not only determined by its distance from the coast but also by its East-West positioning. This East-West positioning has a large influence on the corresponding wave climate (see Figure 11).

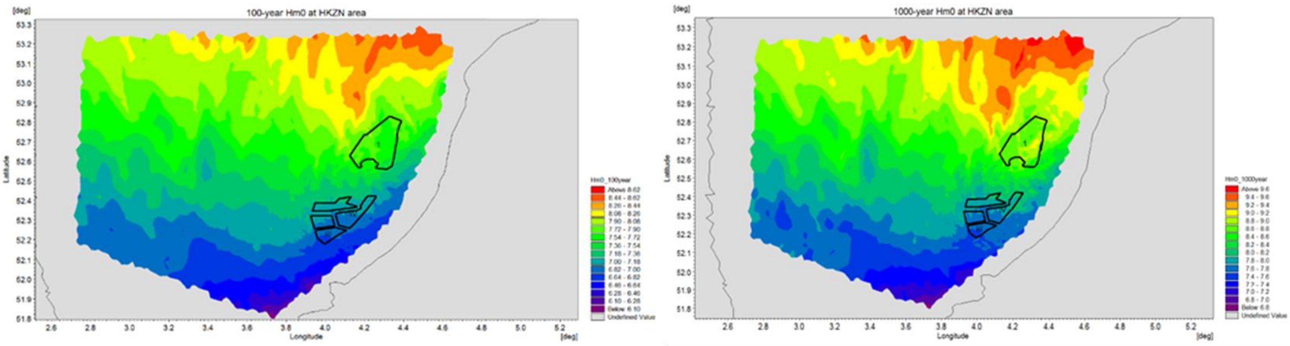

Figure 11 100 (left) and 1000 (right) year significant wave heights[xviii]

The location of the island in the Quick-scan Eiland op Zee is located in the middle of the area (H_{m0} = 8.45 m) and thus serves as a good average for the influence of the East-West positioning and thus the influence of the wave climate. The influence of a milder or more severe wave climate is included in the bandwidth.

3.5.2.4. Boundary conditions for the design of the island

The design criteria for the island are taken from the Quick-scan Eiland op Zee:

- Construction depth is at -23 m LAT
- The height of the island is at +8 m LAT
- Design of the island for 1/250 year storm conditions
- Design water level at +4.9 m LAT
- Design wave height Hs = 8.45 m
- Overtopping 0.1 l/m/s

3.5.2.5. Design of the island

The design of the island in the Quick-scan Eiland op Zee serves as a basis for the CAPEX and OPEX estimations. In order to have a verified and executable design, an extensive study with model research, scheduling, risk analysis and such will be necessary. DEME and Boskalis have performed a mutual rating of the design and budget estimate in the Quick-scan Eiland op Zee. DEME and Boskalis have agreed that uncertainties related to design, scheduling, risk and such are included in the bandwidth of +/-35%.

3.5.3. CAPEX and OPEX island construction

3.5.3.1. Basis for CAPEX island construction

In Table 4 the unit prices of the different elements of the island that serve as a basis for the CAPEX calculations can be found. The bandwidth on these unit prices is -35%/+35%.

As discussed before, this bandwidth takes the following into account:

- The influence of the East-West positioning and the corresponding wave climate
- Uncertainties related to design, scheduling and risk

The influence of the distance from the coast and the larger construction depth for scenario B will be taken into account by adding a percentage to the unit prices of the revetment and the breakwater. This percentage takes into account the sand pancake that will be constructed from -30 m LAT to -23 m LAT.

Table 4: Unit prices of the different element of the island.

Code	Description	Budget Unit Prices (-35%/+35%)
	Building Cost Island without infrastructure	
1	Revetment	200.000 €/m
2	Breakwater	225.000 €/m
3	Sand fill (incl. royalties and compaction)	7,50 €/m³
4	Cable landing facilities	45.000.000 €/TP
5a	Harbor, quay walls incl. scour protection and bollards	125.000 €/m
5b	Harbor, slope + jetty	25.000 €/m

3.5.3.2. Basis for OPEX island construction

The budget price for OPEX is also based on the findings in the Quick-scan Eiland in Zee (RWS, 2018). The budget for management and maintenance of the island is 3.000.000 €/year. The bandwidth on this budget price is -25%/+100%.

3.5.3.3. CAPEX & OPEX estimations island construction

Figure 12 shows the CAPEX estimations without infrastructure costs for the various scenarios. A break-down of the CAPEX and OPEX can be found in Appendix C.

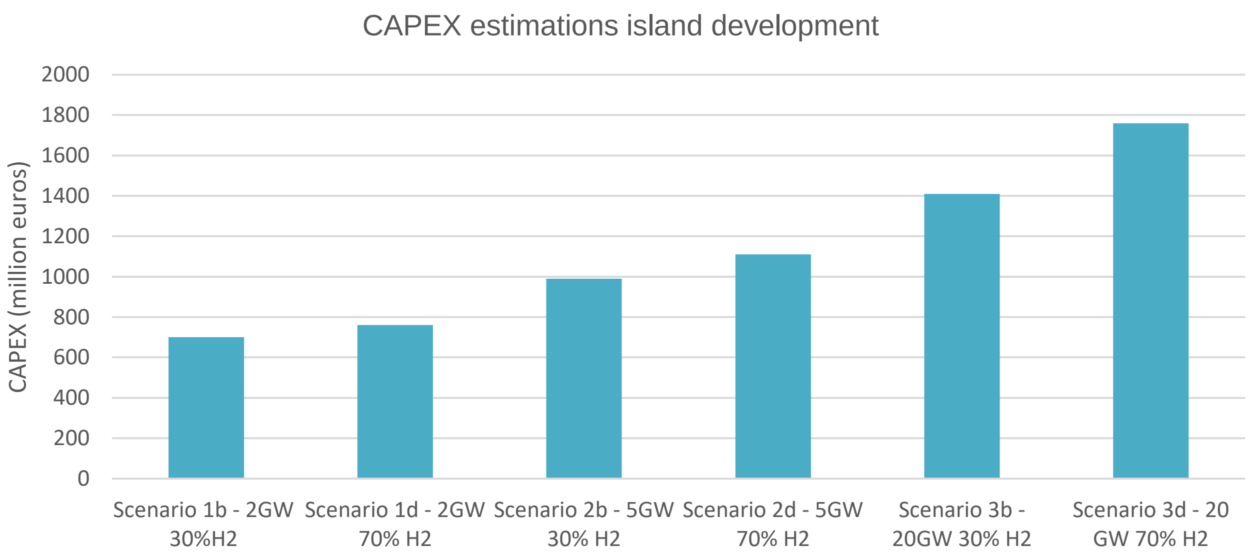

Figure 12 CAPEX estimations for island construction. All estimations are +/- 35% uncertainty. The OPEX are set at a fixed rate of 3 million euros per year with a bandwidth of -25/+100%.

3.6. Techno-economic analysis of combined electricity transmission and hydrogen production on an offshore energy island

In this chapter the methods and results of the techno-economic analysis of the development of an offshore island are discussed. This concerns specifically the development of an island combining electrical transmission and hydrogen production.

3.6.1. Techno-economic methods

3.6.1.1. Energy flow accounting

This chapter describes how the process was designed and what techniques/installations are used in the analysis. The aim is to compare various different island setups of these complete chains, assumptions and choices need to be easily traceable. The technical setup applies for both the onshore and the offshore option. A material energy flow analysis (MEFA) structure is used to build the various comparable cases.

One of the main purposes of a MEFA model is to be able to evaluate certain energy flow quantities, such as electricity consumed by the desalination and compression units in a techno-economic context. Within the boundaries of the described offshore business ecosystem it implies that the model needs to calculate the quantities of the main value stream of hydrogen production including conversion, transportation efficiencies and generated revenues.

Material flow accounting (MFA) reports only the physical material flows in a socio-economic system from their origin, e.g. extraction of raw materials, to final use and disposal or reuse. Similar to MFA, the energy flow analysis (EFA) has the same system boundaries but bases its flows on energy content rather than on mass (Haberl H., 2006, p. 99)[xix]. The MEFA combines both approaches with the aim to measure and account material and energy flows going through a metabolism system. The importance lies here in the link between the material and energy flows to related economic activity in general (Haberl, 2003)[xx].

3.6.1.2. Economic accounting

It is in the interest of stakeholders that a certain economic value can be assigned to the proposed innovation itself. Hence, if we regard the innovation as an investment opportunity, its economic value can be determined by the sum of future profits generated divided by a discount factor which takes the time-value into account.
Consequently, this approach can be seen as an income approach which is, besides the market and cost approach, one of the mainstream approaches to rate an investment. In compliance with this approach the net present value (NPV) method is a suitable tool. It basically subtracts the initial investments from the sum of future discounted cash flows (
Equation 1).

Levelized cost of energy (LCOE) is a measurement that allows for a comparative lifetime costs of energy generation alternatives. The definition set by BEIS is used and set out in
Equation 2. The outcome is equal to the constant energy price required for the revenues generated from the project to be sufficient to return the discount rate (Aldersey-Williams, 2019)[xxi]. No large deviations from the NREL method to determine the LCOE are expected, as the project has constant annual output and costs, all construction spending occurs in the first two years[8] and there are no decommissioning costs. Financing costs are not taken into account[9].
Financials like NPV and LCOE can be well used as benchmark or to rank various scenario's. It, however, both metrics fail take into account wider system costs, value dispatchability or to deal with intermittency.

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[8] This implies that there are no revenues in the first two years.
[9] We consider a WACC of 10%, which includes basically the interest, inflation as well as the compensation set for equity financing.

$$NPV = \sum_{t=0}^{N} \frac{FCF_t}{(1+r)^t}$$

Equation 1: Calculation of the net present value

$$LCOE = \frac{\sum_{t=0}^{N} \left[\frac{I_t + O_t + F_t}{(1+r)^t}\right]}{\sum_{t=o}^{N} \left[\frac{E_t}{(1+r)^t}\right]}$$

Equation 2: Calculation of the LCOE

Where, FCF is the free cash-flow, I_t is the total capital expenses in year t, O_t is the total O&M costs in year t, F_t the fuel cost in year t, and E_t the energy generated in year t. r is the risk adjusted discount rate set at 10%. The load factor for offshore wind is set at 63%, project lifetime (t) is 40 years, OPEX is set at 2% with the exception of the OPEX for the compression system, which is set at 8%. The market value for electricity and hydrogen is set at 50€/MWh and 2€/kg respectively. The market value for electricity is used as a production cost for the electrolyser process, desalination process, compression process and ultimately the electric losses. No economic value has been set to electricity sales to the market, as these activities are expected to belong to the wind park operator. The volumes of hydrogen are expected to be sold at a market price of €2/kg at point of delivery onshore. No costs for onshore land acquisition for either the integration of electricity or conversion of electricity has been taken into account.

3.6.1.2.1. Production profile

The stochastic nature of wind energy production is well known, with wind farms outputting highly variable production profiles over time. The wind energy production profile is assessed on the basis of the power curve that was established by HINT (see D3.2-3.6). The power curve was validated by calculating a turbine's capacity factor at each of the wind sites, and comparing to the published results for the Haliade-X in the North Sea (63%). The wind energy production profile is an important parameter in the Power-2-X process as it influence the operational patterns of all subsequent processes. In the timeframe analysed, we assumed that PEM electrolysers will have a flexibility range of 0-100+%, making them compatible with this production profile[10][xxii]. The operational mode of the electrolyser is also an important factor in this analysis, as it determines a hydrogen feed profile to the synthesis processes. Optimisation of the operational mode can lead to serious cost-reductions in the cost price of hydrogen. The analysis uses constant production as operational mode for the electrolysers. In this mode, the electrolyser would be operating at its nominal capacity whenever there is sufficient wind power, with the surplus of power being transmitted via the electrical transmission system. When the wind power is below the nominal capacity of the electrolyser, all of it is converted to hydrogen, meaning no

[10] The PEM is advantageous given the shorter start-up time from cold to minimum load (5-15 minutes rather than 20-60+ minutes). Literature indicates that the current PEM electrolysers require at least a minimum load of 3-10% (instead of 10-20% as for alkaline). Though, technological improvement is expected in this field reaching 0% by 2025. Moreover, PEM electrolysers have the capacity to run above their nominal capacity for short periods of time also, being currently able to operate at 160% of P_{nom} for typically a 10 minute period. By 2025 the minimum load is expected to be 0%, and the max load to be 200% of P_{nom} for the same 10 minute period (Hinicio & Trancatabel Engineering S.A.). This technological advancement has not yet been incorporated as production above P_{nom} as production above P_{nom} can only take place for short periods, and will have consequences for efficiency and pressure. It was decided, therefore, given the unpredictability in the production of wind, to not depend on the potential to produce above P_{nom}, but be rather conservative with the 0-100%. Though, an upward benefit of this is that the electrolysers could offer more flexibility to the system, which is not yet valued, by operate (for a short period) at even a higher load.

power transmission via cable (see Figure 13). The advantages of this would be much more constant production of hydrogen (with an average wind energy covering factor of 25%), higher conversion and compression efficiency and the highest capacity factor for the electrolyser (a very significant cost factor). The disadvantages of this operational mode would be the opportunity cost of electricity sales at sometimes higher prices (essentially fuel cost for the electrolyser) and a highly variable electricity production profile (and less efficient use of electrical infrastructure).

3.6.1.2.2. System boundaries

The system boundaries of this study start physically at the delivery point of offshore wind to the island (landing point). Hence the focus is on the transmission of wind energy to shore and it does not take into account cost of wind energy production and the collection system (66kV-system) to bring the wind energy to the island. At the interconnection point on the island economic value is assigned to the product based on normal market prices for electricity (set to €50/MWh in the base case). Distribution of the product towards its final consumer is not included in the scope of the study. The system includes the conversion and the transportation of the energy to shore, as well as the economic value from the electricity and/or hydrogen sales to the market. The location where the energy conversion is assumed to take place on an energy island.

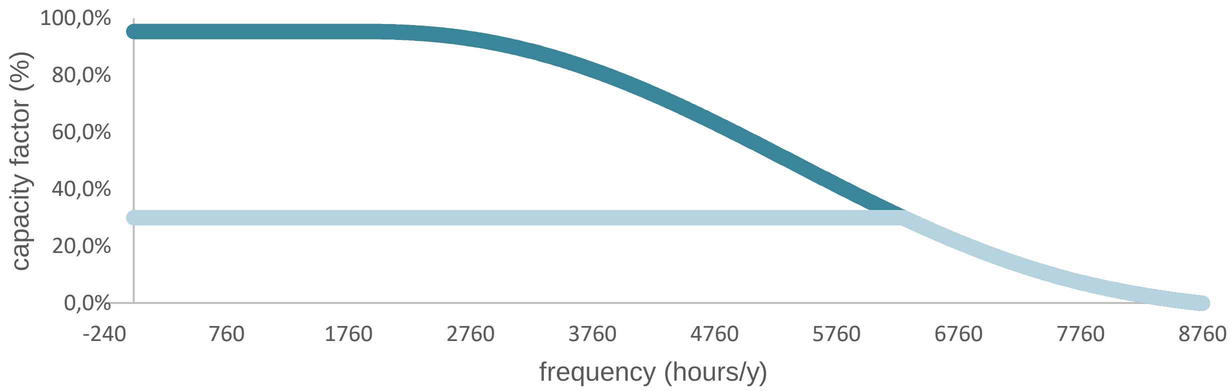

Figure 13 Frequency domain outline of constant production mode (Light blue: wind profile, dark blue: hydrogen profile)

The NPV analysis gives a clear comparison of total system value of the various scenario. Note that system costs/revenues, such as balancing the grid, are not taking into account. The rationale for this is that the costs/revenues strongly depend on the development of the electrical system, and since the location of the energy island is (yet) unknown it is hardly possible to make any predictions on this[11]. However, what is taken into account, is the potential savings on offshore transmission infrastructure by making smart combinations between the electrical and molecular transport system[12].

3.6.1.2.3. Allocation principle

Noteworthy is that the various cost components do not say anything about the allocation to the system costs (electric or molecular). The structure costs are shared between the electric and molecular system on the basis of the relative capex distribution. Next to that, a share of the transmission costs is allocated to the molecular system, as in the onshore scenarios this electricity is directly used to feed the electrolyser. The allocation of transmission costs is based on the distribution of energy to the molecular and electric system. The allocation

[11] The expectation is that serious congestion problems will arise by 2030 increasing the need for congestion management and thus increase the need of / benefit from Power-to-Gas applications.
[12] Any impact on potential required enforcement of the onshore electrical grid is not taken into account, although, the expectation is that this could also lead to significant savings in time and costs.

Table 5 Allocation of costs to the molecular system

	Offshore		**Onshore**	
	30% scenario	70% scenario	30% scenario	70% scenario
Total structure costs (M€)	920	1100	590	590
Allocation cost island structure	54%	81%	41%	42%
Total costs electric system (M€)	1720	880	3270	3270
Allocation cost electric system	0%	0%	38%	76%

of costs is of great importance in order to make proper judgements on the LCOE costs of both the electric and molecular system.
The allocation of structure costs for energy island varies across the scenarios. Table 5 provides an overview on the allocation outcomes for the 5GW scenario. The island costs are allocated on the basis of the relative capex distribution. Although, the island configuration for onshore hydrogen production only consist of electric system components, a 40% share of the island costs is expected to be carried by the molecular system. The is based on the relative capex distribution of the electric and molecular system. As the electric system has higher capex in the onshore scenarios, a smaller proportional share of the island structure costs is carried by the molecular system. The scenarios with offshore hydrogen production on islands show a higher allocation of costs to the molecular system. This increases, as expected, when conversion rates increase from 30% to 70%. The allocation of transmission costs is based on the distribution of energy (MWh) to the molecular and electric system. In the offshore production variants no transmission costs are allocated to the molecular system. Although, the electrolyser capacity is set to either 30% or 70% of the total wind capacity installed, the distribution of energy to the electrolyser is slightly higher, which can be explained by the production profile of both the wind farm as the electrolyser (see Figure 13). To illustrate, the load factor of an offshore wind park is 63% (about 5520 hours), whereas the load factor of the production profile for the electrolyser in the 30% case reaches 79% (6920 hours). Hence, the electricity distributed to the electrolyser system (MWh) lies above the capacity factor applied.

3.6.2. Techno-economics of the scenarios - Base case NPV comparison

The NPV outcomes are positive for all 30% cases (see Figure 14), and negative for all 70% cases under the assumptions described in the previous chapters. The rationale for this is that the revenue from electricity, which are larger in the 30% scenarios, contribute significantly to a positive business case. In all scenarios the NPV of the all-electric reference case is most economically preferable. This can be explained by the fact that you have less conversion and losses. If the electric system has enough capacity to absorb the electricity, than all-electric scenario will be most optimal. However, with the growing influx of intermittent renewable electricity the absorption of electricity by the existing electric system becomes limited and congestion issues will arise. The conversion of hydrogen, just like other flexibility options, could release the pressure that intermittent electricity production places on the electricity grid. These system costs for congestion and costs for potential reinforcement of the onshore electrical grid are not (yet) taken into account.

An interesting outcome is the economic tipping point of onshore versus offshore production. In the 2 GW-30% and 5 GW-30% scenarios, hydrogen production seems economically just preferable at an onshore location (minor difference), however, the onshore preference changes to offshore preference when the proportion of energy converted to molecules increases to 70%. This tipping point is not present at the 20 GW scenario, which can be explained by a relatively high share of the electrical infrastructure costs (73%) making onshore production already less favourable at a molecular proportion of 30%.

In general, 70% hydrogen conversion is in economic terms less preferable for our scenarios. This can be partly explained by the missing monetized values in avoided grid congestion and grid reinforcement costs, as it is

expected that these values will be much larger within a 70% electric scenario. The main factors of importance here, that lay within the system boundaries, are the cost price of electrolyser technology, the electricity price, and the willingness-to-pay for (green) hydrogen. The marginal cost price of hydrogen under the base case assumptions is €2.45/kg[13]. Hence, the NPV will worsen with any increase in hydrogen sales, as the market price €2/kg lies below the marginal cost level of €2.45/kg. Moreover, This can be partly explained by the missing monetized values in avoided grid congestion and grid reinforcement costs contribute to the outcome, as it is expected that these values will be much larger within a 70% electric scenario. Sensitivity analysis were executed to see the economic implications of these parameters (see Section 3.6.3).
The electrolysis costs highly affect the investment structure of the power-to-hydrogen scenarios. This is illustrated by
Figure 15, highlighting the main elements of the capex structure of the 5 GW-30% hydrogen scenarios.

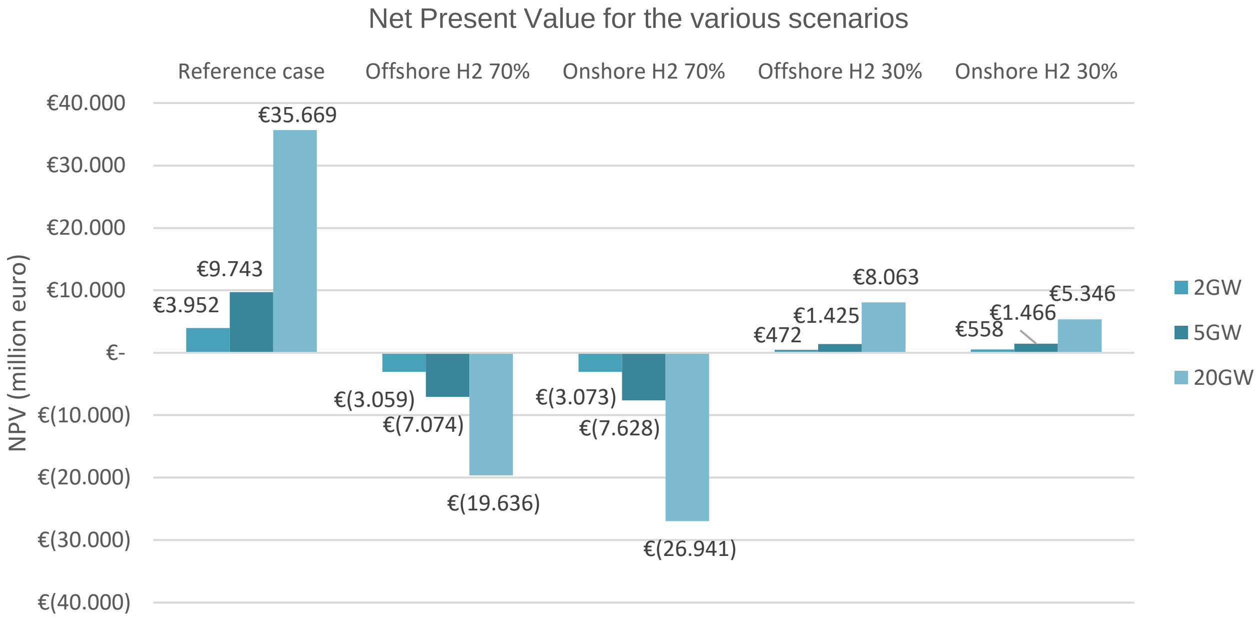

Figure 14 NPV for various scenarios in million euros.

The costs share of hydrogen production is noteworthy as it covers about 45% of the total investment costs. The current island scenarios only include new pipeline solutions for the transport of hydrogen, as the exact location of the energy island is (yet) unknown. A new hydrogen pipeline contributes (only) to about 3% of the total system costs. The structure costs of the energy island only comprise 19% of the overall investment costs.

Some general remarks with regard to the CAPEX distribution of the other scenarios are:

- Structure costs decline relatively if wind capacity/distance increases or if the proportion of molecules increases
- Electric costs increase relatively if wind capacity/distance increase and decreases if the proportion of molecules increases.
- Pipeline costs decline relatively if the proportion of molecules decreases, but an increase in wind capacity/distance seems to have a neutral effect. This might be explained by the (yet) small contribution of pipelines (incl. compression) to the overall costs.

[13] In the base case we assume an efficiency of 49kWh/kg and an electricity price of €50MWh a marginal cost price of green hydrogen of €2.45kg could be realised.

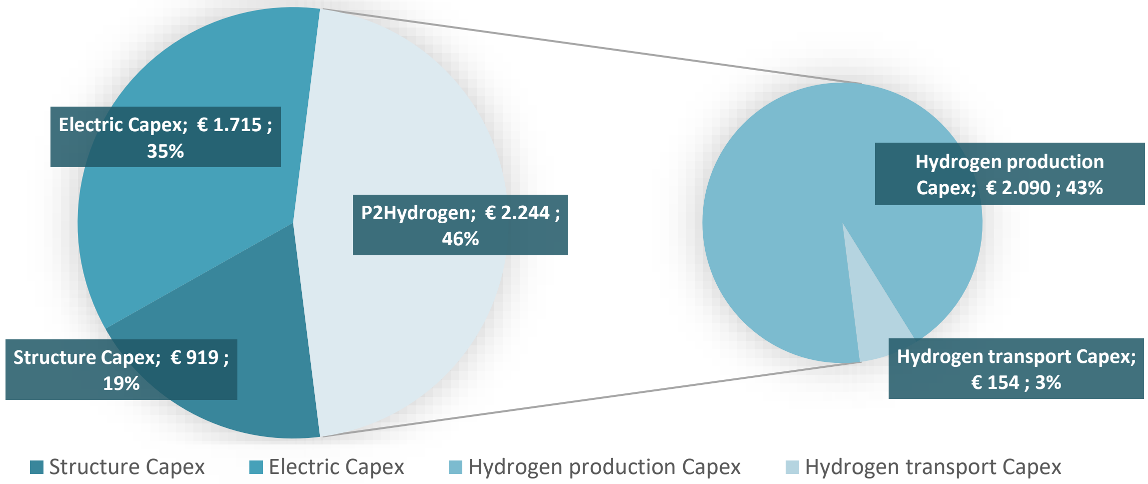

Figure 15 Capex distribution of the 5 GW - 30% scenario

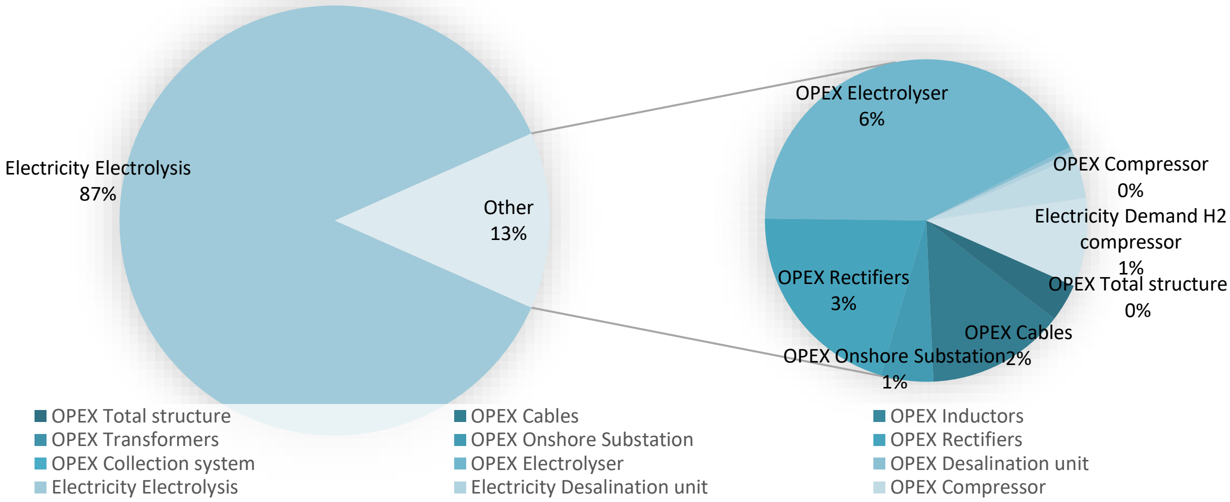

Figure 16 OPEX distribution of the 5GW - 30% scenario

To give a better insight in the NPV of the system the distribution of the OPEX has been depicted in Figure 16. Electricity consumption of the electrolysis system is by far the most demanding cost factor per year, followed by its OPEX due to the large capital costs. The DC cabling is the most costly to operate after the hydrogen related expenses, due to its costly rectifier system.
For more insight, we refer to Appendix E and F. Appendix E shows the distribution of various cost components and corresponding NPVs for each scenario. Appendix F describes a short analysis on Levelized Cost of Energy for both electricity and hydrogen.

3.6.3. Sensitivity analyses

A sensitivity analysis is carried out to determine the effect of uncertainty of some parameters on the economic potential of energy islands and more specific hybrid energy systems. The sensitivities can be divided in two parts: system costs allocation, and market value. Table 6 provides an overview of the parameters considered within the sensitivity analysis, their value in the base case and the values used within the sensitivity analysis. As for all sensitivities, the percentage of the sensitivity compares the NPV of the new scenario to the NPV of the base case.

Table 6 Overview of sensitivity parameters

Parameter	Base case	Sensitivity analysis
System costs allocation		
Electrolyser costs	100%	+50% and -50%
Offshore costs factor	Onshore	1, 1.5 and 2.5
Market value		
Electricity price	50 €/kWh	25 and 85 €/kWh
Hydrogen price	2 €/kg	1-6 €/kg

3.6.3.1. Sensitivity analysis cost allocation

3.6.3.1.1. Electrolyser costs

Although electrolysis technology develops fast, much uncertainty exists about its cost development. Current learning rates for electrolyser technology show a slightly declining trend towards 2050 by ranges between 16.8% (2017) and 12% (2050) for PEM electrolysers (Böhm 2018)[xxiii]. In actual practice electrolyser costs might come down more and probably faster than projected, due to international competition and economics of scale. Nevertheless, the electrolyser costs comprise a large proportion of the overall investment costs (as seen in Figure 15). A sensitivity of -50% and +50% on the electrolyser costs is applied to analysis the impact of cost reduction on the overall potential of energy islands.

The development of the electrolyser cost price has, with a relative impact of 20% to 60%, quite some impact on the economic potential of energy islands and the development of carbon free hydrogen production in particular (see Figure 17 and 18). The 70% scenarios are affected at a higher degree, for instance, a decrease of electrolyser capex in the 5GW offshore scenario leads to an improvement in the NPV by some M2.500€, whereas the same decrease only leads to an improvement of M1.500€ in the 5GW 30% offshore scenario. The effect can be explained by the higher share of electrolyser cost in the total system costs (68% vs. 43%). However, even with technology breakthroughs leading to 50% decreases in electrolyser cost, the business case for the 70% scenarios remains negative.

The share of electrolysers of total CAPEX is also higher in the offshore cases (some 5 to 10%), which causes that the offshore hydrogen production scenarios are affected to a higher degree. In addition, the 2GW and 5GW scenario are affected (relatively) to a higher degree, due to the relatively higher share of electrolysers in total costs (e.g. about 10% to 20% higher). The potential installation of a 20GW island is only foreseen after 2040, and therefore the initial scenario already comprised of a lower electrolyser cost price. The lower absolute cost price is reflected in a lower share of electrolyser costs to total system costs, explaining the lower effect of price reductions on the NPV of the 20GW scenarios.

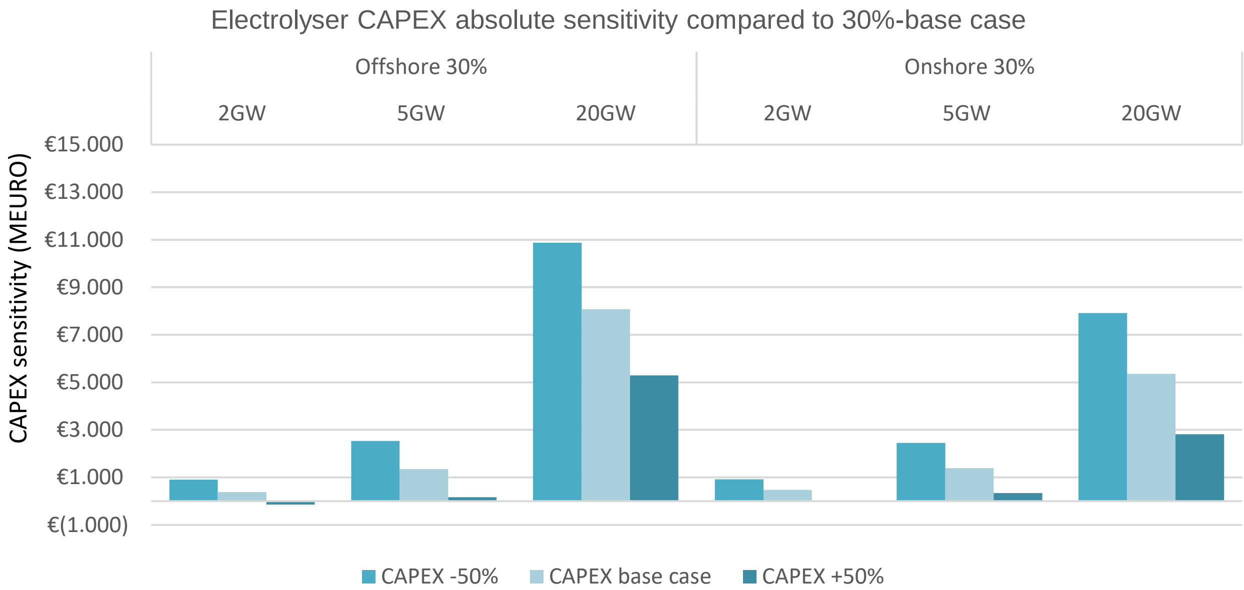

Figure 17 CAPEX sensitivity to electrolyser costs in million euros compared to the 30% hydrogen conversion base case.

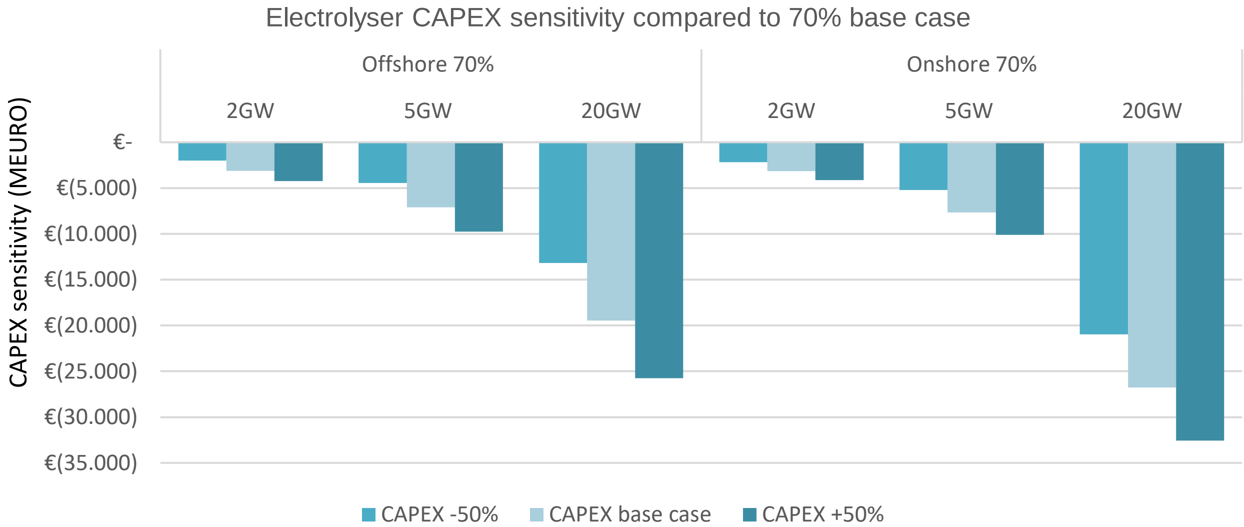

Figure 18 CAPEX sensitivity to electrolyser costs in million euros compared to the 70% hydrogen conversion base case.

3.6.3.1.2. Offshore cost factor

The base cases do not consider any additional cost for offshore production in comparison to onshore production of hydrogen. However, given different environmental circumstances as well as a likely increase in installation costs and operations and maintenance costs, we performed a sensitivity on an offshore cost factor. Although experience can be taken from offshore platforms, the Maasvlakte, or the Dutch islands, much is unknown about the actual offshore costs factor for an energy island in the middle of the North Sea. Sensitivities on offshore cost factors (1.5 and 2.5) were applied to provide insight into the effect of the offshore cost factor on the economic potential of energy islands. All the systems which are installed on the island, including CAPEX and OPEX, are considered to be potentially affected by the extra offshore cost.

The allowable cost factor provides insight in the additional costs for offshore production at which it still breaks-even with onshore production (see Figure 19). Noteworthy is that with an increase in scale, the additional costs that might be allocated for offshore hydrogen production increases due to the higher offshore cost factor. For the smaller scale scenarios (2 GW and 5 GW) NPVs for onshore and offshore are similar for an offshore cost factor of 1. This means that for these scenarios installing the conversion system offshore has to be equally expensive as it is onshore equivalent to have the same NPV, which may be considered unlikely. In the 20 GW scenario, the onshore scenario has the same NPV as the offshore scenario with an offshore cost factor of 1.5. This means that in the 20 GW case the offshore costs for hydrogen production are allowed to be up to 50% more expensive than onshore hydrogen production, while maintaining a higher NPV. The high conversion scenario's (70%) are more affected by the sensitivity due to the higher share of electrolyser systems. The low conversion scenarios (30%) are less affected due to their large share of subsea cabling cost which are not affected by the offshore cost factor. However, despite the lower impact of the factor, these offshore 30% scenarios yield negative NPVs for an offshore cost factor of 2.5.

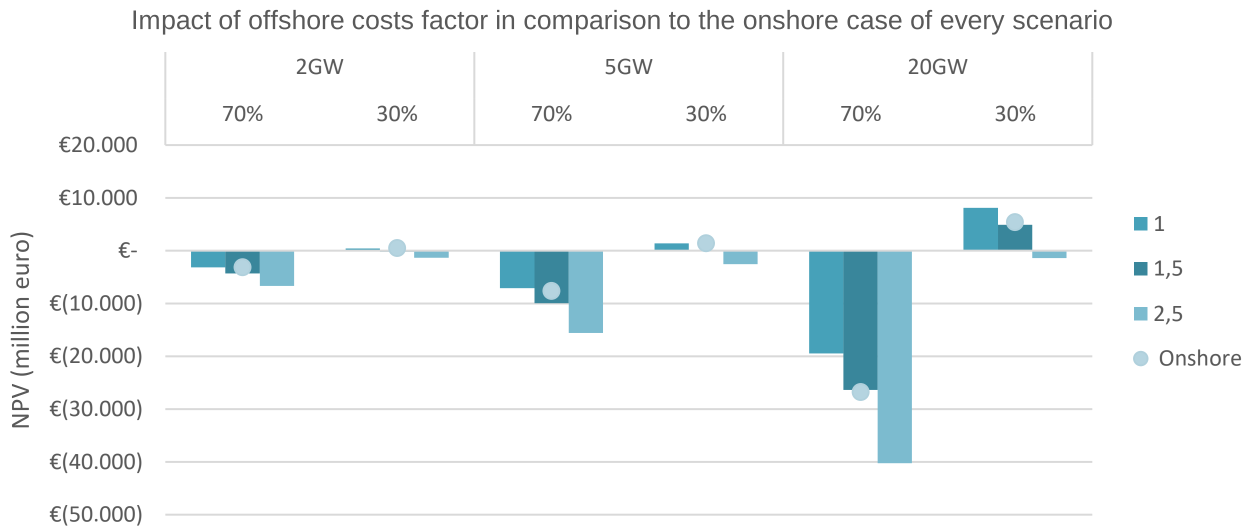

Figure 19 Impact of the offshore cost factor to the onshore NPV (in million euros). The onshore alternative belonging to the respective scenario is set as the base of comparison. The dot represents the NPV corresponding to the onshore scenario.

3.6.3.2. Market Value

3.6.3.2.1. Electricity price

The electricity price affects the complete system. A rise of the electricity price results in an increase in revenues from electricity sales, but on the contrary also results in higher operational costs of the electrolyser. The two opposing effects become especially visible by comparing the relative effects of a price increase/decrease on the NPV outcomes of the 30% and 70% scenario (see Figure 20 and Figure 21).

In the 5GW 30% scenario a decrease in the electricity price by €25/MWh leads to a decline of the NPV by 112%, however, in the 5GW 70% a similar decrease in the electricity price leads to an improvement of the NPV by 61%. The rationale for this lies in the proportion of electrons/molecules produced by the system, as electricity prices has a positive effect on electricity sales, but affects the cost price of hydrogen production negatively. Striking is that, in case of the 70% scenario, even a decrease of the electricity price to €25/MWh, which would result in marginal cost of €1.23/kg, does not lead to a positive NPV. The price effect for onshore and offshore production are in the same order, though, the price effect seems to be slightly lower for offshore production.

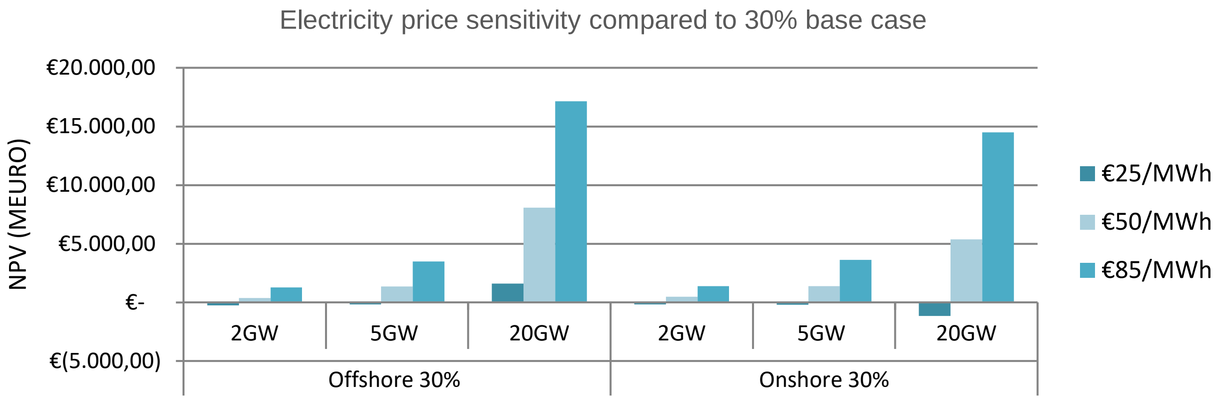

Figure 20 Impact of the electricity price for various 30% scenarios in million euros. In the base case the electricity price is set at 50 €/MWh.

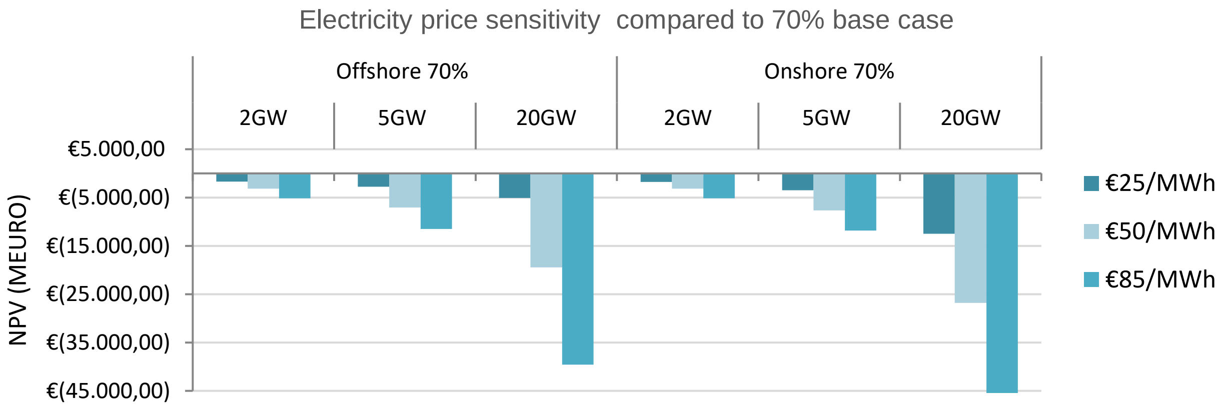

Figure 21: Impact of the electricity price for various 70% scenarios in million euros. In the base case the electricity price is set at 50 €/MWh.

3.6.3.2.2. Hydrogen price

The hydrogen price affects the profitability of the system. The hydrogen produced within the electrolysis process is very pure, and hence it might be suitable to serve as an energy carrier or as a potential fuel for the mobility sector. Sectors that require high quality standards for hydrogen are willing to pay a higher price. For instance, prices of 6€/kg of hydrogen are relatively normal for the mobility sector. The willingness-to-pay a higher price for hydrogen has great impact on the business case for hybrid offshore energy islands.

Figure 22 and Figure 23 highlight the effect of a higher hydrogen price on the total NPV of hybrid energy islands. As expected, in all scenarios, an increase of the hydrogen price to 6€/kg results in a (more) positive business case. Whereas, the initial NPV for the 70% scenarios is negative, it already will turns positive with a hydrogen price of 3.6€/kg. However, if green hydrogen production has to compete with grey hydrogen in the market, prices may drop to 1€/kg. Surprisingly, the 20GW (30% conversion) provides then still a positive NPV (although very small), which is in contrast to the onshore variant. In all other scenarios, a price drop to 1€/kg results in a negative NPV. Results show that the NPV has relatively the most impact on the large-scale cases, where a large share of the NPV is determined by the revenue of hydrogen. The effect is even more profound if the scale of the electrolyser increases from 30% to 70% or from 2GW to 20GW.

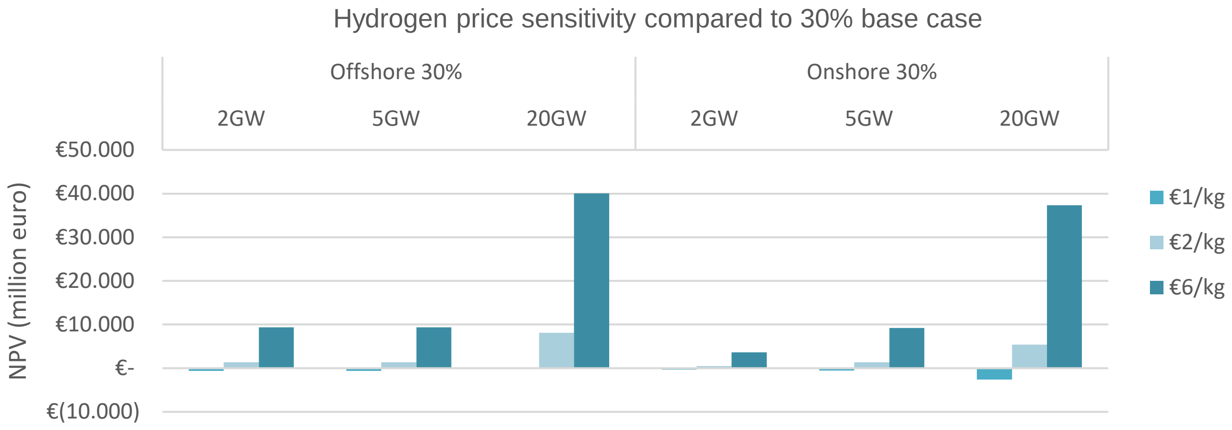

Figure 22: Impact of the hydrogen price for various 30% scenarios in million euros. In the base case the hydrogen price is set at 2 €/kg.

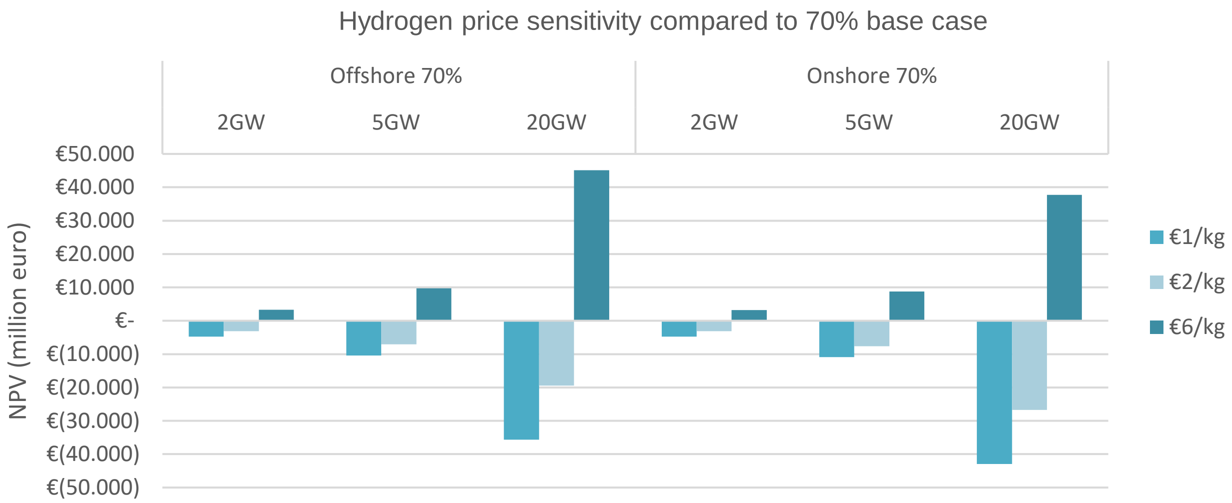

Figure 23: Impact of the hydrogen price for various 70% scenarios in million euros. In the base case the hydrogen price is set at 2 €/kg.

4. Qualitative scoring of potential other use functions of offshore energy islands

4.1. Scoring of additional use functions

Offshore energy islands are considered as an option to facilitate cost-effective onshoring of the large amounts of wind energy foreseen on the North Sea over the coming decades. Electricity conversion (voltage, AC/DC) and hydrogen production are considered part of a set of core use functions of such islands. Here, we report on the qualitative scoring of *additional* use functions listed in Table 7. The functions can be split according to functional category and applicable island size.

Table 7 Additional use functions for offshore energy islands as identified and scored in this work package

Category	Use function	Island size
Electrons	O&M offshore wind	≥2GW
Electrons	Floating solar arrays	≥2GW
Electrons	Interconnection electricity	≥2GW
Hydrogen	H_2 storage aboveground buffer	≥2GW
Hydrogen	Offshore H_2 fuel station	≥5GW
Hydrogen	Large-scale energy storage	≥5GW
Oil and gas	Electrification platforms	≥2GW
Oil and gas	O&M offshore O&G	≥5GW
Oil and gas	Interconnection gas	≥5GW
Oil and gas	Gas compression service	≥20GW
Liquids	Production power to liquids	≥5GW
Liquids	Liquid storage	≥20GW
Liquids	Offshore liquids fuel station	≥20GW
CCS	CO2 hub compression	≥2GW
CCS	Shipping dock	≥2GW
CCS	CO2 buffer storage	≥2GW
CCS	CO2 permanent storage	≥2GW
Macro algae	Biomass drying and transport	≥20GW
Macro algae	Biomass storage and conversion	≥20GW
Ancillary services	Safe and rescue	≥2GW
Ancillary services	Safe harbor	≥2GW
Ancillary services	Data centers	≥2GW
Ancillary services	Data transmission	≥2GW
Ancillary services	Airstrip at sea	≥5GW
Ancillary services	Recreational hotel	≥20GW
Ancillary services	Marina	≥20GW
Ancillary services	Ecological research institute	≥20GW

The use functions were scored during a workshop with experts from TNO and RoyalHaskoning-DHV according to the functions' political, economic, technological, timing and organizational, societal, environmental and legal and regulatory (PESTTEL) aspects. For a full description of the methodology, and our interpretation of the results, see Appendix G.

Of twenty seven scored use functions, six score high and are considered promising, fourteen score medium with significant uncertainties and six scored low or were considered to contain red flags for implementation (Figure 24; see Appendix G for scoring argumentation).

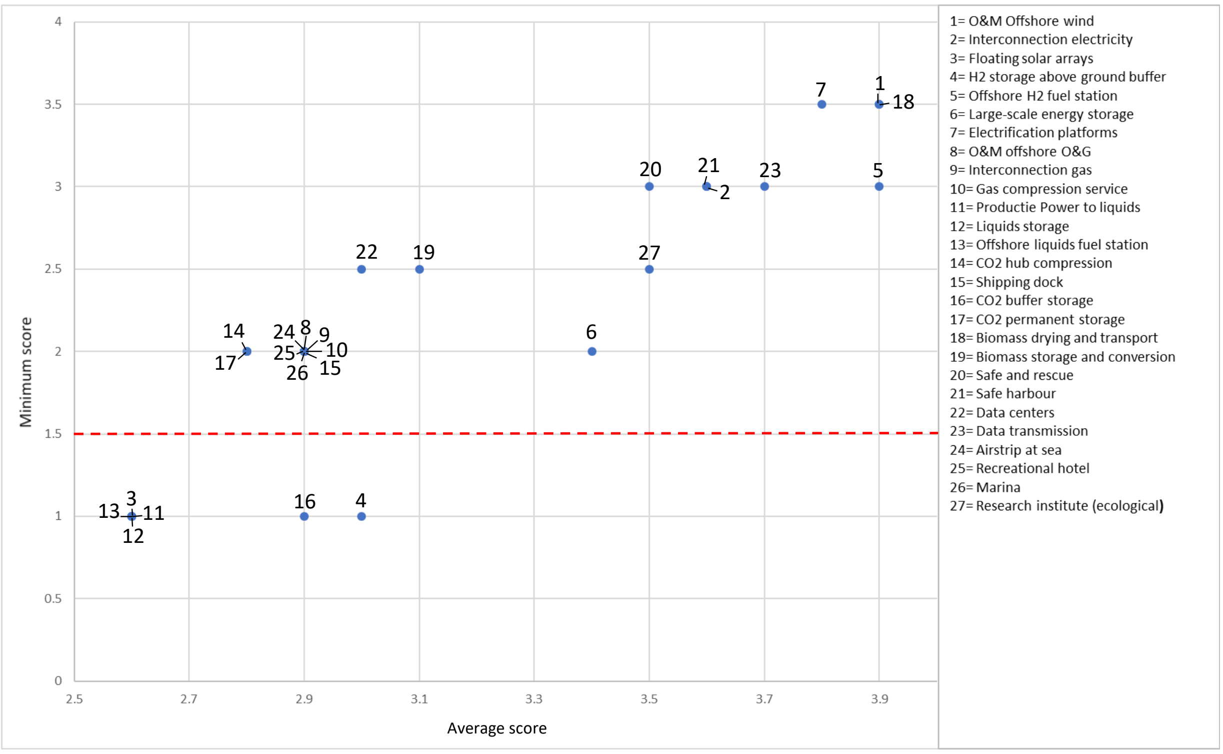

Figure 24. Overview of average (x-axis) and minimum (y-axis) scoring for the 27 additional use functions. The red horizontal line indicates those use functions with red flag (score = 1) aspects.

4.2. Scoring results

4.2.1. High potentials

Functions: Operations & Maintenance offshore wind, offshore hydrogen fuel station, electrification platforms, biomass drying and transport, safe harbor, data transmission, interconnection electricity

These functions score well on all PESTTEL aspects, and exhibit no characteristics thought to have a high chance of acting as a red flag for their implementation. Generally, they are thought to have a good chance of being advantageous over, or to provide an additional service when compared to, their onshore alternatives. Although uncertainties associated with these functions obviously exist; they are considered less severe compared to the other score use functions. Further study into the demand for, and practical implementation of, these functions will show whether they can be implemented on the short/medium term.

4.2.2. Medium potentials

Functions: large-scale energy storage, Operations & Maintenance offshore gas, interconnection gas, gas compression service, CO_2 hub compression, shipping dock, CO_2 permanent storage, biomass storage and conversion, safe and rescue, data centers, airstrip at sea, recreational hotel, marina, research institute

The majority of use functions show medium average values with mixed scores for the different PESTTEL aspects. They are characterized by complex, time-dependent uncertainties in one or more of the scoring aspects. As a result, it is currently not clear whether these functions would be able to provide additional services or value over their onshore alternatives. Future developments in the characteristics of these functions as well as external conditions will be key to determine whether these functions will progress towards high potential candidates.

4.2.3. Uncertainties

Functions: floating solar arrays, hydrogen storage above ground buffer, production power to liquids, liquids storage, offshore liquids fuel station, CO_2 buffer storage

These functions show low average scores or were given the minimum score for one or more PESTTEL aspects, indicating a red flag characteristic that could severely limit the functions' implementation. They are thought to have a small chance of providing a valuable additional service, or being advantageous over the onshore alternative. Research into the details and time-dependence of the red flag aspects will have to be conducted before these functions are pursued further or written off entirely.

4.3. Discussion

On the basis of the results of the qualitative assessment presented here we see reason to further investigate the business case of a number of high potential use functions. Also, we find that a large number of use functions are characterized by uncertainties or red flags that must be assessed in more detail. One interesting example of the red flags is the fact that offshore power-2-liquids is disconnected from the interesting options based on organizational aspects. This is a good example of progress in insights. Offshore power-2-Liquids has been extensively assessed on techno-economics in D3.2-3.6. However, we foresee serious challenges from an organizational perspective.

The scoring was done by relying on the opinion of various experts from relevant domains. We do, however, acknowledge that our methodology introduces subjectivity and uncertainty in the outcome, as is for every expert-opinion based assignment. Also, equal weights were assigned to the scores of the different PESTTEL factors, while in reality certain factors might be more important. Therefore, we present these results not as a definitive judgement, but as a first indication of which of these functions warrant further research in the short-term.

5. Environmental and ecological challenges & merits for developing and implementing offshore energy islands

Developing an (energy) island goes hand in hand with environmental challenges. Every activity causes impact on the environment, but what are those impacts and effects? And could the environment benefit from such an energy island?

The construction and operation of an island in the North Sea is expected to have a number of negative environmental impacts. A first general overview of these impacts is prepared, see the QuickScan included in Appendix H. However, the extent of the impacts is highly location specific, especially for the impacts on ecology above and below the sea level. The environmental impacts of such an energy island should be assessed in detail in a (strategic) environmental impact assessment as part of a permit application process. The QuickScan also mentions a number of critical knowledge gaps, such as the cumulative impact with other activities, the impact of a dredging plume, impact on invasive species and migratory birds.

At the same time, an island on the North Sea could have benefits. Ecological values could benefit, when the island is designed well. The most likely way of construction is a combination of hard and soft elements. Hard elements (rocks and concrete) are necessary to keep the island in place within the environment of the North Sea. The side where the waves come in, with a strong dynamic environment, is expected to be less beneficial for ecological development. This side of the island will be constructed of hard elements. On the lee side of an island, the circumstances are calmer, and a sandy solution could be possible with less steeper slopes. Or the use of special and extra hard substrate could have a positive effect on biomass. Slopes will give species (flora and fauna) the chance to settle and develop. In accordance this will lead to more food for fish, sea mammals and birds.

During the preparation of this QuickScan, two points of attention were encountered, which are valuable for follow-up research:

a. An integral design process

In order to increase the support among stakeholders for the development of energy islands it should be beneficial to start the design process from the perspective of the best ecological option, instead of thinking from a technical perspective and adding ecological aspects for compensation. Following this line of thought one could also think of including both technical and ecological aspects in the design processes from the very beginning. Not two separate tracks, but an integrated design process with iterations combining a technical and ecological perspective, a real nature-inclusive design.

b. Valorise the ecological benefits

In general, not only in the development of energy islands, it is very difficult to quantify ecological benefits and include these in a project’s business case. As it is difficult to quantify the contribution of ecological benefits, ecological measures are likely to be left out of the business case as they only cost money and do not yield a monetary value. Costs are mostly quite comprehensible/easy to determine, but how to assess the value of the benefits? A next step in a follow-up study could focus on this question. Not only for the development of energy islands, but for other infrastructural developments as well.

6. Legal assessment of the development of a sand-based offshore energy island

This section provides an overview of the primary findings of the legal assessment of an offshore sand-based energy island to be constructed and operated within Dutch jurisdiction. The primary aims of this legal assessment are to establish the definition for a sand-based energy island and identify what regulatory barriers exist in the construction and operation thereof.

As outlined, this legal assessment considers the regulatory barriers to constructing a sand-based energy island under Dutch jurisdiction. In location C, as described in Section 3.5.2.2. of this report, a sand-based energy island could potentially be located in the jurisdiction of another state. Hence, an assessment of the legal impact of location C is outside the scope of this assessment, as it considers only the regulation of a sand-based energy island under Dutch jurisdiction. Furthermore, as the primary aim of Deliverable D3.8 is to consider the use of a sand-based energy island for the purposes of electrical transmission and hydrogen production, the scope of this report is limited to the legal implications for such uses under Dutch jurisdiction. The legal implications for all other uses are therefore not considered. In order to conduct this legal assessment, both international and national legal regimes are analysed, both of which regulate offshore activities within the jurisdiction of the Netherlands.

6.1. International Law

6.1.1. Rights and responsibilities of coastal states

Under international law, the primary legal instrument dealing with the regulation of maritime areas is the United Nations Convention on the Law of the Sea (UNCLOS). As evident in Figure 1, the UNCLOS principally divides the sea into various maritime zones, Each zone has different characteristics in terms of coastal state jurisdiction and sovereignty (or sovereign rights). Two such zones are of most relevance to this legal assessment, which are: the Exclusive Economic Zone (EEZ) and the Continental Shelf (CS). The CS refers to the subsoil on the geological continental shelf of a state extending between 12 nautical miles and 200 nautical miles from shore. The EEZ, however, refers to the water column which extends up to 200 nautical miles from shore. Both locations A and B, as described in Section 3.5.2.2. of this report, foresee a sand-based energy island to be located at a distance of 50km and 100km from shore, respectively. Hence, the construction of a sand-based energy island at location A or location B would place it within the EEZ and CS zones.

Coastal states possess various sovereign rights in both the EEZ and CS zones, including the right to explore for and exploit resources, which are, however, actionable only when seeking to produce energy from the water, currents and winds, or serve another economic purpose, otherwise referred to as a ‘functional jurisdiction’. Coastal states also have the exclusive right to construct and to authorise and regulate the construction, operation and use of ‘artificial islands, installations and structures’ for the purposes of economic exploitation and exploration within both zones. However, this right is subject to certain limitations including the prohibition of their construction “where interference may be caused to the use of recognized sea lanes essential to international navigation”, or where the , the principle of the freedom of the high seas, as well as the lawful uses of the sea related thereto, are interfered. In addition, coastal states possess certain responsibilities when constructing offshore infrastructure. This includes the provision of due notice to other sea users of their construction, while also obliging coastal states to remove “[a]ny installations or structures which are abandoned or disused.”

This means that coastal states, including the Netherlands, have the right to authorise construction of a sand-based energy island within its EEZ for economic purposes, in so far as it does not obstruct recognised sea lanes essential to international navigation or interfere with the principle of the freedom of the high seas. Furthermore, this right is accompanied by obligations, such as the provision of due notice of their construction and the removal of 'installations' and 'structures' once abandoned or disused. However, the removal obligation in UNCLOS does not explicitly include 'artificial islands', implying that such infrastructure is not subject to the same removal obligation. It is unclear why an obligation to remove abandoned or disused 'installations' and 'structures' is not extended to 'artificial islands' particularly as such infrastructure would likely interfere with the freedom of the high seas. One could make the case that this is contrary to the basic duty to have due regard to the rights of other parties seeking access to the marine area. Furthermore, as the UNCLOS does not provide a definition for an 'artificial island' or an 'installation' or 'structure', it is unclear what legal effects this omission from the obligation to remove once abandoned or disused might have. Therefore, it is unclear whether an energy island constructed within the Dutch EEZ could operate on a permanent basis, though it seems that as long as it continues to serve an economic purpose, it need not cease activities or be removed.

6.1.2. Defining an energy island in Law

A key issue in the legal assessment of a sand-based energy island is its legal definition. An energy island is most likely to be defined under Article 60 UNCLOS as an 'artificial island, installation or structure'. But a definitional problem seems to emerge, since neither UNCLOS, nor any other international legal instrument provides any detail on what an 'artificial island' actually is. This is particularly problematic when one tries to distinguish it from an 'installation' or 'structure', particularly with regard to the obligation to remove once abandoned or disused.

This issue has been the source of much academic commentary, although consensus seems to be found within the idea that 'artificial islands' can be distinguished from 'installations' because their construction typically involves the use of natural materials, like sand or rocks, unlike 'installations', which are constructed using non-natural materials like steel or concrete. Likewise, the objectives for using an 'artificial island' seem to be more permanent than 'installations' or 'structures' in the sense that its use assist projects of considerable duration. But while it seems most likely that a sand-based energy island would be classified as an 'artificial island', the basis for such classification is unclear as no provision in international law lends it to be defined as such. Hence, further clarification on the definition of 'artificial islands, installations and structures' under international law is needed.

6.2. Dutch law

In exercising its functional jurisdiction in the North Sea, various Dutch laws apply in the Dutch EEZ and CS. The Mining Act (Mijnbouwwet), the Wind Energy at Sea Act (Wet Windenergie op Zee) and the Excavation Act (Ontgrondingenwet), cover sector-specific activities in the North Sea, namely the exploration and production of hydrocarbons, the production of wind energy and excavation and dredging activities, respectively. Neither contain specific provisions for the construction or operation of an energy island. However, it is conceivably possible that the Mining Act could regulate an energy island if involved in activities related to the production or exploration of hydrocarbons. The Wind Energy at Sea Act does not explicitly apply to a sand-based energy island. However, should a developer of an energy island seek to produce hydrogen from wind electricity produced at sea, or transmit electricity thereon, then a connection would have to be secured, which is regulated under the Wind Energy at Sea Act.

The explicit applicability of the Wind Energy at Sea Act or the Mining Act to artificial islands would, however, require amendments to those acts. But if both acts apply simultaneously regulatory alignment would be needed in order to provide sufficient legal clarity on the interplay between these acts in case both activities occur on an energy island. Otherwise, the Water Act (Waterwet), which contains general provisions for all activities in the North Sea that do not fall under sector-specific acts, would apply. This would apply both to the construction of an energy island and may apply to the production of hydrogen thereon.

6.2.1. Required permits

Any excavation work at sea is prohibited without a permit, under Article 3 of the Excavation Act. This means that when seeking to construct an energy island at sea the developer must first obtain an excavation permit. However, an additional permit is required in order to construct and operate an energy island under Water Legislation. Article 6 (5) (c) of the Water Act requires that a water permit be obtained in order to make use of a water management structure other than in accordance with the function, on or in national waters, including the EEZ. Article 6 (13) of the Ministerial Water Decree (Waterbesluit) elaborates further on the requirement in Article 6 (5) (c) by explicitly stating that a permit must be obtained when seeking to raise or harden the soil or to reclaim land, or to install or lay installations, cables or pipelines in the Dutch part of the North Sea. Once constructed, however, it is unclear how the operations of an energy island would be regulated. There are no specific provisions with regard to the operation of water management structures, or any other objects constructed in the water which require a water permit. Moreover, Article 6 (1) of the Water Regulation (Waterregelingen) provides that a permit may not exceed 10 years in length. It is unclear what would happen upon completion of this 10-year term and whether an operator of an energy island could simply re-apply for the same permit or whether the island would have to be de-constructed as a consequence.

In addition, an energy island would require a connection to an offshore wind farm, which may prove difficult to obtain. Under the regulation of the Wind Energy at Sea Act, a plot decision is taken by the Minister which designates specific areas where an offshore wind farm may be built by a developer and includes a designated connection point for that plot. Should an energy island seek to be connected to a wind farm, then an amendment of the plot decision may be required. Furthermore, various obstacles under the Dutch regulation of offshore wind are present, since the current regulation provides that TenneT, as the TSO, is responsible for securing connections between the offshore transmission network, offshore wind farms and the onshore grid, under the terms of the Electricity Act (Electriciteitswet). This means that if an energy island sought to be connected to an offshore wind farm then it could fall to the developer of energy island themselves to secure a connection as TenneT is only responsible for connections to the onshore grid. Alternatively, should an energy island seek a connection both to an offshore wind farm and to the onshore grid for the purposes of electricity transmission, then the energy island may be seen as an extension or a part of a typical connection, although this situation remains equally unclear, not least because that cable cannot be defined under the current regulations.

An energy island is therefore subject to the excavation- and water permitting regimes. Hence, issues may arise, particularly because a water permit may include an obligation to remove such an island upon expiry of the permit, which may only be valid for a maximum of 10 years. There is, therefore, considerable legal uncertainty when constructing and operating an energy island, since no specific provisions are currently provided therefor. In light of the lack of detail provided by international law, it is unclear whether the Netherlands is obligated to ensure the removal of an energy island once disused or abandoned, and no detail is provided in the Water Act as to the consequence of a water permit expiry after the 10 year limit. The requirement to remove an energy island under the Water Act is dependent on the Ministry for Infrastructure and Water Management to determine when granting a water permit. If granted a permit, however, it remains unclear how the operations taking place on an energy island, such as the production of hydrogen, would be regulated considering that there is no regulation of the operational activities under the water permit regime. Furthermore, difficulties may be incurred in securing a connection between offshore wind farms and the offshore transmission network under the offshore wind regulations, given the limited scope thereof, and lack of detail provided therein.

6.2.2. Artificial Islands and North Sea Policy

In recent months, the Ministry for Infrastructure and Water Management has announced plans to deliver a policy framework specifically concerning the construction of artificial islands in the Dutch part of the North Sea. Although this framework has yet to be officially published, the Ministry has indicated that the construction of artificial islands will be permitted, only where it involves an activity of national interest, where there is a need for it to take place at sea and where there is no reasonable alternative, i.e. an installation or structure. Furthermore, any decision involving such a permission will account for certain factors viewed as important by the Dutch government. These are (1) the scarce space on the Dutch North Sea, (2) the permanent character that artificial islands can have, (3) the unknown effects on the ecosystem, and (4) any international legal obligations. It follows that an energy island must accommodate such interests in order to be constructed in the North Sea.

6.3. Conclusions of the legal assessment

There are three primary conclusions to be drawn from this legal assessment. First, the coastal states, including the Netherlands, have a functional jurisdiction under international law to impose regulations governing a sand-based energy island, though it is accompanied by various responsibilities, some of which are dependent on how such an island is legally defined. This is particularly difficult to determine, given the lack of explicit detail in international law on such a definition. Although it is likely that an energy island is to be defined as an 'artificial island', no such definition is currently incorporated in UNCLOS or elsewhere in international law, meaning a considerable lack of clarity exists. Potential barriers to constructing an energy island may emerge from a prohibition to construct an artificial island where interference may be caused to the use of recognized sea lanes essential to international navigation or the freedom of the high seas. Other barriers to such construction may include environmental protection. However, once constructed no explicit obligation seem to exist for coastal states to remove an 'artificial island' under international law, although this is open to interpretation given the obligation for coastal States to respect the use of marine waters by third parties.

In addition, the construction of a sand-based energy island could face potential difficulties under the Dutch regulations which may pertain to artificial islands, given the varying interests of different parties in the North Sea, which the Government seeks to balance. Separate permits are likely to be required under the Excavation-, and Water Acts and any such authorisation will involve determinations by the Ministry for Infrastructure and Water Management on how a sand-based energy island could impact other parties in the North Sea. Under the current water permit rules, difficulties may be incurred due to the maximum length of such permits being 10 years, as well as the insufficient detail provided on the consequences for permit holders thereafter. In addition, securing a connection between an energy island and offshore wind farms and the offshore transmission network appears to be quite difficult, particularly due to the narrow scope of current applicable regulations and lack of clarity therein. Ultimately, current rules pertaining to the construction of an energy island or other artificial islands are in need of elaboration given the absence of sector-specific legislation for the construction of artificial islands, installations or structures, particularly those which do not fall under the Mining Act or Wind Energy at Sea Act.

7. Synthesis & Outlook

7.1. General trends

The Net Present Value for both the all-electric and 30% conversion scenarios are positive under the conditions that we assumed. We also see that for the conditions that we assumed, the NPV shows a preference for offshore over onshore production of hydrogen for the smaller island scenarios (2 GW, 5 GW) at larger conversion rates. This is a similar result as was shown for the hub-and-spoke concept of the North Sea Wind Power Hub, where there is a tendency for multiple smaller islands instead of one big island.
The above implies that in case you believe that hydrogen will be part of the energy system, we expect that there is a tipping point that favors offshore production under the assumptions that we used in this study. However, the reference case with 100% electron transport still shows the best NPV in all cases.

We also see that the cost of the hydrogen production facility has the biggest share in the total costs of the system. The costs of construction of the island form a minor part of the total CAPEX compared to the CAPEX of the hydrogen production facility. Similarly, the costs of pipeline transport are very small compared to the other parts (<5%) in case of new pipelines. This means that from a cost perspective, re-use of pipelines may not strengthen the business case significantly. However, re-use may have benefits from other perspectives like environmental pressure.

It is important to note that economies of scale are important for the business case. We see that it is more important for the molecular system than for the electrical system. The economies of scale also work strongly for the construction costs of the island.

7.2. Future price and cost forecasts strongly effect the business case

We studied several sensitivities of the trends as described above. As we have seen, there are several parameters that are hard to predict at this moment in time, even more when offshore islands are expected to be built after 2030. At first, the speed of development of electrolysers will have a strong influence on the business case as the electrolyser cost price has a relative impact of 20-60%. In case that electrolysers turn out to become exponentially cheaper (as e.g. happened for solar PV and wind electricity[xxiv]) the business case of offshore energy islands may become positive earlier than expected under the conditions that were assumed in this study.

A similar reasoning holds for the allowable offshore cost factor. Experience has shown that offshore projects are (almost) always more expensive than similar projects onshore. However, it is hard to predict how large this offshore cost factor will be and how it will develop over the course of time. It is therefore important to analyze what the maximum offshore cost factor is allowed to be to make offshore hydrogen production an interesting add-on to energy islands. We saw that for the large scale scenario (20 GW) the offshore cost factor can be up to 1.5 to compete with onshore hydrogen production under the assumptions in this study.

Also the price of hydrogen in the future is still very uncertain. This will strongly depend on e.g. if and how the hydrogen economy will develop and most importantly what the willingness-to-pay for high-purity hydrogen will be at a certain point in time. Green hydrogen production will end in high quality hydrogen compared to e.g. blue hydrogen production. If willingness to pay for green hydrogen is high, and this might be the case in some applications and/or sectors then this may lead to positive NPVs.

7.3. Societal value of offshore islands

In the scenarios and assumptions as were used in this study, we solely look at the business case of offshore islands from a project development perspective. However, offshore hydrogen production may not only prove to have an attractive business case on project level, but it may also solve some of the societal challenges that arise from implementing large shares of offshore wind and other intermittent renewables in our energy system. It is expected that grid congestion challenges may arise after 2030[xxv]. Production of hydrogen on an offshore island may help to mitigate these challenges by opening opportunities for grid balancing (by e.g. hydrogen storage) and prevention of onshore grid extension/reinforcements (as part of the electricity comes to shore in the form of hydrogen that can we used as feedstock for various processes). These processes are hard to monetize for a single operator, but have a strong impact on the societal costs of the transition, as part of solution of these challenges will be paid for by the Dutch society. How to rate the value of these system advantages is however not straightforward and needs be to imposed by the government and/or TSO. We do foresee that this might in the end be a key enabler of the offshore energy islands, creating a win-win situation for both the island operator, wind operators and the TSO.

7.4. Improving the business case of offshore energy islands

In the current study we made a first attempt to address the larger trends for offshore island combining electrical transmission and hydrogen production. We have used a base case with a straightforward setup. No smart options have been considered so far, which could improve the business case of the island. This includes e.g. the addition of other use functions (see next section), but also smart arrangements of the considered use functions. One of the other options could be stacking of the hydrogen production facilities. In the current setup we chose for single-floor electrolysers, but stacking of the electrolyser packages may save space and therefore costs. However, it needs to be confirmed that this has a real benefit for the business case as stacked electrolysers may be more complex, yet more expensive and might require a different design of the supporting island structure due to high weight pressure per meter squared. This type of dynamics in the business case need to be further studied, especially when a specific island setup and location is available.
Even though we did not take it into account, off course smart location selection is very important as well. We have seen that e.g. the wind capacity factor has a strong influence on the LCOE of mainly electricity.
As was described in Chapter 3, at least seven other use functions than considered in the techno-economic study can be highlighted as potential add-ons to strengthen the business case of offshore energy islands. As the cost of construction of the island is relatively low compared to the price of the hydrogen production facility, it might be an interesting option to increase the island size to add space for such high potential use functions. However, it is important to consider who should be the case owner of the business case of these use functions.

7.5. Legal considerations

From a legal point of view, several observations have been made. First, the Dutch state has a functional jurisdiction under international law to impose regulations governing a sand-based energy island, though it is accompanied by various responsibilities, some of which are dependent on how such an island is legally defined. The latter however is currently not explicitly defined in international law. Potential barriers to constructing an energy island may emerge from a prohibition to construct an artificial island where interference may be caused to the use of recognized sea lanes essential to international navigation. Other barriers to such construction may include environmental protection. However, once constructed no explicit obligation seem to exist for the Dutch state to remove any such 'artificial island' under international law. Under the current water permit rules, however, removal of sand-based energy islands is expected to be required under Dutch law. Current rules pertaining to the construction of an energy island or other artificial islands are in need of elaboration given the absence of sector-specific legislation for the construction of artificial islands, installations or structures, particularly those which do not fall under the Mining Act or Wind Energy at Sea Act.

7.6. Working towards nature-inclusive design

We concluded that the balance between positive and negative effects of island construction on both ecology and environment is delicate and there is no straight forward answer to the question how to deal with these aspects in the construction of offshore islands. A question that pops up more and more is how to come to a more nature-inclusive design[14] of energy projects in general, which also holds for offshore energy islands. Stakeholder perception around new energy projects, amongst other considerations, emphasizes the importance of answering this question. We do realize that this is not an easy question, and as was discussed in Chapter 4 further study is needed to answer this question. This will be further developed in the North Sea Energy 2020-2021 program.

[14] A term introduced by Witteveen+Bos (https://www.witteveenbos.com/news/transforming-offshore-infrastructures-into-ecological-hubs/))

Appendix A Island plots plans

Bilfinger Tebodin has developed island plot plans for each island scenario (with 30% and 70% conversion to hydrogen, respectively). The basis of the plot space of each individual area is described in the attached report of Bilfinger Tebodin. Table 8 shows an overview of the areal claims for the individual areas per scenario. Table 9 shows the fixed areal claims for various other items on the island. The plot plans for all scenarios are shown below in Figure 25-30.

Table 8 Spatial claims for individual areas with varying scenarios.

	HVAC (m^2)	HVDC (m^2)	Desali-nation unit (m^2)	H2 production unit (m^2)	Compres-sion (m^2)	D	FBW	Space	Ware-house (m^2)	Full island (m^2)
Scenario 1b	28.875		3.600	33.000	256	400	10.000	50.000	20.000	220.875
Scenario 1d	30.250		8.400	77.000	512	700	10.000	50.000	20.000	271.350
Scenario 2b	103.925	62.000	9.000	82.500	512	700	15.000	10.000	30.000	388.125
Scenario 2d	115.425	62.000	21.000	165.000	912	1.000	15.000		30.000	484.425
Scenario 3b		40.1760	36.000	330.000	1.520	2.000	20.000		40.000	904.760
Scenario 3d		43.1575	84.000	770.000	3.648	4.000	20.000		40.000	1.424.575

Table 9 Spatial claims for fixed items

Island item	**Fixed surface claim (m^2)**
Harbor	40.000
Heliport	10.000
Living areas/accommodation	10.000
Lay-down area	10.000
E contr./off	5.000

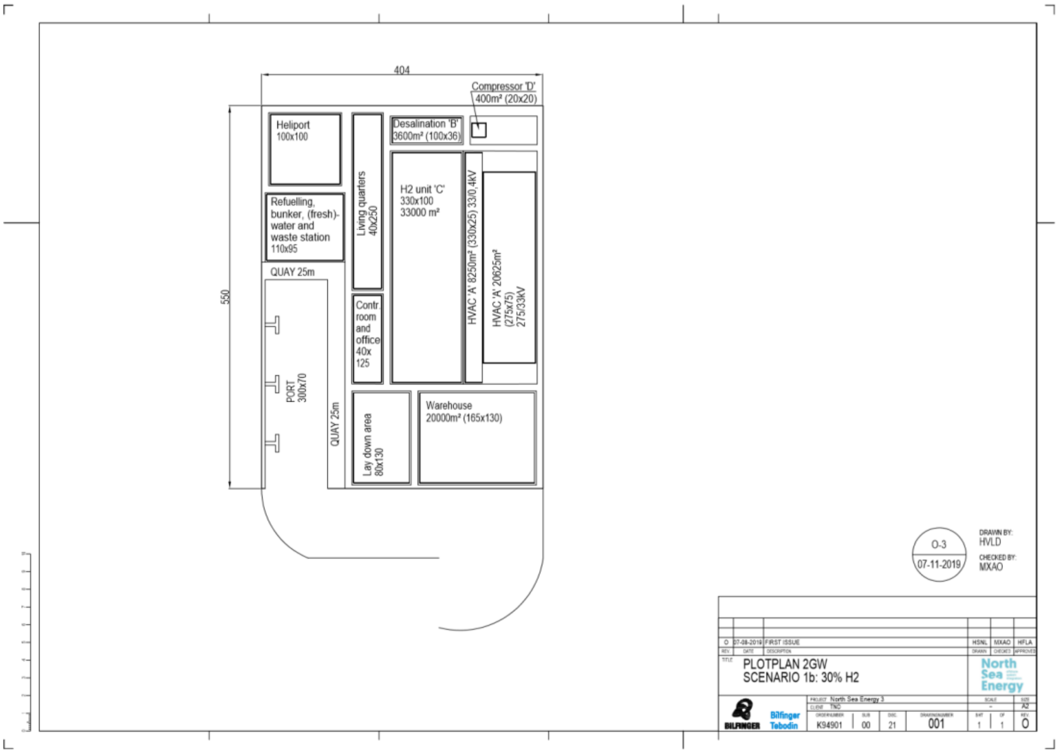

Figure 25 Island Plot Plan Scenario 1b - 2GW 30% H2 conversion

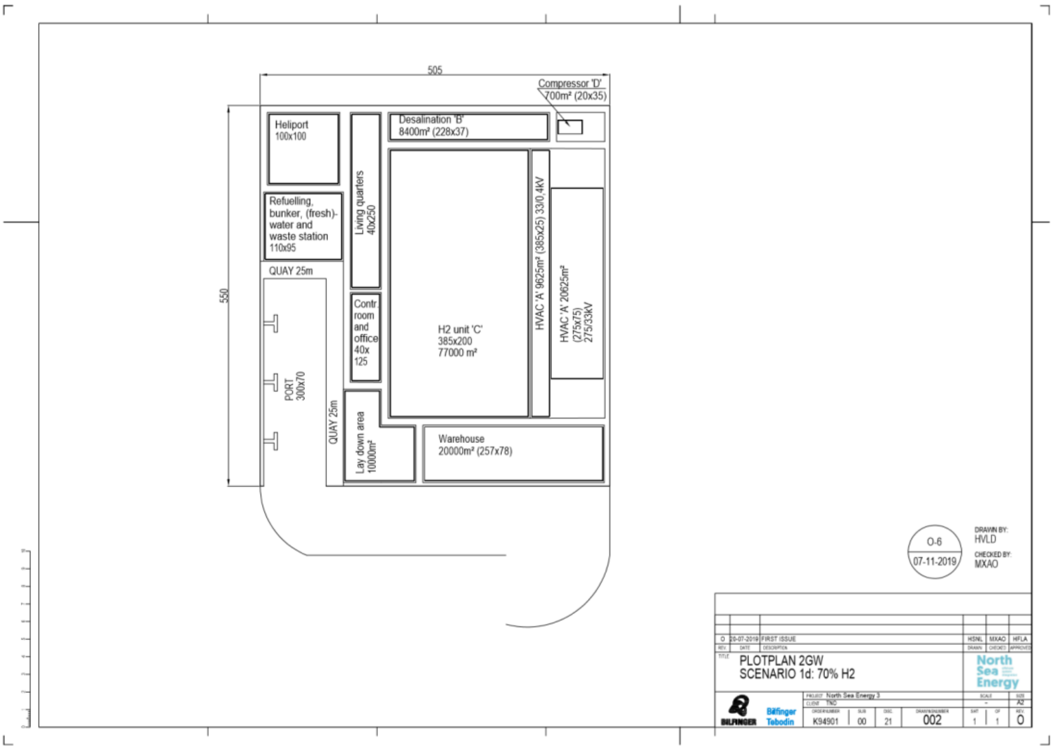

Figure 26 Island Plot Plan Scenario 1d - 2GW 70% H2 conversion

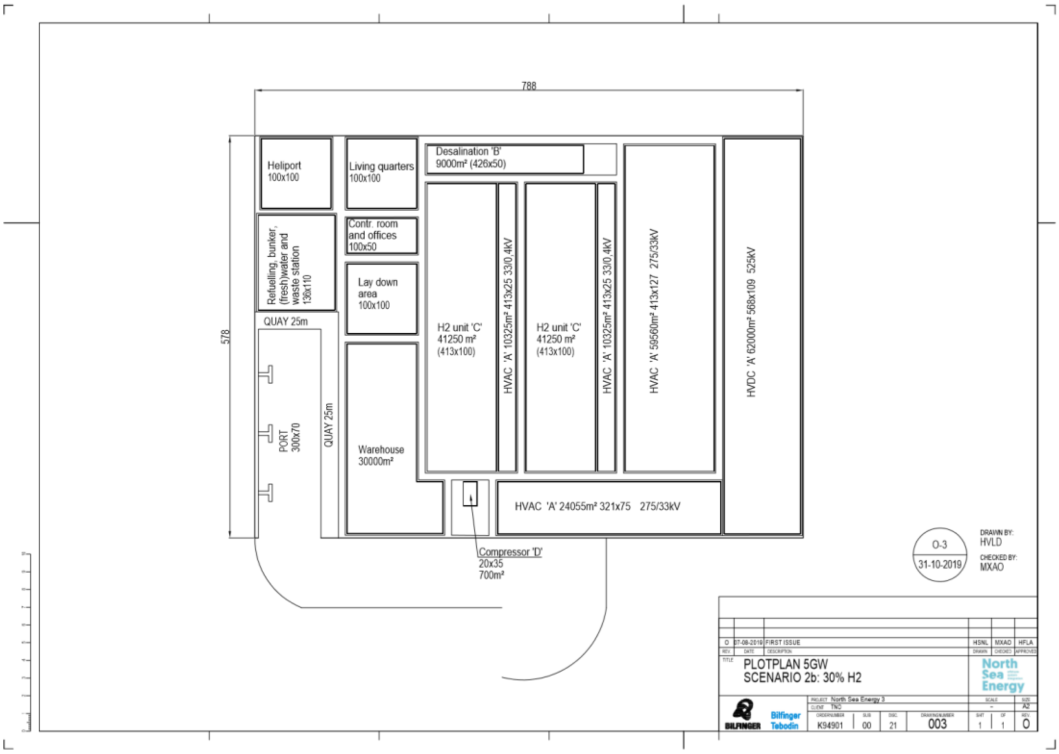

Figure 27 Island Plot Plan Scenario 2b - 52GW 30% H2 conversion

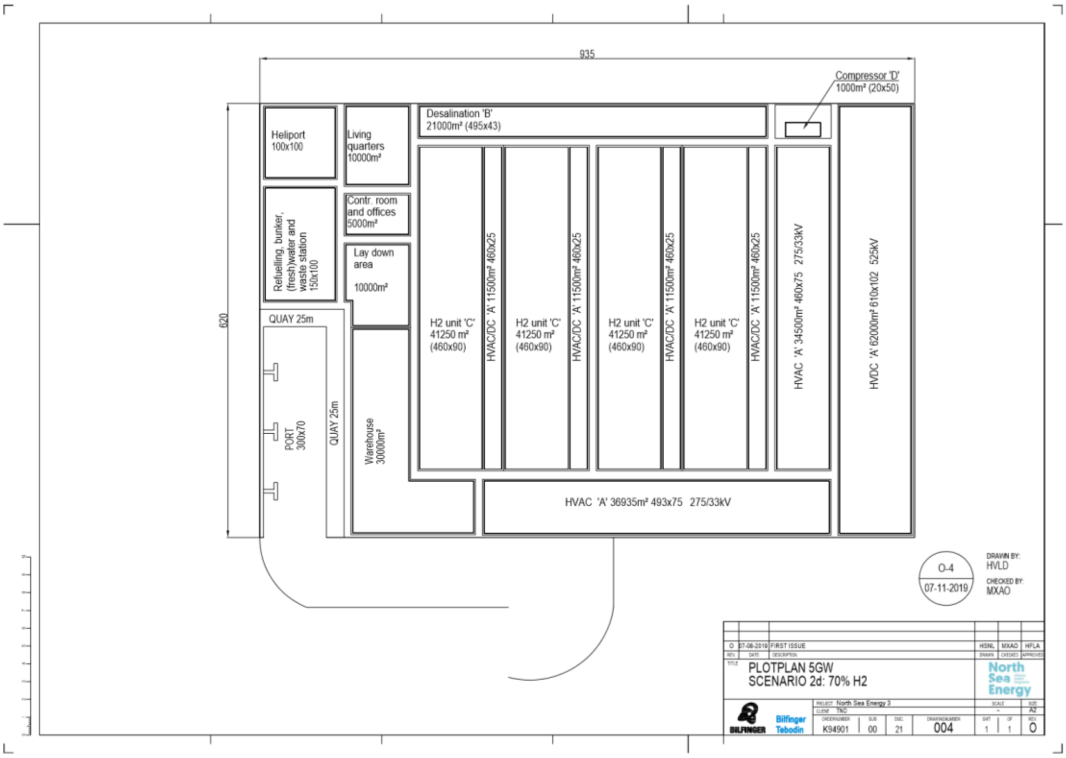

Figure 28 Island Plot Plan Scenario 2d – 5 GW 70% H2 conversion

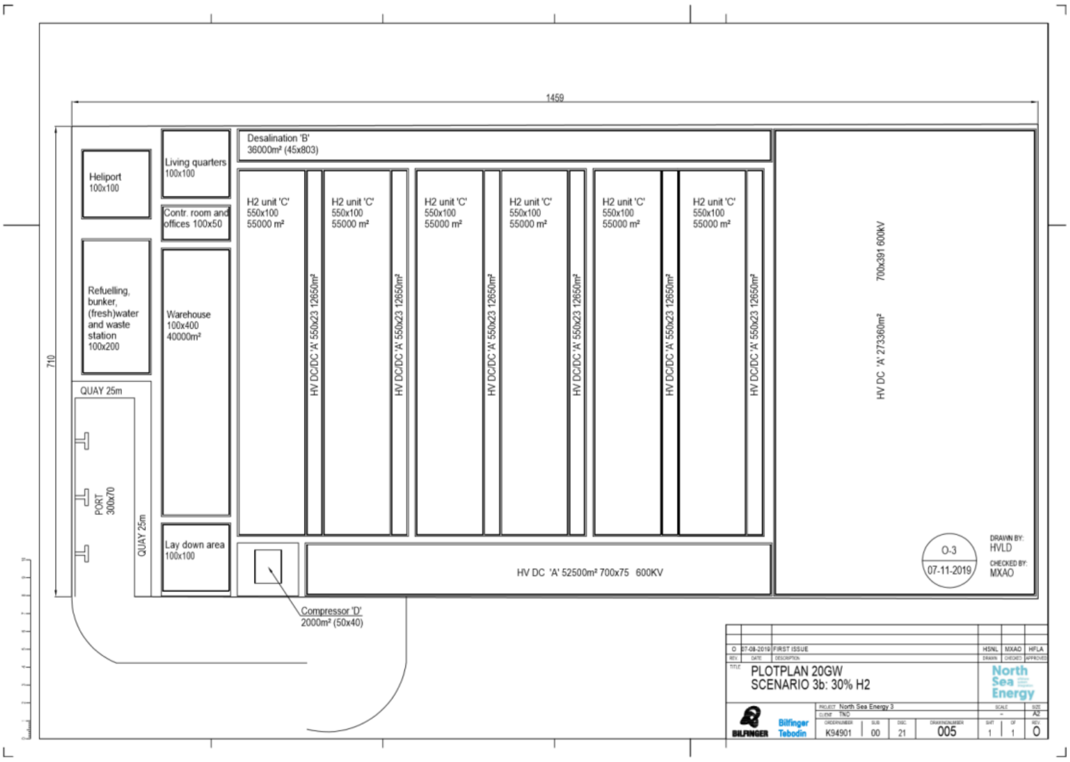

Figure 29 Island Plot Plan Scenario 3b - 20GW 30% H2 conversion

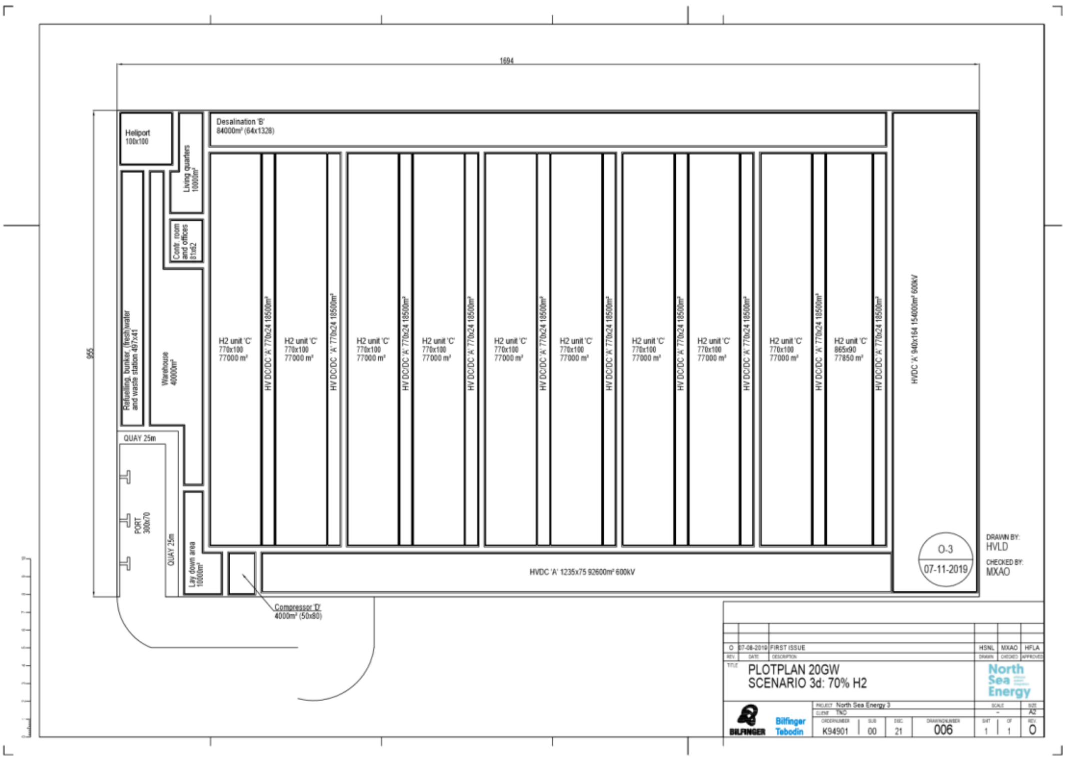

Figure 30 Island Plot Plan Scenario 3d - 20GW 70% H2 conversion

Appendix B Methods for island construction

The construction of an offshore energy island consists of the following steps:

1. Design and engineering phase

2. Materials supply phase:
   2.1 Rock supply from quarry
   2.2 Concrete pre-cast blocks and slabs from pre-cast yard

3. Construction sequence phase:
   3.1 Reclamation of sand pancake by TSHD + filter layer on sand pancake
   3.2 Execution of Shore protection
   3.3 Sand fill
   3.4 Priority on construction of quay wall
   3.5 Deep compaction (Vibro- & Dynamic compaction) and surface compaction
   3.6 Completion works

For island installation, customized tools were developed. One of these tools is the custom made balance crane with camera and echographic image recognition for efficient placing of Accropodes underwater, from land or from pontoon.


Figure 31 Sand fill by TSHD


Figure 32 Shore protection installation (Accropodes train)

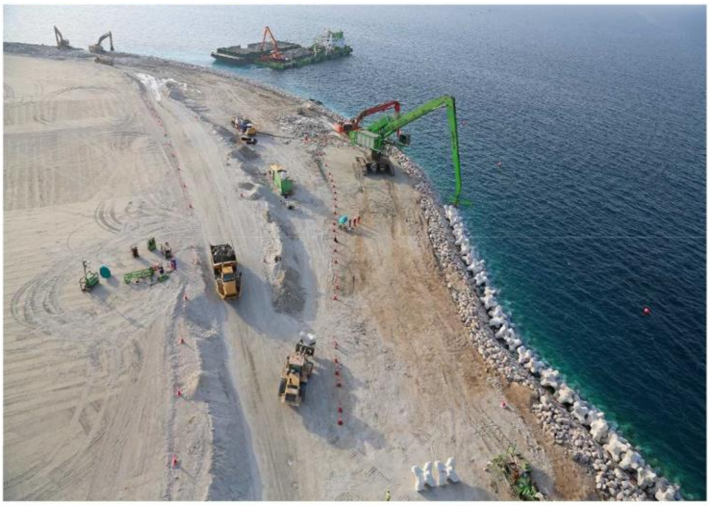

Figure 33: Shore protection train

Figure 34: Custom made balance crane with camera and echographic image recognition

Figure 35: Multitude of activities, incl. vibro compaction

Appendix C Break-down island construction costs

This appendix describes the break-down in CAPEX and OPEX for the various scenarios.

Island 2GW – 70% hydrogen at location A (Scenario 1d)

It is referred to Figure 26 for a general overview of the 2GW – 70% H2 island.

Table 10: Island 2GW – 70% H2 at location A

Construction depth	-23.00 m LAT (see 3.5.2.2)
Surface island	256.750 m² (see plot X)
Height island	31.0 m (from -23 m LAT tot +8 m LAT) (see 3.5.2.4)
Volume sand (incl. 5% losses)	9.360.000 m³
Length breakwater	800 m (see 3.5.2.1)
Length revetment	2040 m (see plot X)
Harbour, length of the quay walls	370 m (see 3.5.2.1)
Harbour, length of slope + jetty	300 m (see 3.5.2.1)

Table 11: Unit prices of the different element of the island.

Code	Description	E.P.	Quantity	Total budget price
	Building Cost Island without infrastructure			**756.950.000 € (-35%/+35%)**
1	Revetment	200.000 €/m	2040 m	408.000.000 €
2	Breakwater	225.000 €/m	800 m	180.000.000 €
3	Sand fill (incl. royalties and compaction)	7,50 €/m³	9.360.000 m³	70.200.000 €
4	Cable landing facilities	45.000.000 €/TP	1 TP	45.000.000 €
5a	Harbor, quay walls incl. scour protection and bollards	125.000 €/m	370 m	46.250.000 €
5b	Harbor, slope + jetty	25.000 €/m	300 m	7.500.000 €

	Management and maintenance	**3.000.000 €/year**		**3.000.000 € (-25%/+100%)**

Island 2 GW – 30% H2 at location A (1b)

It is referred to Figure 25 for a general overview of the 2GW – 30% H2 island.

Table 12: Island 2GW – 30% H2 at location A

Construction depth	-23.00 m LAT (see 3.5.2.2)
Surface island	201.200 m² (see plot X)
Height island	31.0 m (from -23 m LAT tot +8 m LAT) (see 3.5.2.4)
Volume sand (incl. 5% losses)	7.340.000 m³
Length breakwater	800 m (see 3.5.2.1)
Length revetment	1838 m (see plot X)
Harbour, length of the quay walls	370 m (see 3.5.2.1)
Harbour, length of slope + jetty	300 m (see 3.5.2.1)

Table 13: Unit prices of the different element of the island.

Code	Description	E.P.	Quantity	Total budget price
	Building Cost Island without infrastructure			**701.400.000 € (-35%/+35%)**
1	Revetment	200.000 €/m	1838 m	367.600.000 €
2	Breakwater	225.000 €/m	800 m	180.000.000 €
3	Sand fill (incl. royalties and compaction)	7,50 €/m³	7.340.000 m³	55.050.000 €
4	Cable landing facilities	45.000.000 €/TP	1 TP	45.000.000 €
5a	Harbor, quay walls incl. scour protection and bollards	125.000 €/m	370 m	46.250.000 €
5b	Harbor, slope + jetty	25.000 €/m	300 m	7.500.000 €

	Management and maintenance	**3.000.000 €/year**		**3.000.000 € (-25%/+100%)**

Island 5 GW – 70% H2 at location B (2d)

It is referred to Figure 28 for a general overview of the 5GW – 70% H2 island.

Table 14: Island 5GW – 70% H2 at location B

Construction depth	-30.00 m LAT (see 3.5.2.2)
Surface island	558.700 m² (see plot X)
Height island	38.0 m (from -30 m LAT tot +8 m LAT) (see 3.5.2.4)
Volume sand (incl. 5% losses)	24.980.000 m³
Length breakwater	800 m (see 3.5.2.1)
Length revetment	3040 m (see plot X)
Harbour, length of the quay walls	370 m (see 3.5.2.1)
Harbour, length of slope + jetty	300 m (see 3.5.2.1)

Table 15: Unit prices of the different element of the island.

Code	Description	E.P.	Quantity	Total budget price
	Building Cost Island without infrastructure			**1.111.700.000 € (-35%/+35%)**
1	Revetment *	200.000 €/m + 5%	3040 m	638.400.000 €
2	Breakwater **	225.000 €/m + 4%	800 m	187.200.000 €
3	Sand fill (incl. royalties and compaction)	7,50 €/m³	24.980.000 m³	187.350.000 €
4	Cable landing facilities	45.000.000 €/TP	1 TP	45.000.000 €
5a	Harbor, quay walls incl. scour protection and bollards	125.000 €/m	370 m	46.250.000 €
5b	Harbor, slope + jetty	25.000 €/m	300 m	7.500.000 €

	Management and maintenance	**3.000.000 €/year**		**3.000.000 € (-25%/+100%)**

- 5% increase in unit rate revetment due to larger construction depth
- 4 % increase in unit rate breakwater due to larger construction depth

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Island 5 GW – 30% H2 at location B (2b)

It is referred to Figure 27 for a general overview of the 5GW – 30% H2 island.

Table 16: Island 5GW – 30% H2 at location B

Construction depth	-30.00 m LAT (see 3.5.2.2)
Surface island	434.464 m² (see plot X)
Height island	38.0 m (from -30 m LAT tot +8 m LAT) (see 3.5.2.4)
Volume sand (incl. 5% losses)	19.420.000 m³
Length breakwater	800 m (see 3.5.2.1)
Length revetment	2662 m (see plot X)
Harbour, length of the quay walls	370 m (see 3.5.2.1)
Harbour, length of slope + jetty	300 m (see 3.5.2.1)

Table 17: Unit prices of the different element of the island.

Code	Description	E.P.	Quantity	Total budget price
	Building Cost Island without infrastructure			**990.620.000 € (-35%/+35%)**
1	Revetment *	200.000 €/m + 5%	2662 m	559.020.000 €
2	Breakwater **	225.000 €/m + 4%	800 m	187.200.000 €
3	Sand fill (incl. royalties and compaction)	7,50 €/m³	19.420.000 m³	145.650.000 €
4	Cable landing facilities	45.000.000 €/TP	1 TP	45.000.000 €
5a	Harbor, quay walls incl. scour protection and bollards	125.000 €/m	370 m	46.250.000 €
5b	Harbor, slope + jetty	25.000 €/m	300 m	7.500.000 €
	Management and maintenance	**3.000.000 €/year**		**3.000.000 € (-25%/+100%)**

- 5% increase in unit rate revetment due to larger construction depth
- 4 % increase in unit rate breakwater due to larger construction depth

Island 20GW – 70% H2 at location C (3d)

It is referred to Figure 30 for a general overview of the 20 GW – 70% H2 island.

Table 18: Island 20 GW – 70% H2 at location C

Construction depth	-23 m LAT (see 3.5.2.2)
Surface island	1.596.770 m²
Height island	31 m (from -23 m LAT tot +8 m LAT) (see 3.5.2.4)
Volume sand (incl. 5% losses)	58.240.000 m³
Length breakwater	800 m (see 3.5.2.1)
Length revetment	5228 m (see plot X)
Harbour, length of the quay walls	370 m (see 3.5.2.1)
Harbour, length of slope + jetty	300 m (see 3.5.2.1)

Table 19: Unit prices of the different element of the island.

Code	Description	E.P.	Quantity	Total budget price
	Building Cost Island without infrastructure			**1.761.150.000 € (-35%/+35%)**
1	Revetment	200.000 €/m	5228 m	1.045.600.000 €
2	Breakwater	225.000 €/m	800 m	180.000.000 €
3	Sand fill (incl. royalties and compaction)	7,50 €/m³	58.240.000 m³	436.800.000 €
4	Cable landing facilities	45.000.000 €/TP	1 TP	45.000.000 €
5a	Harbor, quay walls incl. scour protection and bollards	125.000 €/m	370 m	46.250.000 €
5b	Harbor, slope + jetty	25.000 €/m	300 m	7.500.000 €

	Management and maintenance	**3.000.000 €/year**		**3.000.000 € (-25%/+100%)**

Island 20 GW – 30% H2 at location C (3b)

It is referred to Figure 29 for a general overview of the 20 GW – 30% H2 island.

Table 20: Island 20 GW – 30% H2 at location C

Construction depth	-23 m LAT (see 3.5.2.2)
Surface island	1.014.890 m²
Height island	31 m (from -23 m LAT tot +8 m LAT) (see 3.5.2.4)
Volume sand (incl. 5% losses)	37.010.000 m³
Length breakwater	800 m (see 3.5.2.1)
Length revetment	4268 m (see plot X)
Harbour, length of the quay walls	370 m (see 3.5.2.1)
Harbour, length of slope + jetty	300 m (see 3.5.2.1)

Table 21: Unit prices of the different element of the island.

Code	Description	E.P.	Quantity	Total budget price
	Building Cost Island without infrastructure			**1.409.925.000 € (-35%/+35%)**
1	Revetment	200.000 €/m	4268 m	853.600.000 €
2	Breakwater	225.000 €/m	800 m	180.000.000 €
3	Sand fill (incl. royalties and compaction)	7,50 €/m³	37.010.000 m³	277.575.000 €
4	Cable landing facilities	45.000.000 €/TP	1 TP	45.000.000 €
5a	Harbor, quay walls incl. scour protection and bollards	125.000 €/m	370 m	46.250.000 €
5b	Harbor, slope + jetty	25.000 €/m	300 m	7.500.000 €

	Management and maintenance	**3.000.000 €/year**		**3.000.000 € (-25%/+100%)**

Appendix D Background desalination & compression

Desalination unit

The salinity of North Sea water averages between 34 and 35 grams of salt per litre; desalination via reverse osmosis implies high energy usage to ensure the right operating pressure of seawater, this way, almost all (around 95 to 99%) of dissolved salts is left behind in the reject stream. This may imply that additional technologies have to be applied to make sure that pure demineralised water can be fed into the electrolyser system. Usually, desalination units are not terribly big. The required demi-water for the Silyzer 200 and probably also for the Silyzer 300 needs to be non-conductive with a quality of <1 micro Siemens and further its required that the control unit of the water treatment system is connected to the electrolysis plant's SIMATIC PCS7. Demi water is quite aggressive for metals, even for stainless steel. So in many cases plastic materials are used to transport the demi water.

In order to retrieve demi-water from saltwater we need a complete process of desalination including:

- Pre-treatment, to remove dissolved solid content (feed pump + multimedia filtration)
- Sea water Reverse Osmosis, to remove salts towards 300 ppm (cartridge filtration + high pressure pump + reverse osmosis modules)
- Low brackish water Reverse Osmosis, to bring it down to a level <50ppm.
- Post-treatment, ion exchange resin and to ensure water quality reaches < 1 uS/cm (or 0, 641ppm) (remineralisation).

More information on the various sub-processes is given in Deliverable 3.2-3.6 Power-to-X. The focus is on large scale uptake of seawater, and therefore the largest pre-treatment system, 100m³/h, has been used within the economic analysis. Although the reverse osmosis has high investment cost (some €3500/kWh), it has relatively low operational costs in comparison with its first best alternative chemical desalination (Gomez, 2019)[xxvi]. For instance, energy is recovered by turbine or pressure exchanges. The largest capacity scale of LennRO SW and the BWRO-L require a power connection of some 280-360kW and 56kW respectively (Gomez, 2019).

Hydrogen compression and booster

In each offshore scenario the hydrogen is compressed to satisfy the required downstream receiving pressures of 30 barg at shore. The input pressure varies between all of the scenarios as it is determined by the pressure drop calculation tool. The pressure drop occurring in the pipe due to friction when transporting hydrogen (or any other gas) depends on: the pipe diameter, the gas throughput, the surface properties of the pipe material, the velocity level in the pipe, and the density of the gas. At shore, the hydrogen is compressed (via a booster) to 68 barg. At shore, an additional booster is assumed to increase the pressure from 30 to 68 bar making it comparable to the pressure on the existing gas grid.

For each of the scenarios compression costs are included. For this purpose, a compression power, noted P in kW, is calculated determining together with the operating hours and the load profile the energy required for compression (Equation 3).

$$P = \frac{Q}{3600 * 24 * 33.33} \times \frac{Z \times T \times R}{M_{H_2} \times \eta_{comp}} \times \frac{N_\gamma}{\gamma - 1} \times \left[\left(\frac{P_{out}}{P_{in}} \right)^{\frac{\gamma-1}{N\gamma}} - 1 \right]$$

Equation 3: Compression power based on (Castello, 2005)[xxvii] & (Jean Andre, 2014).[xxviii]

where:

- Q the flow rate (in kWh per day) by taking a low heating value (LHV) of 33.33 kWh/kg specific to hydrogen,
- P_{in} the inlet pressure of the compressor (suction),
- P_{out} the outlet pressure of the compressor (discharge),
- Z the hydrogen compressibility factor,
- N the number of compressor stages,
- T the inlet temperature of the compressor (278 K),
- γ the diatomic constant factor (1.4),
- M_{H2} the molecular mass of hydrogen (2.0158 g/mol),
- η_{comp} the compressor efficiency ratio (here taken as 75%),
- the universal constant of ideal gas R = 8.314 J K-1 mol-1.

Appendix E Cost structure for NPVs (confidential)

Appendix F Levelized Cost of Energy analysis (confidential)

Appendix G Methodology & argumentation qualitative scoring of other use functions

Applied Methodology

Additional use functions next to wind transmission and hydrogen production might strengthen the business case of offshore energy islands. A qualitative scoring has been done to gain first insight into the potential of twenty-six different additional use functions.

Within this analysis we did not aim to score the use functions in a quantitative and measurable manner, but in a qualitative way that reflects the experiences, perspectives, opinions, and knowledge of experts. A scoring workshop was organized with five experts from RoyalHaskoning-DHV and TNO from relevant domains (oil and gas offshore wind, ecology, hydrogen, system integration). The use functions were scored by following a PESTTEL analysis (Political, Economic, Social, Technological, Timing and organizational, Environmental and Legislative), where the scores were defined as follows: very positive (++), positive (+), neutral (0), negative (-) and very negative (--). A positive result of ++ or + for all of the PESTTEL factors of one use function would serve as an indication of a high-potential use function. Whereas, when a score of -- was given for at least one of the PESTTEL factors, we assigned the respective use function to a red flag category even if the other factors score high. Any other use functions with average scores in between (and no -- scores for one of the PESTTEL factors) need further investigation on the effect degrees of each PESTTEL factor, as these are not expected to have similar orders of magnitude of influence per use function. We captured the arguments behind the scoring in order to come to a good first understanding of the most important opportunities, uncertainties and risks for the different use functions. This has to be done in order to specify the critical points of interest that might be used to inform future lines of research.

Furthermore, we specifically note that the results from the method applied in this study are not objective. Therefore, the results cannot be used as-is to make conclusions and take decisions on the different use functions and one cannot include or exclude certain use functions into the business case based on this study alone. However, the aim of the qualitative scoring methodology is to provide a first-order estimation of the potential applicability of the various use functions into the business case with respect to offshore energy islands.

In the scoring, we have not included nature reserves/ecology as a use function, as a bit more elaborate analysis is presented in Appendix H.

Use function scoring argumentation

The aim of this phase is to strengthen the business case by providing an overview on the potential applicability of various use functions at offshore energy islands. First, the important and relevant use functions for each island concept (2, 5 and 20 GW) were differentiated.

Operation and Maintenance of offshore wind

The 2 GW offshore energy islands will decrease the trafficking (and emissions) necessary for operations and maintenance of offshore wind facilities, which might have a positive influence on the political and environmental view point. Due to the increase in efficiency (less transport) there might also be an economical benefit. Technologically, timing and organizationally speaking this use functions is already in a well-developed state. There could be a slight negative perception from the legal point of view as licenses need to be provided.

Floating solar arrays

Floating solar arrays could contribute to political support for offshore energy islands. However, technically we see the offshore as a too harsh (moist, wind, salinity) environment for sustainable deployment of floating solar arrays. Also from an environmental perspective, the decrease of light throughput at locations of floating solar may have a negative effect on the ecology living beneath it.

Hydrogen storage above ground buffer (2 GW)

A hydrogen above ground buffer could be installed to ensure smart delivery of hydrogen to the network and to locally store hydrogen on the island. As this is technically feasible, it can be doubted whether there is an economical and organizational advantage over onshore buffering. As this is probably more advantageous because of harsh offshore conditions,

Offshore hydrogen fueling station (20 GW)

An offshore hydrogen fueling station might have political and environmental support as it can serve as a large-scale offshore fueling service, decreasing shipping traffic for bunkering in the harbors. As extensive knowledge and experience is available for this use function, no barriers are foreseen on a technological and organizational level. There might be a legal challenge since offshore energy sales is currently not covered in Dutch legislation. Thereby, storage facilities need to be installed that can store both electricity and hydrogen.

Large-scale energy storage of hydrogen (20 GW)

Social acceptance is seen as a deal-breaker for subsurface hydrogen storage, though no major issues are expected for storage in the offshore. The main challenge for this type of storage is timing and organization in nature, as storage assets (caverns, depleted gas fields) need to be available at the start of storage.

Electrification of oil and gas platforms

Combining electrical transport for electrification of platforms and electrical transmission can be interesting from both a technical, economical and organizational perspective. For that reason, we consider this as a high potential additional use function.

Interconnection electricity

One of the interesting options as an additional use function on offshore energy islands is to include electrical interconnection on the island. We expect no red flags nor serious challenges for this in the future. Further study is off course needed, but this function should be considered as a high potential use function.

Operation and maintenance offshore oil and gas (5 GW)

As acceptance for oil and gas production is decreasing, political acceptance of this use function might be limited. Economically speaking operation and maintenance of offshore oil and gas is more expensive compared to onshore. It does decrease transport time and distance, but the question remains whether the cost of the additional piece of island will outweigh these cost savings. Due to strong experience in the oil and gas industry, no technological, timing and organizational issues are expected.

Interconnection natural gas (5 GW)

No legal, timing and organizational issues are expected for this use function because strong experience in the gas industry. Because of the strategic location of energy islands between countries, this could be a very interesting addition to the business case of offshore energy islands.

Liquid conversion, storage or station

Liquid production is a complex and expensive process and requires a lot of space. For that reason, conversion and storage of liquids on an offshore energy island is unlikely to take place because of organizational challenges. The TRL of Power-2-Liquids is high enough, so no technological showstoppers are foreseen.

CO2 hub compression and storage

When new infrastructure is needed for this use function, this may strongly increase the costs of this use function. Thereby, depleted gas fields for storing need to be close-by to make compression on an island attractive. Re-use of nearby infrastructure might increase the applicability of this use function, though the timing of availability of this infrastructure in then crucial.

Biomass drying and transport

We expect this use function to gain political and social support as it contributes to the food and energy transition at sea. The economic value of drying at the island is that it enables bulk transport per ship, which lowers the cost and decrease emissions related to this transport. Technology is available. From an environmental perspective, more research is needed in potential disturbances of e.g. seaweed farming on the local environment.

Biomass storage and conversion

No positive business case of storage and conversion of biomass offshore is known, although this depend on the type of stored product. TRL and timing issues depend on the type of conversion. Complex processing actions are not expected to be successful offshore. Similarly, some major hurdles are expected from a legal perspective.

Ancillary services

From a technological, and timing and organizational perspective, no issues are expected for the proposed use functions associated with ancillary services.

Safety and rescue
Safety and rescue scores neutral to slightly positive at most aspects. This is, because with the increase in work and traffic at the North Sea a safe and well developed rescue system and environment (e.g. safe harbors) needs to be present. No legal barriers are expected as well.

Data centers
Local sales of electricity may improve the business case of the offshore island, as lower electrical transport capacity to shore is needed. We expect political support for this type of activity.

Data transmission
Similarly for other interconnection options, a small-scale additional use function could be data transmission and interconnection.

Airstrip at sea (20 GW)
An airstrip at sea might be interesting at the larger islands, as it allows for fast transport of personnel.

Recreational hotel (20GW)
For recreational hotels, there might be a challenge with (permanent) staffing, which poses economical and organizational challenges to this use function.

Marina (20GW)
For a marina, there might be a challenge with (permanent) staffing, which poses economical and organizational challenges to this use function.

Ecological research institute (20GW)
No political, societal and technological barriers are foreseen for the establishment of an ecological research institute. It is unclear whether legislation enables the development of such an institute in this stage.

Appendix H QuickScan environmental and ecological challenges for developing and implementing offshore energy islands

Energy islands may become a critical element in the energy transition. Islands will be able to support the necessary infrastructure required to get the large amount of electrical power to shore, for instance by the offshore production of hydrogen.

Developing an island goes hand in hand with environmental challenges. Every activity related to the construction and operations of an energy island causes impact on the environment, but what are those impacts and effects? And at the same time, is there a way that the environment could benefit from such an energy island?

The main question for this QuickScan is to identify the environmental impacts and determine possible benefits to ecology in order to have a first general overview. What can be expected when developing an energy island? These ecological benefits (positive impacts) and environmental costs (negative impacts) are described in general, as the NSE III program does not consider a specific location for such an energy island, but rather the concept of an energy island on the North Sea in general. Different island scenarios are defined. Scenarios for different locations and for different type of islands. As environmental impacts can be quite different for different type of islands, varying assessments are made. Based on these assessments an advice is drawn up how islands could be beneficial for ecology. How an energy island could become beneficial for the marine ecosystem, is presented in the final notes.

Starting point – island scenarios

An energy island could have several functions: an AC/DC transformation facility to transport the produced power to shore, an interconnector providing links to systems of other European countries, an offshore production facility of green hydrogen, an operation and maintenance facility for offshore wind farms, an electrical service station to power up electrical sea vessels and be used by national services such as the coast guard and an ecological research station. Depending on the proposed island functions, the impacts could differ as well, because the size of an island will increase with the number of functions. In any case a multifunctional island will always be spatially connected to nearby windfarms.

In the NSE III program, different options and scenarios are investigated for an energy island. As part of the program three different scenarios for the location and size of an energy island are defined, namely:

- Nearby
    - 60 km from the coast
    - Good for about 2GW energy supply
    - Surface of 6 to 13 ha
- Midway
    - 100 km from the coast
    - Good for about 5GW energy supply
    - Surface of 50 ha
- Faraway
    - >300 km from the coast
    - Good for about 20GW energy supply
    - Surface of 130 ha

Within this QuickScan, only the extreme scenarios are taken into account. Which means, a nearby island and a faraway island. Using this distinction, the environmental and ecological impacts are best indicated. From an ecological point of view, the nearby island would have a maximum distance of 30 km from the coast, instead of the 60 km as defined for the NSE III program. At a distance of more than 30 km the ecological system changes from a coastal system to a complete offshore marine system.

Island concepts
There are many concepts for the construction of an island, such as floating, seabed based or submerged island concepts, see Figure 36. An energy island in the North Sea is most likely to consist of a combination of hard elements, rocks and concrete, and soft elements, sand, see Figure 37; whereby the outer layer of the island will be created with rocks and concrete and filled with sand to create the actual surface area of the island.

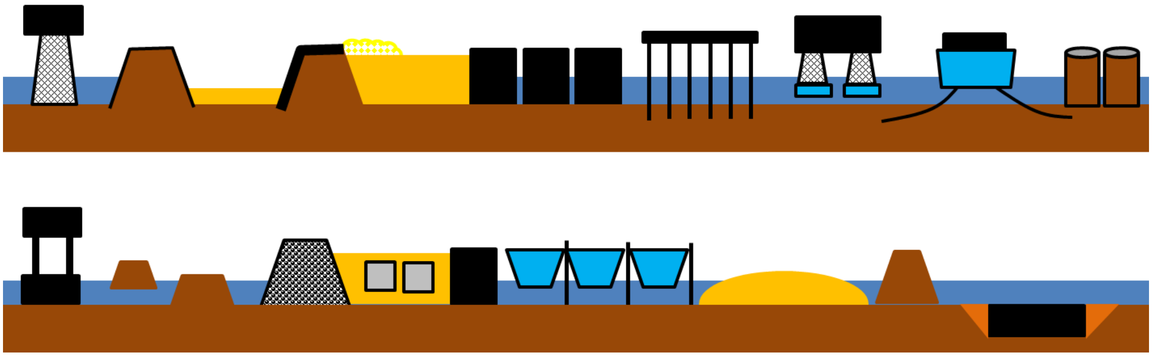

Figure 36 – Different island concepts, ranging from floating, submerged, to polder options (combination of rocks and sand), to a caisson island (picture by Royal HaskoningDHV)

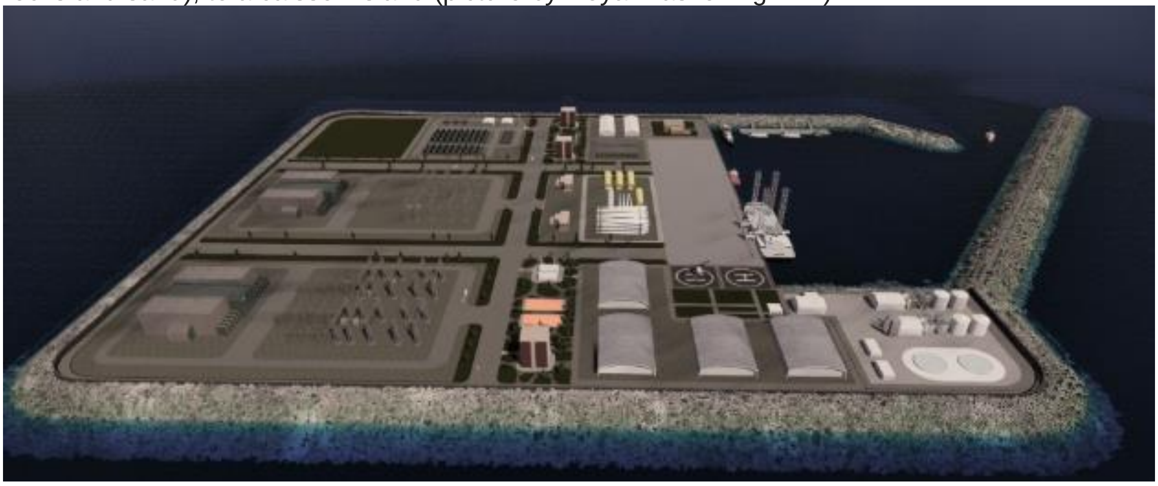

Figure 37 – Example of an offshore energy island, as developed by Royal HaskoningDHV for Offshore Service Facilities

How to assess the impacts
As part of permit applications, an extensive Environmental Impact Assessment (EIA) is to be completed. In this QuickScan the impact of developing an energy island on the environment and ecology will only be assessed on a strategic level to get a first general overview. This QuickScan gives a first indication of the possible effects, based on a qualitative approach, and aims to see if ecological benefits can be added/developed.

The following assumptions are the basis for this QuickScan:

- The reference situation is the situation without an island: this means that to determine the impacts a comparison is made between the situation of an island versus the situation with no island;
- The impacts are assessed for both the construction and the operation phase;
- Assessed activities are only related to the island building, activities on the island (e.g. building a hydrogen power plant) and cable/pipelines are not included;
- The impacts are described at high level in a qualitative way based on publicly available information. Where public information is not available the description of impacts is based on experience and expert judgement;
- Following the *People, Planet, Profitability* approach an assessment framework is prepared. This framework structures the various environmental aspects (see also textbox for more information);
- Tables show the scores per phase and environmental aspect. Note that by comparing the energy island with the reference situation, the score of the reference situation is always zero;
- The impact assessment uses a scoring system with seven categories, see the details in the table below;
- In case no impact is possible, the environmental aspect has a grey marking.

- - -	**Strongly negative**, effect is outside of the judicial framework (show stopper)
- -	**Negative**, mitigation measures should be investigated
-	**Moderately negative**, no disrupting effect
0	No impact / Neutral
+	**Moderately positive**, no significant improvement
+ +	**Positive**, clear improvement compared to the reference situation
+ + +	**Strongly positive**, the development has clear added value
	No impact possible

Planet, People, Profitability
Sustainable development is development that meets the needs of the present without limiting the ability of future generations to meet their own needs. There are three sustainable development capitals, on which the criteria used in this assessment are based: PLANET, PEOPLE, PROFITABILITY, also known as the 3Ps. Using this approach allows for an integrated assessment of the possible environmental impacts. The 3Ps' approach is in line with the approach used in the Strategic Environmental Assessments prepared for the designation of the offshore wind energy areas.

Environmental impacts

As described in previous paragraph, the environmental impacts are scored. A distinction is made in the construction and operational phase. In some situations, the effects could be different according to the location of the island. Therefore, when applicable different scores are indicated for an island nearby and an island faraway.

The table shows the total overview. Most of the effects depend on the location or location specific occurrences of an environmental aspect. Per theme the effects are described, for some themes an obvious/straight forward score cannot be given as the dependency on the location is critical. Each theme is detailed shortly below.

Table 22 – Overview of environmental impacts (qualitative QuickScan at strategic level)

	Theme	Island nearby		Island faraway	
		construction	operational	construction	operational
Planet	Ecology (above water surface)	- / - -	-/+	- -	-/+
	Ecology (below water surface)	- -	-/+	- -	-/+
	Seabed	- -	-/+	- -	-/+
	Water quality	- -	-	- -	-
	Sound	- -	0	- -	-
	Air	-	0	- -	-
	Light	-	- / +	-	- / +
	Landscape	0	0	0	0
	Cultural heritage and archaeology	-	0	-	0
People	Sustainable Energy use	- -	+ +	- -	+ +
	Traffic	- -	0 / +	- -	0 / +
	Operational safety	-	*	-	*
Profitability	Other spatial uses	-	0	-	0

Ecology above water surface – birds and bats

Theme	Island nearby		Island faraway	
	construction	operational	construction	operational
Ecology (above water surface)	- / - -	-/+	- -	-/+

Construction (negative effects)
Sea birds could be disturbed by vessels (noise and light) used during the construction phase. Sea birds are expected to avoid the construction area at a distance of 2 km (RHDHV, 2017a)[xxix]. Accordingly, a small area will not be used, the actual impact will depend on the way birds use the area (- -).

Several hundred million of migratory birds and bats of many different species cross the North Sea from Europe and Scandinavia to Britain during the spring and autumn migration. No exact migration routes are known, it is assumed that birds and bats use the whole North Sea (RHDHV, 2016)[xxx]. Depending on the location of the island (especially further offshore), migratory birds and bats are expected to be disturbed or disoriented due to light caused by the construction activities of an island (RHDHV, 2016). Therefore, it is expected that the impact during construction phase are more negative in case of an island faraway (- -).

Operation (varying effects)
During operation varying effects could occur, ranging from negative to positive. The island could be used as a 'safe heaven' by birds (+) and as a resting and foraging place for cormorants (+). Depending on the design of the island, it can be attractive to breeding birds as a foraging area (+). It should be noted that a foraging area does not depend on the distance to the coast. Foraging species could reach the island. The main difference in a nearby and faraway island is that a closer to the coast a larger variety of species occur.

It should be noted that there is a chance that the food chain could change, as different species that did not occur on the island location are now able to reach the location. With the construction of an island ecological processes are extended further offshore: what used to be a marine system, will become a coastal system. This could bring negative effects but could be positive as well. For instance, an island could result in the presence of birds of prey which are not present in the existing marine environment. On the other hand, and island could create an interesting foraging area for cormorants, which can rest on the island and forage on the fish available.

Ecology below water surface – benthos, fish and sea mammals

Theme	**Island nearby**		**Island faraway**	
	construction	operational	construction	operational
Ecology (below water surface)	- -	-/+	- -	-/+

Based on studies conducted for the North Sea Wind Power Hub (NSWPH) a number of possible impacts on ecology below the water surface have been defined (RHDHV, 2017a) and a description per construction and operational phase is included below. These are:

Habitat / species	**Construction phase**	**Operational phase**
Water column	Turbidity of the water column, primary production may decrease, impact on the food chain	-
Sand banks	Disturbance, loss and change of habitat	Loss and change of habitat
Marine mammals	Avoidance of areas with underwater noise	Possible attraction to islands due to high food abundance
Fish	Disturbance, change and loss of habitat Negative impact on fish eggs and larvae	Increased food availability leads locally to higher biomass and larger fish
Benthos	Disturbance, loss and change of habitat of soft substrate species	Higher biodiversity and a higher biomass of hard substrate species, stepping stone for invasive species

Construction (negative effects)
Depending on the way the island is constructed the underwater noise impact will vary. In contrast to the common construction methods for the foundations of wind turbines in the North Sea, piling will not be necessary for the island construction activities. It is expected that rock dumping, sand mining and sand filling will be the key construction activities generating noise. Due to this construction noise sea mammals and fish are expected to avoid the noise and (temporary) leave the area during the construction phase (- -). Due to the nature of the construction activities it is not expected that sea mammals will experience temporary hearing disorder or permanent hearing damage. In any case permanent hearing damage needs to be avoided, as it could cause death of sea mammals.

The construction activities will impact the seabed and the different species living at the seabed in the construction and the sand mining area. Especially with dredging activities, temporary disturbance in the water due to sediment and chemicals will occur. Locally the seabed habitat will be destroyed, impacting the food availability and fauna depending on it, which could cause incidental deaths of fauna. Furthermore, turbidity has a negative effect on the sight and foraging function of fish and sea mammals. Benthos might die, due to turbidity or under brushing. One island on the North Sea is small (nearby scenario 6 to 13 ha, and faraway 130 ha) compared to the total surface area of the North Sea, or the Dutch Exclusive Economic Zone (EEZ) (59000 km^2). Hence, the total impact on the seabed and related flora and fauna is negative, but local and limited compared to the whole of the North Sea or the Dutch EEZ (- -). It is not expected that the population levels of species will be impacted due to the construction activities of an island. There is no significant difference in the effects for an island nearby and faraway.

Operation (varying effects)
During operation varying effects could occur, ranging from negative to positive. Positive effects could be a result of the slopes of the island. Species of fish and benthos can live on the hard substrate of the slopes of the island, optimising these benefits can have a positive effect (+). On the other hand, habitat and foraging area will be lost locally, but on the large scale of the North Sea the impact is limited (-). It should be noted that the impacts are highly location specific. In case the island is constructed at a location where only specific species occur the impact could be strongly negative.
The island could be used as a stepping stone (in both scenarios): coastal species (both fauna and flora) could spread to the United Kingdom or Norway. This could lead to dispersion of invasive species. It is uncertain if that can lead to positive or negative effects (+/-). With the construction of an island ecological processes are extended further offshore: what used to be a marine system, will become a coastal system, for instance seals may be able to extent their habitat by using the island as a resting place. Normally seals swim around 30 km, but 60 km is also reachable, hence they could reach a nearby / midway island. The presence of an island may be interesting for seals to raise their young. It is (not yet) clear if this will have a positive or negative impact.

Seabed

Theme	Island nearby		Island faraway	
	construction	operational	construction	operational
Seabed	- -	- /+	- -	-/+

Construction (mostly negative effects)
With every island concept, either nearby or faraway, the seabed will be affected. New land (sand, caissons, etc.) will affect the existing seabed (- -). In case the island will be constructed using concrete or rocks combined with sand, the sand mining will cause impact on the seabed at the mining location (- -). An increase in suspended sediment concentration (dredging plume) is expected during the construction phase (- -).

Operation (varying effects)
Wave induced currents transport sediment and could cause changes in the shape of the island, which could have a negative impact (-) on the integrity of the island but could have positive effects at the same time on the existing of valuable species (+). There are species that can live because of the transport of sediment. Positive effects can be created due to the slope of the island, as a lot of ‘seabed’ is already present in the North Sea, adding more ‘slope’ would create more variety at the seabed.

Water quality

Theme	Island nearby		Island faraway	
	construction	operational	construction	operational
Water quality	- -	-	- -	-

Construction (negative effects)
Negative effects on the water quality could occur during construction, due to turbidity and suspended sediment. These have mainly impact on nature/ecological values. As the concentration of sediment changes, the benthos will change as well. The more suspended sediment, the worse for benthos. The water quality will also be

affected by the ships/material that is used for construction; emissions, toxic materials from the ship (e.g. paint, steel) (- -).

Operation (moderately negative effects)
The sediment concentration around the island is expected to increase. Negative effects can be expected due to these dynamic circumstances, which may stabilise at a later stage (-). Due to sediment in suspension, that will settle, the seabed becomes siltier.

Installations on the island are expected to produce wastewater, in case this will be discharged in the North Sea it will have a small negative effect. The wastewater will disperse; therefore, the concentrations are small and could be neglected. Besides, in case of hydrogen production, it is expected that it will be necessary to convert large amounts of salt water into fresh water. Therefore, the salt is disposed in the sea, resulting in a locally higher concentration of salt. Locally this will have a negative effect, but on the large scale of the North Sea this can be neglected.

Sound

Theme	**Island nearby**		**Island faraway**	
	construction	operational	construction	operational
Sound	- -	0	- -	-

Construction (negative effects)
The construction activities will cause construction noise underwater. The noise impact will differ for different activities, e.g. rock dumping or sand filling, but is expected to be negative (- -). In addition to underwater sound, there is sound above the water surface coming from ships and helicopters. It is expected that these effects are not significant compared to the normal activities on the North Sea (-).

Operation (moderately negative)
Negative effects will be caused by noise from transport movements. However, for a nearby island the effects are expected to be comparable to existing transport movement (0). For a faraway island the impacts due to transportation to the island are expected to be moderately negative as the distance for transportation is larger (-). Depending on the installations and functions on the island, noise emissions could differ, for instance in case the island will have an operation and maintenance function for nearby windfarms the number of transportation movements to these windfarms will be reduced substantially.

Air

Theme	**Island nearby**		**Island faraway**	
	construction	operational	construction	operational
Air	-	0	- -	-

Construction (negative effects)
Air emissions are caused by transport movements and construction activities. More emissions can be expected in case of an island faraway (- -) compared to a nearby island (-), due to longer transportation routes.

Operation (moderately negative effects)
Negative effects will be caused by emissions from transport movements. However, the effects are expected to be much smaller and comparable to existing transport movement for a nearby island (0). For a faraway island

the impacts due to transportation to the island are expected to be moderately negative as the distance for transportation is larger (-). Depending on the installations and functions on the island, air emissions could differ.

Light

Theme	Island nearby		Island faraway	
	construction	operational	construction	operational
Light	-	- / +	-	- / +

Construction (moderately negative effects)
Due to transport operations and the light of the ships and other construction equipment, more light is produced within an area which is dark in the reference situation of no island (-).

Operation (moderately negative and moderately positive effects)
During operation, less ship movements/transport operations are necessary for the island itself, these effects are not significant and comparable to 'normal' transport operations at the North Sea. However, the island could function as an operation and maintenance hub for nearby windfarms, which will cause an increase in the number of transportation movements around the island.

Negative effects can also be expected due to light on the island, but these can 'easily' be mitigated (e.g. limited light, lights facing down). These negative effects are location specific (-). The lights at the island could also have also a possible positive effect for ships, or animals, e.g. during a storm when ships or animals get disorientated, the island can act as save heaven or resting place (+).

Landscape

Theme	Island nearby		Island faraway	
	construction	operational	construction	operational
Landscape	0	0	0	0

Construction (no effects)
The distance of both nearby and faraway islands to the coast is too large to speak of visual disturbance. The transport operations/ship movements can cause slight visual disturbance but are not significant compared to the normal transport operations (0).

Operation (no effects)
The distance of both nearby and faraway islands to the coast is too large to speak of visual disturbance (0). For sailors, recreational fishermen or boaters the visual impact of the island will be limited as it will reach about maximum 15 meters into the air. However, an island could be an visual object of interest for people visiting the area.

Cultural heritage and archaeology

Theme	Island nearby		Island faraway	
	construction	operational	construction	operational
Cultural heritage and archaeology	-	0	-	0

Construction (moderately negative effects)
There is a possibility to find shipwrecks in the North Sea, closer to the coast, more wrecks can be found. Other archaeological values could be present as well. The presence of archaeologic values depends on the location. Detailed studies of the seabed are able to provide more information, based on which mitigation measures can be taken (avoid, protect in situ or excavate).

Operation (no effects)

Sustainable energy

Theme	Island nearby		Island faraway	
	construction	operational	construction	operational
Sustainable Energy use	- -	+ +	- -	+ +

Construction (negative effects)
Negative effects can be expected due to the need and use of energy for construction. The current ships and material are not working on electrical or sustainable energy (- -).

Operation (positive effects)
Assuming the energy island will be used for or contribute to the generation of sustainable energy in one way or the other (wind energy, green hydrogen, charging facility for fishing boats, etc.), the operations of the island will have a positive impact on the production of sustainable energy (++).

Traffic

Theme	Island nearby		Island faraway	
	construction	operational	construction	operational
Traffic	- -	0 / +	- -	0 / +

Construction (negative effects)
Negative effects on the shipping traffic on the North Sea can be expected due to transport operations. The impact and effects on other traffic on the North Sea depend on the intensity and is location specific. The North Sea is the busiest sea in the world and therefore includes many shipping lanes between the UK and the Netherlands. Due to the offshore wind farms that will be built till 2030 commercial shipping is expected to be even more concentrated in the shipping lanes. Additional boat movements for construction will have a negative impact on the ship safety (RHDHV, 2015)[xxxi].

Closer to the coast, less/ shorter transport operations are needed, but at the same time the coastal area is intensely used by all sorts of shipping traffic (-). In case of a faraway island, ship movements and transport operations are longer (more) (-).

Operation (positive effects)
Now and then maintenance transport operations will be required, which have no significant effects compared to the existing shipping movements (0). The island can be used as hub, supply station in the middle of the sea, which could have a positive effect on traffic (+).

Operational safety

Theme	**Island nearby**		**Island faraway**	
	construction	operational	construction	operational
Operational safety	-	*	-	*

Construction (moderately negative effects)
During construction there are risks, related to normal construction works. These risks have negative effects on operational safety but can be mitigate by safety measures (-).

Operation (not known)
Depending on the use of the island, effects can occur on operational safety and possible risk could/must be mitigated by safety measures. This QuickScan only assesses activities related to the island building, onshore activities on the island (e.g. building a hydrogen power plant) and cable/pipelines are not included.

Other spatial uses

Theme	**Island nearby**		**Island faraway**	
	construction	operational	construction	operational
Other spatial uses	-	0	-	0

Construction (moderately negative effects)
The construction and transportation activities are expected to impact other spatial users, due to intensified traffic (-).

Operation (no effects)
One island on the North Sea is small (nearby scenario 6 to 13 ha, and faraway 130 ha) compared to the total surface area of the North Sea, or the Dutch Exclusive Economic Zone (59000 km^2). Hence, as this QuickScan only considered the impact of an island itself the impact on other spatial uses during the operations is so small that this is scored as no impact.

Ecological benefits

Most of the environmental effects are negative, also on the ecology. Would it be possible to alter these negative impacts into a positive impact? What ecological benefits can be combined in developing an energy island?

To answer these questions a general approach is taken. A specific island location is not part of the analysis of NSE III Program, but the two scenarios for a nearby and faraway island are used. As these scenarios are clearly distinctive. In general; a nearby island (in this QuickScan up to 30 km) has a coastal ecological environment and a faraway island (>150km) is identified as a clear offshore marine environment.

For both scenarios the most likely way of construction is a combination of hard and soft elements. Hard elements (rocks and concrete) are necessary to keep the island in place within the environment of the North Sea. The outer ring of hard elements is filled with sand to create the island surface. The side where the waves come in, with a strong dynamic environment, is expected to be less beneficial for ecological development. This side of the island will be constructed of hard elements. On the lee side of an island, the circumstances are calmer, and a sandy solution could be possible with less steeper slopes. Or the use of special and extra hard substrate will have a positive effect on biomass. Slopes will give species (flora and fauna) the chance to settle and develop. Depending on the steepness of the slope a beneficial environment can be created for various species, see Figure 43. The slope needs to be rough, with spaces where species can settle, so no flat surface. Different gradients of the slopes, i.e. an underwater berm, will provide hard substrate that will be beneficial for various underwater species of fish and benthos. In accordance this will lead to more food for fish, sea mammals and birds.

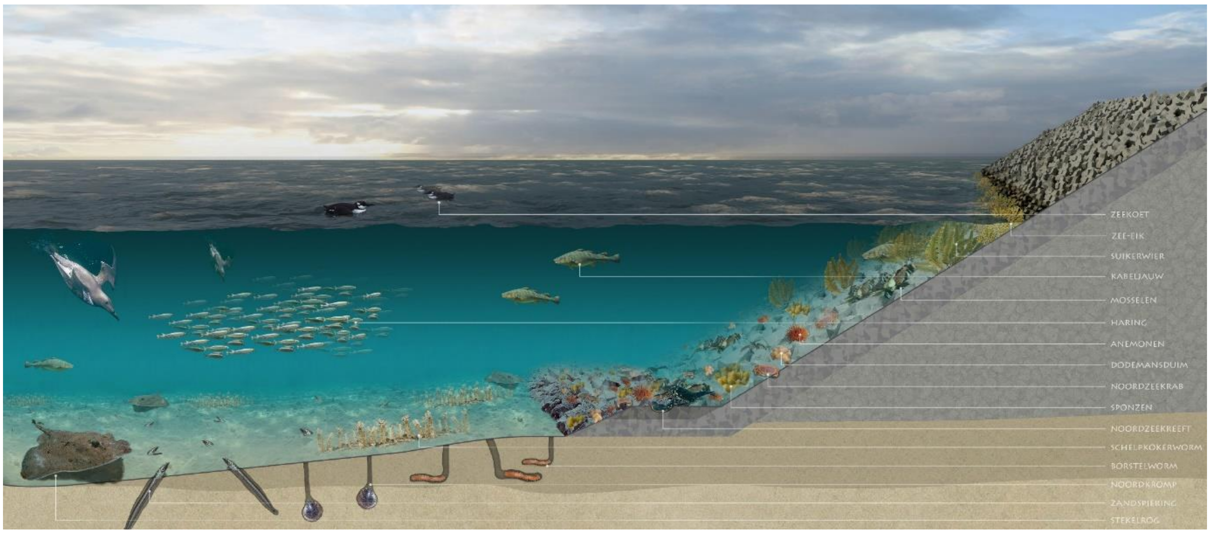

Figure 38 - Potential for ecological enhancement below the surface (source: Royal HaskoningDHV)

For a nearby island (< 30km from the coast) it could be beneficial to create an environment on top of the island which could contribute to the coastal ecological environment. The formation of dunes could be beneficial for vegetation (depending on the available space), birds (with low collision risk with wind turbines, such as gulls and auks) and seals (RHDHV, 2016). A mixture of (dry) sand and a wet dune valley, is a perfect place for a diversity of flora and development of vegetation, a resting and breeding place for birds. Besides, the sandy parts of the island are attractive for seals to rest.

The focus for the ecological benefits of a faraway island should be on the marine underwater environment only, in order to avoid the creation of a coastal ecological environment and the introduction of species which are currently not present in this type of environment (open sea).

Concluding remarks – how can we make an energy islands with ecological benefits reality?

The construction and operation of an island in the North Sea is expected to have negative environmental impacts. This QuickScan provides a first general overview of possible impacts. However, the extent of the impacts is highly location specific especially for the impacts on ecology above and below the sea level. The environmental impacts of such an energy island should be assessed in detail in a (strategic) environmental impact assessment as part of a permit application process. It should be noted that there are also a number of critical knowledge gaps (RHDHV, 2017b)[xxxii]:

- What is the cumulative impact with other activities?
- What is the impact of a dredging plume on the primary production during construction?
- What is the impact of light on birds: how much light will there be on the island, what is the impact on birds and how will migration routes be affected?
- What is the role of an island as hub for invasive species: what species will colonise the island and will they be invasive?
- How can an island play a role as breeding and resting area for birds: what bird species will be attracted by the island and what will be the side effect?

At the same time, an island on the North Sea could have benefits. Ecological values could benefit, when the island is designed well. The most likely way of construction is a combination of hard and soft elements. Hard elements (rocks and concrete) are necessary to keep the island in place within the environment of the North Sea. The side where the waves come in, with a strong dynamic environment, is expected to be less beneficial for ecological development. This side of the island will be constructed of hard elements. On the lee side of an island, the circumstances are calmer, and a sandy solution could be possible with less steeper slopes. Or the use of special and extra hard substrate could have a positive effect on biomass. Slopes will give species (flora and fauna) the chance to settle and develop. In accordance this will lead to more food for fish, sea mammals and birds.

During the preparation of this QuickScan, two points of attention were encountered, which are valuable for follow-up research:

- An integral design process
- Valorise the ecological benefits

Integral design process
In order to increase the support among stakeholders for the development of energy islands it should be beneficial to start the design process from the perspective of the best ecological option, instead of thinking from a technical perspective and adding ecological aspects for compensation. Following this line of thought one could also think of including both technical and ecological aspects in the design processes from the very beginning. Not two separate tracks, but an integrated design process with iterations combining a technical and ecological perspective, a real nature-inclusive design.

Valorise ecological benefits
In general, not only in the development of energy islands, it is very difficult to quantify ecological benefits and include these in a project’s business case. As it is difficult to quantify the contribution of ecological benefits, ecological measures are likely to be left out of the business case as they only cost money and do not yield a monetary value. Costs are mostly quite comprehensible/ easy to determine, but how to assess the value of the benefits? A next step in a follow-up study could focus on this question. Not only for the development of energy islands, but for other infrastructural developments as well.

TenneT and its consortium partners in the North Sea Wind Power Hub have presented in June 2019 their vision on the offshore wind development on the North Sea including the building of a series of islands up to 2050. It is therefore good to start experimenting with a pilot island in the short term, operational by 2030. One of the objectives of such a pilot island could also be research into the development of the best island solution for the marine ecology.

Appendix I Electric transport cost function description (confidential)

Appendix J NSE 3 Report Bilfinger Tebodin – H2 production on North Sea Islands (confidential)

Appendix K Full report Legal Assessment of the development of a sand-based offshore energy island

This appendix contains the full report of the Rijksuniversiteit Groningen on the legal assessment of the development of a sand-based energy island. This report is available as a separate document.

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