

Reliability assessment for an offshore green hydrogen production platform

Lukas Sepulveda Clasen^{ID*}, Arto Niemi^{ID}, Frank Sill Torres^{ID}

DLR Institute for the Protection of Maritime Infrastructures, Fischkai 1, Bremerhaven, 27572, Germany

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ABSTRACT

For the decarbonization of the current energy supply offshore renewable energy sources are gaining increasing significance. One of the challenges is to transport the produced energy onshore. Because of the increasing capacities of offshore wind farms and their distance to the shore, the losses arising from transporting electricity also increase. Offshore hydrogen production addresses this issue and can serve as a technology to overcome this challenge. Producing hydrogen offshore requires a production platform. Such a hydrogen production platform requires large investments to be built and entails considerable risk. Therefore, it is necessary to investigate and assess the operations and availability of it. This work proposes a simulation model of an offshore hydrogen production platform using discrete event simulation. The model incorporates different components from the presented system layout and includes dependencies between the components, as well as corrective maintenance. The results show that the overall availability of PEM electrolyzers stays above 94%. Our conclusion is that the failure rates have less impact on the overall availability than logistical changes like increasing the wave height threshold for human transfer onto the offshore platform. The results demonstrate that the proposed model can be used to simulate offshore platform operations under various system parameters and scenarios. These can be used to evaluate the performance and availability of individual components, as well as the platform as a whole.

1. Introduction

Transitioning from our fossil fuel dependent global industry to a sustainable one requires use of renewable energy carriers. For some industries and applications, electrification is not a viable option and a renewable fuel is necessary. Green hydrogen is a promising alternative to substitute fossil fuels [1]. It is produced by using electricity from a renewable source to power electrolysis. One growing renewable energy source is the offshore wind industry. In 2023, the installed offshore wind capacity in the European Union (EU) reached 19.38 GW. The EU plans to have at least 60 GW of offshore wind and additionally 1 GW of ocean energy by 2030 [2]. By 2050, the offshore wind capacity and ocean energy should reach 300 GW and 40 GW respectively, demonstrating the growing power capacity.

Transporting the electricity produced by offshore wind farms to the shore is becoming increasingly expensive. The growth in power capacity of the offshore wind turbines lead to more expensive underwater transmission lines, which becomes a limiting factor for the offshore electricity production. Producing hydrogen on an offshore production platform could address this problem since the hydrogen can be transported via pipelines. Hydrogen pipelines are generally considered more cost-efficient than High voltage DC lines for large-scale, long-distance green energy transmission [3].

Offshore platforms are already used in the offshore wind industry and are used as converter or transformer stations to transmit the electricity from the offshore wind farm to shore. The usage of offshore platforms for hydrogen production is subject of research and small scale, prototype-level offshore hydrogen production platforms have been built [4,5].

Most studies on hydrogen platforms are focused on technical implementation [6], economical feasibility [7,8], or safety [9–11]. Our study addresses the maintenance and reliability aspect by proposing a model to assess the production platform reliability. Rodenburg et al. [9] perform a safety assessment, and Zhao et al. [12] address failure finding. Based on our review only Lochhead et al. [13] have modelled the reliability of an offshore hydrogen platform. Compared to this work, our model of a hydrogen platform is more detailed and the platform has a higher installed capacity. We propose a concept that is similar to an approach to assess reliability of oil and gas production plants [14] and our previous paper on offshore wind farm maintenance [15].

A challenge for our study is that large offshore hydrogen platforms do not exist yet. Therefore, Section 2.2 describes relevant literature that led us consider that an offshore hydrogen production platform utilizing PEM electrolysis is a credible option in Germany. Section 2.3 describes background on infrastructure reliability modelling and reasoning for an

* Corresponding author.

E-mail address: lukas.clasen@dlr.de (L. Sepulveda Clasen).

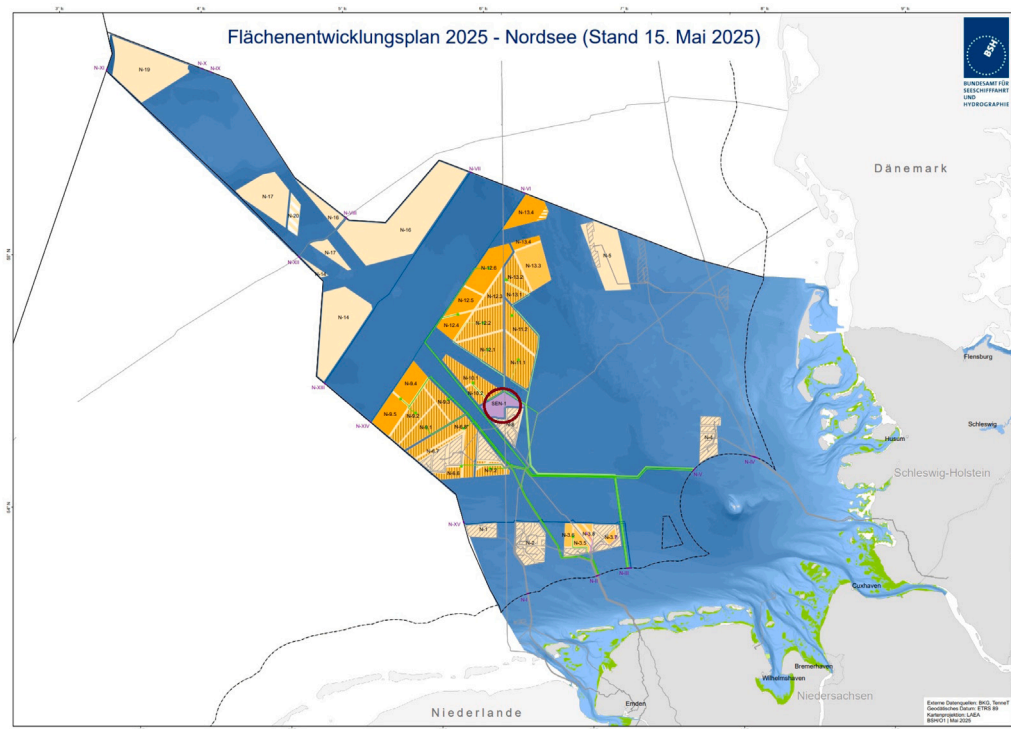


Fig. 1. Location of SEN-1 in the North Sea [21].

approach that resembles works [14,15]. The model itself is presented in Section 3. The challenge that offshore hydrogen production platform do not exist yet also creates a question what data one should use for model inputs. This question is addressed in Section 3.4 on calculation assumptions, which gives sources and justification for our input data. The results of the calculation are presented and discussed in Section 4.

2. Background

2.1. German plans on offshore renewable energy production

The EU's climate targets mandate that the EU cuts its greenhouse gas emissions by at least 55% by 2030, 90% by 2040 and reaching climate-neutral by 2050 [16]. In Germany, the WindSeeG stipulates that by 2030 Germany should have an installed offshore wind power capacity of at least 30 GW [17]. It further specifies that by 2035 the installed capacity should reach at least 40 GW and by 2040 it should reach 70 GW. Currently, Germany's accumulated offshore wind capacity reaches 9.7 GW [18].

Additionally to the planned increase in offshore wind capacity, Germany plans to produce 10 GW of hydrogen by 2030 [19]. Out of the 10 GW it is planned to install 1 GW of the hydrogen production capacity offshore. The installation of 1 GW is planned as part of the SEN-1 pioneering project, which is itself part of a larger project AquaVentus [20]. The objective of the SEN-1 pioneering project is the construction of an offshore hydrogen production platform in the SEN-1 area of the North Sea (Fig. 1).

2.2. Offshore platforms for hydrogen production

In previous works, we studied different options for offshore green hydrogen production in Germany [22]. This initial review found that an offshore platform utilizing PEM electrolysis is a credible approach for large scale hydrogen production. The study considered the concept of operations and utilized technology. In the following Sections 2.2.1 and 2.2.2, we present the considered alternatives and aspects that led us to this conclusion.

2.2.1. Concept of operations

We considered following four alternatives on how hydrogen could be produced utilizing the electricity from offshore wind farms.

1. Onshore electrolysis;
2. Individual electrolyzers for each wind turbine;
3. Offshore platform for electrolyzers; and
4. Energy island

This assessment was mainly informed by two review papers on this topic, i.e. by Calado and Castro [23] and Singlitico et al. [24].

However, several other works have been published on this topic. These include a comprehensive review paper on different technology options [25]; study on optimizing the size and cost of electrolyzers coupled with offshore wind farms located in Ireland [8]; and a case study considering South Wales [7]. The case studies from the British Isles are interesting because the region experiences similar weather as the north of Germany.

Onshore electrolysis. refers to a concept where the electricity produced by an offshore wind farm is transmitted to shore via cable to an onshore electrolyzer. Two options exist on how the electricity is transferred to the shore. As described in [23], the wind farm can be connected through a High Voltage Alternating Current (HVAC) transmission system or a High Voltage Direct Current (HVDC) transmission system. The advantage of HVAC are lower investment costs, as a HVDC requires an offshore converter. However, HVDC has lower losses. So, it is a more economical option when wind farms are located far from shore and/or have high nominal powers.

Electrolysis in each wind turbine. In an option where the hydrogen is produced in individual turbines, the electrolyzer can be located in a turbine nacelle [26] or within the platform [27]. The produced hydrogen is transported to the Hub via small pipelines. There the hydrogen is collected, compressed, and transported to shore via a large pipeline. The economics of scale are not favourable for this solution. Singlitico et al. [24] concludes that while electrolyzers are modular, the required small scales of electrolyzers and the large number of small pipelines drive the cost up.

Offshore platform. is a dedicated offshore platform to house electrolyzers. Dinh et al. [8] considered a connection through HVDC in their study. That found offshore electrolysis more economical than offshore platform considering an Irish use case. The main reason was that the total losses in the HVDC system being higher compared to losses in transferring hydrogen via a pipeline. Also, the initial investment cost of a HVDC was assumed to be higher than that of pipelines. Due to these lower losses, the offshore electrolysis concept is less affected by distance than Onshore electrolysis. Dinh et al. [8] further found that the optimal ratios of electrolyzer to OWF capacity were 91.41 % for offshore electrolysis and 94.54 % for onshore electrolysis. They considered a 600 MW OWF resulting a platform with 540 MW capacity. Several conceptual design studies have been published for offshore hydrogen platforms with different capacities, e.g. by Zhang et al. [6] and project OffSH2ore [28]. First technical demonstration of such platforms have further been carried out by PosHYdon project [5] and by Lhyfe [4].

Energy island. typically considers building an artificial island to house electrolyzers. An artificial island is a more cost effective option to house large amount of electrolyzers compared to an offshore platform. The idea is to build offshore wind farms and hydrogen production capacity to take an advantage of more consistent wind conditions in offshore region, while being free from limitations caused by offshore platform. Singlitico et al. [24] studied this option in a North Sea use case and found it to be more economical than onshore electrolysis, or electrolysis in individual turbines. It is notable that the case study considered a large hub with 3 GW capacity located in the middle of the North Sea. However, the study tested different capacities, between 0.5 to 12 GW, and distances to the shore, from 100 to 370 km. Such an island would be a significant investment. Furthermore, there are legal and regulatory concerns. Nieuwenhout and Andreasson state that the construction and operation of energy islands is currently subject to a number of laws and regulations that remain ill-suited to the novel aspects of artificial energy islands [29]. An alternative option is to build an energy hub in an existing island.

2.2.2. Electrolysis technology

This review of different technology options is based on our earlier review [22], a review by Carmo et al. [30] and a recent review by Nnabuife et al. [31]. All these reviews cover Proton Exchange Membrane (PEM), alkaline and Solid Oxide Electrolysis (SOE) technologies.

PEM electrolysis. was realized by General Electric, in the 1960s [30]. The company developed the first water electrolyzer based on a solid polymer electrolyte concept. The concept was idealized by Grubb, where a solid sulfonated polystyrene membrane was used as an electrolyte [32,33].

PEM electrolysis has an acidic environment and high voltages. The most advanced electrocatalysts for PEM electrolysis are highly active noble metals, like Iridium (IV) oxide (IrO_2) or Ruthenium (IV) oxide (RuO_2), which are used in the O_2 evolution reaction at the anode and the Pt/Pd hydrogen evolution reaction at the cathode [31]. Consequently, the use of noble metals renders PEM electrolysis a bit more costly than alkaline water electrolysis.

One of the primary benefits of PEM electrolysis technologies is the ability to generate high-purity, high-pressure hydrogen. PEM electrolysis technology exhibits a quick start-up, allowing it to operate in all of the nominal working ranges (0%–100%). This capability makes it suited for coupling with renewable energy sources with fluctuating production rate.

Alkaline electrolysis. (AE) is the most mature solution for hydrogen production up to the megawatt range, and also the most used electrolytic technology at a commercial level worldwide [30]. AE are easy to manufacture and have relatively low cost components. Nnabuife et al. state that the main benefits of this technology over competing ones include its maturity, accessibility, and affordability [31].

However, two drawbacks limit AE's suitability for renewable energy applications. Their power range is limited to 20%–100% and variable charges have a negative impact on AE. Operating below the nominal current may cause a buildup of flammable gases. Dynamic charges and turning the electrolyzers on and off reduces their lifespan and lowers the purity of the produced gas. Therefore, Nnabuife et al. conclude that the greater working range and quick response time of PEM electrolysis gives them a substantial benefit over AE [31].

Solid oxide electrolysis. is a promising way to produce green hydrogen via high temperature electrolysis [34]. It uses a solid oxide as the electrolyte material and has a high operational temperature of 650 to 850 °C. As stated by Nnabuife et al. [31], the technology is still in the early stages of development. The advantages of SOE relate to the high operating temperature. However, it also causes disadvantages. The temperature necessitates the use of expensive components and more intricate manufacturing processes. Additionally, cold starts are lengthy, which raises a concern on coupling this technology with renewable energy sources. Therefore, we do not consider this technology as a viable near-future option for offshore electrolysis.

2.3. Reliability modelling

Reliability modelling is a systematic approach that is employed in a number of engineering fields. Its purpose is to predict, analyse and optimize a systems operation and performance under defined operating conditions. There exist several different approaches which can be classified in qualitative and quantitative approaches. The former is a structural, and logic-based discipline and used to understand the structure and logic of a system. The latter is a data-driven and probabilistic discipline and used to make numerical predictions.

One useful indicator that links the system reliability to operational affairs the availability A [35]. Availability describes the likelihood that, a system or piece of equipment is in a predetermined operable state and can be calculated using Equation

$$A = \frac{t_{Uptime}}{t_{Uptime} + t_{Downtime}}, \quad (1)$$

where t is used to denote a time interval, whilst the indices $Uptime$ and $Downtime$ are utilized to identify the time intervals during which a system or component is operating as intended or unavailable, respectively.

A variety of modelling approaches have been undertaken in order to evaluate the reliability of maritime infrastructure and hydrogen equipment. These approaches are outlined in the following paragraphs.

Zio et al. [14] presents a Monte Carlo approach to assess the availability of an offshore installation. In the work of Macedo et al. [36], an assessment of the reliability and availability of four subsea production system was carried out, using Event Sequence Diagrams and Fault Tree Analysis. Shittu et al. [37] conducted a reliability assessment of the structural integrity of offshore wind turbine support structures. Shittu et al. developed a probabilistic model using Finite Element analysis, an artificial neural network, and the first order reliability method to assess the reliability.

Rosca et al. proposed a model to assess the influence of equipment reliability over the activity inside maritime container terminals [38]. The proposed model uses discrete event simulation to simulate disruptions during the operation of the terminal. The terminals operation are described in a flowchart which divides it into different processes. Rosca et al. identified the quay cranes as a key equipment for the terminal's operation. The quay cranes disrupt the terminals operation through random failure events during the simulation. The consequences of that disruption to the port logistics were then analysed.

Whiteley et al. developed a Petri-Net model to analyse the reliability and the degradation of PEM fuel cells [39]. The model incorporates failure modes, which were obtained using a Failure Mode and Effect Analysis and a Fault Tree Analysis. The simulation model was compared

to experimental work analysing a polarization curve drop due to startup and shutdown cycling and showed a good replication.

In the work by Urgan et al. a different simulation approach was chosen to conduct a reliability analysis for hydrogen-integrated composite renewable power systems [40]. Their model utilizes a sequential Monte Carlo simulation framework to assess the reliability and a Convolutional Neural Network to reduce the computational load.

In conclusion, several different modelling approaches have been developed to assess the reliability of a system. The current approach for modelling availability and operations for complex systems, strongly favours discrete event simulation [41–43]. Based on these findings and due to the fact that an offshore hydrogen production platform with a high capacity does not exist, a discrete event simulation approach appears to be the most appropriate to simulate its operations. The modelling of operational dynamics is enhanced by incorporating dependencies among components, thereby improving the representation of system response and recovery behaviour.

We further want to extend the work by Lochhead et al. [13] by considering a large offshore platform. Lochhead et al. studied an approach where the electrolysis takes place in individual turbines (a coupled wind-hydrogen system). When an offshore platform is concerned, the opportunities to design redundancies increases. We further see a higher demand to make a system redundant due to higher cost of unavailability. Lastly, the considered maintenance approach is different. Lochhead et al. utilizes a collection of shore-based vessels. As will be described in Section 3.2, we instead have a service operation vessel (SOV) stationed next to the offshore platform.

3. Methodology

To investigate the reliability and maintenance of the hydrogen production platform, a discrete event simulation model is proposed. The hydrogen production platform is simulated by capturing the state of each individual component on the platform. Additionally, the developed simulation model incorporates the component dependencies and redundancies within the system layout.

3.1. System description

The offshore production platform is assumed to be located in the North Sea at the alternative energy production area (SEN-1), which is approximately 200 km away from mainland. Since a high power capacity offshore hydrogen production platform does not exist, the system layout for the simulation model is based on existing publications, in particular the project OffSH2ore [28]. The layout out of the offshore platform consists of six levels. The hydrogen platform layout and the mass flow is shown in Fig. 2. The first level is the cable deck, where the cables from the offshore wind turbines are connected to the platform. The rest are for hydrogen production. These levels are identical and designed to work independently from one another.

The cable deck consists of six different component types. The cables from the wind turbine are connected to the platform via a switch gear, which distributes the power to the other components and hydrogen production levels. The switch gear is connected with a cooling circuit, consisting of a cooling pump and two redundant heat exchangers. The cooling pump is connected to a seawater distribution line, which is supplied by five seawater lift pumps, which are located beneath the water surface. Six booster pumps are additionally located on the cable deck, which are used to pump the seawater from the distribution line to the hydrogen production levels. The five seawater lift pumps and the six booster pumps are designed to be redundant to ensure operation even if one of the pumps fail.

A hydrogen production level incorporates ten PEM electrolyzer units with a combined power capacity of 100 MW per level and an efficiency of 75 % [44]. Each PEM electrolyzer unit is connected to a Transformer and Rectifier, which provide the necessary electricity to

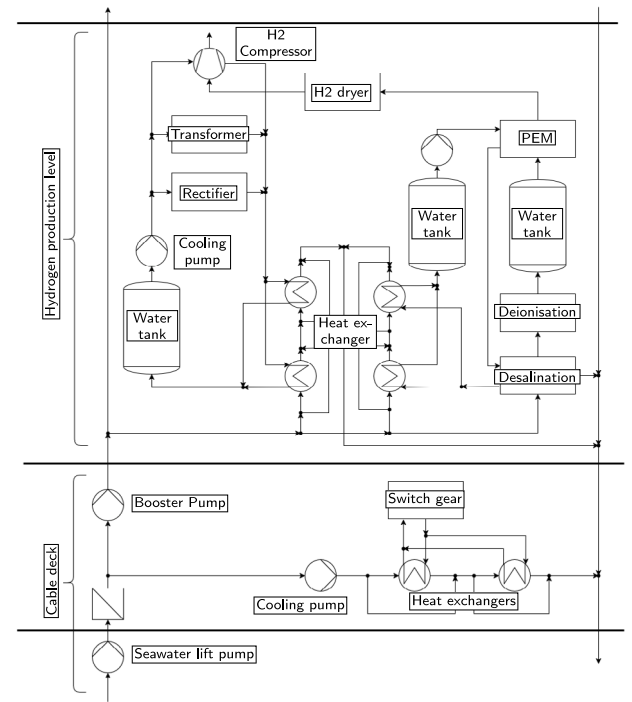


Fig. 2. H2 production platform layout and mass flow, based on [28].

produce hydrogen. On each hydrogen level, there are two independent cooling circuits.

Each cooling circuit contains a cooling water storage tank, a cooling pump and two redundant heat exchangers. The cooling circuits use purified water as a cooling liquid and seawater as a heat sink. The cooling water storage tank has sufficient cooling water to safely cool all connected components until they are shut down in case that both heat exchangers fail. One cooling circuit is connected to the Transformer, Rectifier and Hydrogen compressor, while the other cooling circuit is connected to the PEM electrolyzers and the desalination unit.

To produce hydrogen the seawater is treated in two steps. First the seawater is processed by the desalination unit, which uses the produced heat from the PEM electrolyzers in its process. After that, the water flows through an electro-deionization unit to further purify the water. After purification, the water is stored in a storage water tank. It holds enough purified water for the PEM electrolyzers to safely shut down, in case the desalination unit fails.

The produced hydrogen is further processed in a hydrogen purification unit, where remaining oxygen and moisture are removed. Hydrogen is compressed using two compressors on each hydrogen level before transporting it. The system has extra capacity to compensate for a single compressor failure by redirecting the uncompressed hydrogen to other levels. Each level has 5 % of additional compression capacity for this purpose.

The energy input for the hydrogen platform is assumed to come from an offshore wind farm consisting of 65 wind turbines from the type Vestas V164/9500, which has a capacity of 9.5 MW. This accounts to a total capacity of 617.5 MW for the offshore wind farm and ensures that the capacity of the offshore hydrogen platform can be utilized. The wake effect for the wind farm is assumed to be 15 % [45]. The input power P_{in} for the offshore platform is calculated using

$$P_{in} = \min \{ P_{max}, P_{WF,out} \}. \quad (2)$$

P_{max} stands for the maximum capacity of the PEM electrolyzers which is 500 MW. $P_{WF,out}$ is the output power of the wind farm and is calculated using Equation

$$P_{WF,out} = \omega_{WT} P(v)_{WT}, \quad (3)$$

where ω represents the wake effect of the offshore wind farm, n_{WT} stands for the number of wind turbines and $P(v)_{WT}$ represents the power output of a single wind turbine. $P(v)_{WT}$ is calculated using the power curve of the Vestas V164/9500 [46] and wind data obtained by ERA5 [47]. The resulting power is then used to calculate the amount of hydrogen which is produced m_{H_2} with Equation

$$m_{H_2} = \frac{\eta_{PEM} P_{in}}{e_{H_2}}, \quad (4)$$

where η_{PEM} stands for the efficiency of the PEM electrolyzers and e_{H_2} is the energy density of hydrogen at 20 °C, which is 142 MJ kg⁻¹ [48].

3.2. Platform maintenance

The maintenance of offshore infrastructure is a highly complex process, which is influenced by a number of different factors, including but not limited to weather conditions, location of the offshore infrastructure, equipment availability and human resources.

In practise, there are a number of methods by which a repair crew can be deployed to an offshore platform. Depending on the location of the offshore platform, the type of failure event and available equipment a repair crew is commonly transported to the offshore platform via a Crew Transfer Vessel (CTV), Fast Supply Vessel (FSV), SOV or helicopter. Compared to oil-rigs where the operational crew stays onboard, we consider that this is not necessary for hydrogen production platform. Because, in an oil-rig the crew is required for the drilling operations.

As stated in the guide for the UK offshore wind operations and maintenance by Phillips et al. [49] the most cost effective method to transporting personnel is dependent on the distance to the destination. For distances lower than 12NM a workboat like a CTV or FSV is the optimal choice. For distances between 12 and 40NM combining a workboat with support from helicopters offers the most cost effective solution. If the distances become larger than 40NM, an offshore based approach is the most practical and cost effective choice. Since the location of the modelled offshore platform is approximately 200km away from the mainland, a SOV is used for maintenance and as housing for the crew.

To ensure the reliable operation of offshore platforms and equipment, operators adopt several maintenance approaches. Predictive maintenance, which relies on condition-monitoring data to anticipate failures, scheduled maintenance, which follows a predetermined timetable, and corrective maintenance, which is performed after a fault has occurred.

Our simulation now considers only corrective maintenance. Modelling predictive maintenance would require an assumption on how well condition monitoring approach can detect failure events in advance, allowing to schedule an early intervention. Similarly, a scheduled maintenance approach would require an assumption on how time or utilization affects the item's reliability, to see the effects of scheduled maintenance. Incorporating these approaches would then require a lot more assumptions to be done properly [50]. The likely result would be a small increase of the availability due to avoided failures. Yet, there will be also a loss of availability due to scheduled maintenance.

After a failure event has occurred, the model simulates the procedure of a repair process. The repair process includes the crew transfer from the SOV onto the offshore platform and the duration of the repair on site. Once the on-site repair duration has elapsed, a repair event is triggered which concludes the repair procedure.

3.3. Simulation logic

To simulate the operation of the hydrogen production platform, the state of all individual components is modelled. During the simulation, a component can switch its state depending on the occurring failure or repair event and state of depending components.

Some critical systems on the hydrogen production platform are designed to be redundant. In those cases, a component is dependent on

Table 1

Different states of components and groups.

State	Operational	Failure
Up State	1	0
Down State	0	1
Standby State	0	0

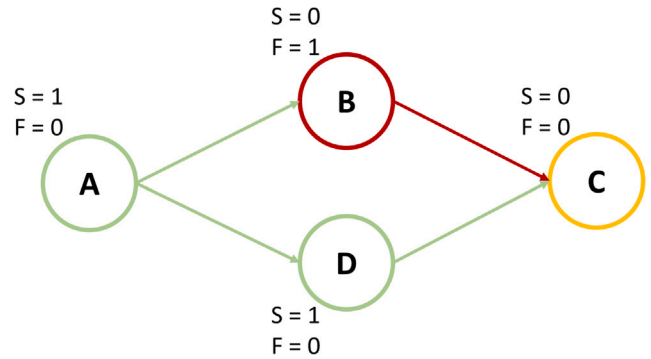


Fig. 3. Simulation logic between component A, B, C and D.

the output of a group of components. This group of components form an entity, which has its own parameter to specify the level of redundancy.

Each installed component or entity can have three different states. These states are represented by two Boolean variables *Operational* and *Failure*. All three states are listed in Table 1.

Up State indicates that the component or entity is working as intended, while *Down State* represents that a failure event has occurred. A component has reached *Standby State* when it can work as intended, but a depending upstream component has failed.

The simulated components have dependencies between other components or entities, which can cause cascading effects when a component fails. These dependencies are modelled using a dependency structure matrix, which is created during initialization of the simulation model. When a failure or repair event occurs, the dependency structure matrix checks, if there are dependencies to other components or entities. Furthermore, the model verifies whether the failed or repaired component is part of an entity and if the redundancy level of that entity has been reached. Fig. 3 illustrates the simulation logic using component A, B, C and D. Component C is dependent on B and D. Therefore, if component B fails component C switches into *Standby State*, which shows the failure propagation. The colours in the figure represent the different states of the components. Green, red and yellow correspond to *Up State*, *Down State* and *Standby State* respectively.

Failure event. The failure events, which occur during the simulation, are randomly generated. During the initialization of a component, a random time step is calculated. When the simulation reaches that specific time step the failure event for that component triggers. The random time step is calculated using an exponential distribution

$$R(t) = e^{-\lambda t}, \quad (5)$$

with λ representing the failure rate and t the time. The assumptions for the failure rates are further discussed in Section 3.4.

Repair event. After a component has failed, the repair process is initiated. This includes the repair-crew transfer from the SOV onto the offshore platform and the repair of the failed component. In order for the crew to safely transfer onto the offshore platform three environmental conditions must be fulfilled, which are shown in Table 2. We formulated the thresholds based on [51,52]. There are no exact standards in the offshore industry for the crew transfer onto a offshore platform. The environmental requirements vary between different offshore maintenance provider [51,52]. In the simulation model, these

Table 2

Parameters and threshold value for human transfer to offshore platform based on [51,52].

Parameters	Threshold
Wave height	2.5 m
Wind speed	10.3 m s ⁻¹
Ambient temperature	0 °C

environmental requirements are compared to weather data obtained from ERA5 [47]. Another requirement for the crew transfer is the availability of the SOV. For this simulation we assumed that the SOV stays offshore for 14 days before returning to shore to exchange crew and supplies [53]. In the simulation the resupply of the SOV takes two days.

After the transfer, a specified amount of time needs to pass in order for the component to change its state. After the crew transfer is completed and the time for the necessary repair has passed, the failed component changes its state. The repaired component switches into the *Up State* if all dependent components upstream are in their *Up State*. If one or more of the dependent components upstream have failed during the repair process, the component goes into its *Standby State*. Similarly to the failure event, the state of the depending components downstream of the repaired component change their state back to *Up State*. The time for the repair for the individual components are further discussed in Section 3.4 and shown in Table 3.

If a failure event occurs while the repair crew is already waiting to transfer to the platform, the simulation assumes that additional crew is available. Thus, the failures will be repaired simultaneously, once the crew could transfer to the offshore platform. This assumption is supported by the low likelihood of 0.25 % that more than three simultaneous failures occur, indicating that such events are statistically rare. Though, this assumption is not valid if (i) failure rates are extremely high, (ii) repair times are extremely long, or (iii) thresholds for personnel transfer to the platform are highly restrictive. Taking into account cumulating tasks would require modelling the availability of personnel resources [54], and a scheme to prioritize between maintenance tasks [55].

3.4. Simulation assumptions

To model the operation of the hydrogen platform the individual components and their operational state were simulated. As mentioned in Section 3, a component can fail and be turned off due to a failure event. These failure events are randomly generated using an exponential distribution with lambda being the failure rate (Eq. (5)). Because of the scarce data availability we assumed a constant failure rate for all components during the simulation.

All types of components and their failure rates are listed in Table 3. A specific challenge of this assessment is the scarcity of failure data from hydrogen equipment. In case of a new system, an analogy-based approach is the preferred option, in which data from similar earlier products are used to estimate model parameters [56]. In our case, we used data from The Offshore and Onshore Reliability Data (OREDA) [57] database. It is a collection of reliability data from the oil and gas industry that have been operational for 35 years. OREDA's primary objective is to establish a comprehensive database of reliability data concerning equipment utilized in offshore operations. This database is an immensely valuable asset for quantitative risk analysis and was utilized for common offshore components. Similar to our work, study by Lochhead et al. [13] also used OREDA data and other sources compensate for lack of specific data from hydrogen equipment. Of course, this practise is not optimal. Therefore, it is being discussed if an OREDA-style reliability data collection approach would be feasible for hydrogen equipment [58].

Table 3

Components with corresponding failure rate and repair time.

Type of components	Failure rate	Repair time	Source
Desalination unit	1.525 f yr ⁻¹	0.943 h	[13]
	0.080 f yr ⁻¹	3.5 h	
	0.114 f yr ⁻¹	11.670 h	
Heat exchanger	0.044 f yr ⁻¹	2 h	[57]
	0.314 f yr ⁻¹	3.6 h	
	0.530 f yr ⁻¹	92 h	
Hydrogen compressor	1.241 f yr ⁻¹	8.8 h	Gas compressor [57]
	0.768 f yr ⁻¹	31 h	
	0.712 f yr ⁻¹	17 h	
Hydrogen purification	0.263 f yr ⁻¹	8 h	Air dryer failure rate [59] and steam turbine cooling unit repair time [57]
PEM electrolyzer	0.558 f yr ⁻¹	1.347 h	[13]
	0.294 f yr ⁻¹	5 h	
	0.103 f yr ⁻¹	16.671 h	
Rectifier	0.038 f yr ⁻¹	3.41 h	Failure rate [60] and Transformer for repair time [61]
Seawater lift pump	0.099 f yr ⁻¹	8 h	[57]
Switch gear	0.019 f yr ⁻¹	240 h	[61]
Transformer	0.005 f yr ⁻¹	3.41 h	[61]
Water pump	0.215 f yr ⁻¹	6.2 h	[57]
	0.121 f yr ⁻¹	32 h	
	0.054 f yr ⁻¹	47 h	

In the proposed hydrogen production level layout, the purification unit uses a refrigerated condenser to separate the remaining moisture from the hydrogen. Owing to limited data available for hydrogen purification units, failure rate data from a refrigerated air dryer [59] was used instead. Similarly, to the availability of failure rate data, repair time data for hydrogen purification unit is scarce. Therefore, repair data from the OREDA database was used for the cooling unit of a single stage steam turbine, which also utilizes a condenser. Attributed to the lack of reliability data for specifically hydrogen compressors, data for gas compressors from the OREDA database were used, due to their analogous operational characteristics and comparable structure.

The failure rate data for the PEM electrolyzers and the desalination units were obtained from work conducted by Lochhead et al. [13]. Their work analyses the availability as well as the operations and maintenance cost of coupled wind-hydrogen systems. In their work, the failure rates for hydrogen specific components such as PEM electrolyzers and desalination units were synthesized by modelling them as a series of components from the OREDA database.

The data set containing failure rates for the switch gear and Transformer was obtained from a study published by Energiforsk [61]. Purpose of the study was to improve reliability data for high voltage components at a component level.

The failure rate data for the rectifier was extracted from work conducted by Pablo et al. [60]. In their work a evaluation method is presented based on IEEE Standards, for different rectifier types.

The heat exchanger, water pump, desalination unit, PEM electrolyzer and hydrogen compressor have three different failure rates. These failure rates correspond to three different failure events which are categorized into minor repair, major repair and major replacement. The three different failure categories represent different severities of a failure event. According to the different failure events, there are also three corresponding repair times.

Upon simulation start-up, the constituent components are initialized. During initialization a random time step is generated for each component, which marks the failure event. After the failure event

Table 4
Simulation scenarios.

Scenario	Assumption
A	Default assumptions
B	Increased wave height threshold to 3.5 m
C	PEM failure rate is reduced by 10 %

occurred and the component has been repaired a new random time step is generated, which predetermines the next failure event for that component.

We consider three scenarios described in Table 4. The preceding assumption combine to result in scenario A. To further analyse the simulation model, a sensitivity analysis is conducted for which two more scenarios are created. In scenario B, the wave height threshold is increased from 2.5 m to 3.5 m and in scenario C, the failure rate of the PEMs is reduced by 10 %. All other parameters stay the same for all three scenarios. The wave height threshold is chosen because it can be increased by using motion compensation access systems or using different kinds of vessels, which are already in use in offshore industry. The failure rate of PEM is also of interest, since it is the actual component which produces hydrogen and the failure rate is object of uncertainty.

4. Results and discussion

In this section, the key findings of the simulation results are presented and discussed. To analyse the operation of the hydrogen platform the model was simulated for the year 2016 to 2025. For each year 100 simulations were conducted to obtaining accurate estimates, which is further discussed in Section 4.2. The results capture the state of all components for every time step and logs every failure and failure type. While the full dataset spans from 2016 to 2025, one year is used as a representative for analysis, since simulations for the different years produce comparable results. The year 2024 is selected because the results and observed trends are broadly consistent with the other datasets.

4.1. Simulation results of scenario A

On average 118.76 failure events occurred during a simulation with a maximum amount of 154 in a simulation for the year 2025 and a minimum of 82 from a simulation for the year 2021. Most failure events are caused by PEMs with an average of 40.8 % of all failures. 23.1 % of failure events where caused by the hydrogen compressors and 16 % where caused by the installed heat exchangers. The desalination unit accounted for 10.3 % of the occurred failure events. Fig. 4 shows the percentage of failure event by component types. The section *Others* includes Rectifier, Seawater Lift Pump, Transformer, and Switch Gear.

One reason for the high percentage of failure events for PEMs is the high failure rate compared to other components. PEMs have the third highest failure rate behind the desalination unit and hydrogen compressors. Another reason is that there are in total 50 PEMs installed on the offshore platform, which increases the chance for a failure event.

One notable limitation of these simulation results is that the failure rate is assumed to be constant. Therefore, possible changes in the failure rate due to degradation are not simulated. Possible degradation could have an impact on the amount and distribution of failure events, since components can be effected differently by degradation.

We consider that the likely result would be a slight decrease in platform availability over time. This outcome would be comparable to the failure characteristic depicted in NASA Reliability Centred Maintenance guide for complex system [62]. However, it is also possible that the failure probability stays relatively constant at all ages.

Although, the majority of failure events come from PEMs, the majority of overall downtime of PEMs is caused by its directly or indirectly

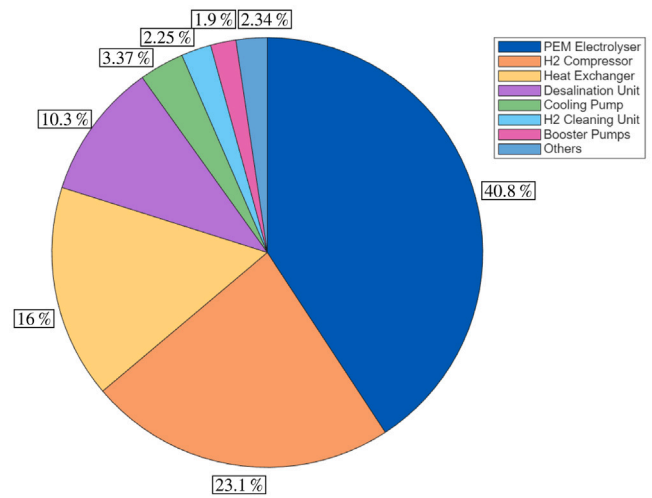


Fig. 4. Failure event by component type.

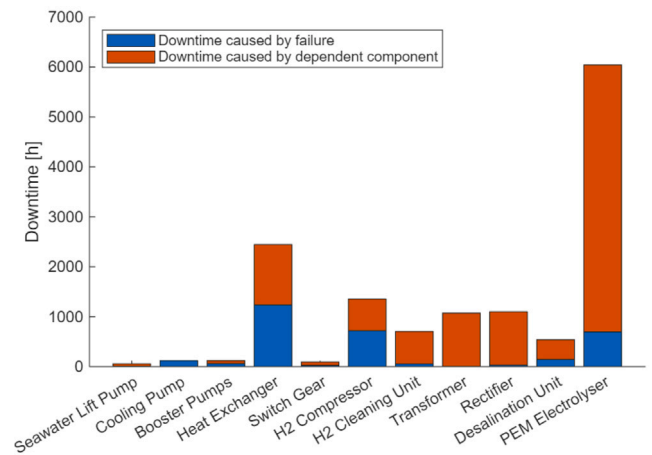


Fig. 5. Downtime of component types.

dependent components, i.e. due to “secondary failures” [35]. Fig. 5 illustrates this by showing the cumulative downtime caused by failures in blue and the overall downtime in orange. The figure consists of the averaged simulation results for the year 2024. The figure shows that 11.49 % of the overall downtime of PEMs is caused by failure events of that type. Noticeably, the downtime causes by failure for the installed heat exchanger is around 50.55 %. However, due to their redundant design, the downtime due to failure event does not get passed on, as only one heat exchanger failed.

One valuable indicator for the operation of different components is the availability. The calculation of the availability is achieved through the utilization of Eq. (1). For better comparison over the duration of the year, a moving average scheme with a fixed time interval of four weeks is used. Fig. 6 depicts the average availability for each PEM out of the conducted simulations in blue and the red line shows the average availability for all PEMs combined over the simulation time for the year 2024.

The availability for the PEMs stays above 98.5 % for more then 75 % of the year. The diagram shows a drop of the availability from 98.5 % to 96.1 % around 300 h. It is also noticeable, that the availability decreases around 7700 h from 99 % to 98 %.

These drops are explained by the weather condition, which limit the possibility for a safe transfer for the repair crew from the SOV to the offshore platform. The results show, that the availability of the

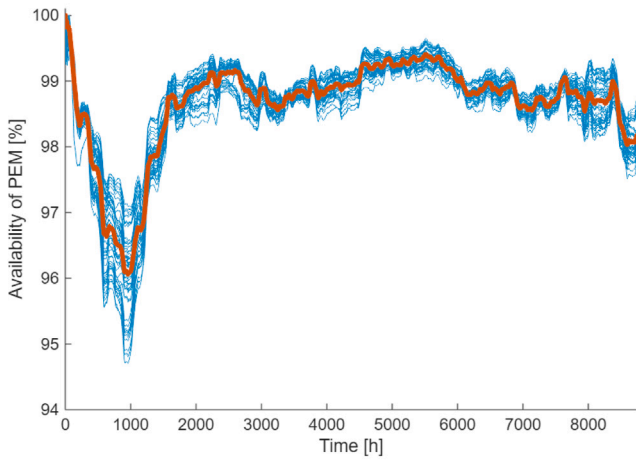


Fig. 6. Availability of PEM.

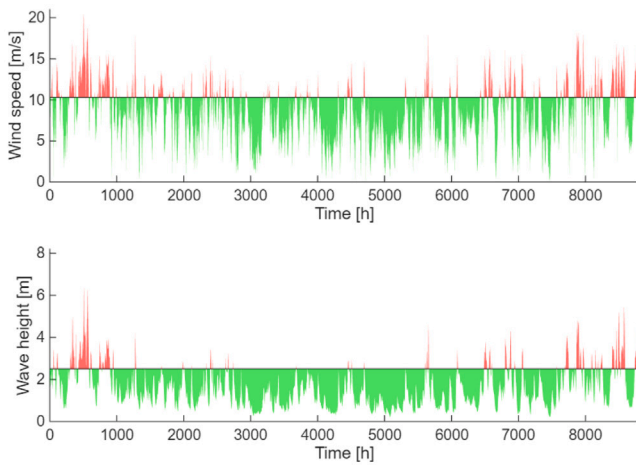


Fig. 7. Wind speed and wave height with threshold for safe transfer.

repair crew is a significant factor for the availability of the installed components.

In Fig. 7 the wind speed and wave height are plotted into a diagram, with the corresponding threshold values for a safe transfer from the SOV to the offshore platform. The green areas indicate time periods where safe transfer is possible while the red areas indicate time periods where a safe transfer is not possible.

As demonstrated in Fig. 7, the wave height and wind speed exceed their corresponding threshold values of 2.5 m and 10.3 m s^{-1} starting at around 300 h and reach the maximum value at around 500 h. Between the time period of 300 h to 1000 h the wave height and wind speed exceed the thresholds more frequently and for longer periods of time, which are the main contributing factors for the decreased availability. This is consistent with the observed drop in availability. Similarly, starting at around 7700 h the wave height and wind speed increase again and surpass their thresholds again more frequently and for longer periods of time, which also leads to a drop of availability.

A key limitation of the simulation results is, that it only includes a corrective maintenance approach. Although this approach is straightforward and involves minimal initial costs, it results in significant unplanned downtime. The expansion of offshore wind farms has rendered the corrective maintenance approach increasingly obsolete, thus giving rise to the adoption of preventive maintenance strategies as the prevailing paradigm [63]. Preventive maintenance is less disruptive for the operational availability that corrective maintenance, as it can

Table 5
Confidence intervals for PEM.

Scenario	m	s	Interval
A	98.27 %	1.62 %	[97.95 %, 98.59 %]
B	98.61 %	1.43 %	[98.33 %, 98.89 %]
C	98.45 %	1.57 %	[98.15 %, 98.76 %]

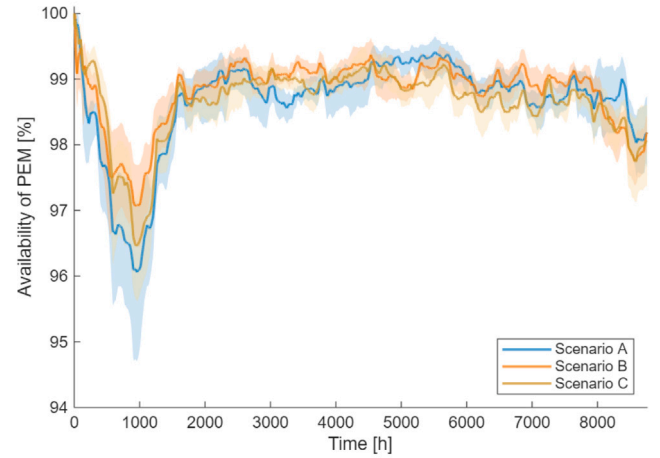


Fig. 8. Comparison of average availability for PEMs (2024).

be conducted at most opportune time. As discussed in Section 3.2, considering preventive maintenance approaches would require making more assumptions.

4.2. Sensitivity analysis

For the sensitivity analysis, the hydrogen platform model is simulated again for the year 2016 to 2025 and 100 times for each year. To assess the accuracy of the results, the mean availability m and standard deviation s is calculated for every component to estimate the actual mean μ using Equation

$$m - 1.96 \frac{s}{\sqrt{N}} < \mu < m + 1.96 \frac{s}{\sqrt{N}}, \quad (6)$$

which gives the 95 % confidence intervals for the sample size N . The confidence intervals for Scenario A, B and C for the PEMs are shown in Table 5. The narrow confidence intervals observed from the results indicate that a sample size of 100 simulations is adequate for achieving precise estimates.

In Fig. 8 the average availability of the PEMs for Scenarios A, B and C over a year is compared. The result show that the availability of the PEM for the time period between 1500 h and 8000 h for the scenario B and C are similar to the original scenario A. This indicates that the availability of PEMs during operation, where transfer from the SOV to the platform is possible, is limited by other components and therefore the system design, rather than the failure rate of the PEMs. Notably, the drop in availability at around 1000 h is not that significant in scenarios B and C. The minimum average availability increases from 96.1 % to 97.1 % in scenario B and to 96.5 % in scenario C. This shows that an increase in the wave height threshold for human transfer has more impact on the availability than decreasing the failure rate of the PEMs by 10 %.

The different amount of availability for scenario A, B and C also leads to different amounts of produced hydrogen. The total amount of hydrogen for scenario A, B and C for the year 2024 reached 34 458 t, 34 530 t and 34 464 t respectively. The result shows an increase of 72 t between scenario A and B and an increase of 6 t between scenario A and C. The production changes less than 1 % between the scenarios

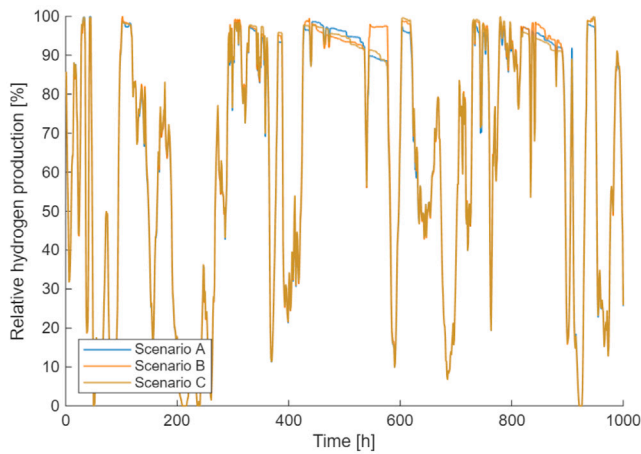


Fig. 9. Relative hydrogen production.

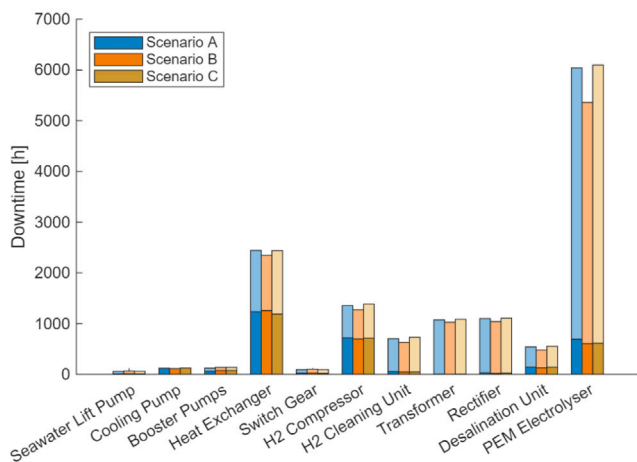


Fig. 10. Comparing downtime of component types (2024).

showing that the increased availability of the PEMs does not transfer to an equally increased hydrogen production. The underlying cause of this effect is the limitation imposed on hydrogen production by the electricity generation of the wind farm. This limitation is illustrated in Fig. 9, which shows the relative hydrogen production for Scenario A, B and C for the first 1000 h of the simulation. Noticeably, the relative hydrogen production for Scenario A, B and C are overlaying, which shows that the limitation is the electricity production from the wind farm. In contrast, between 400 h and 600 h Scenario A, B and C show distinct hydrogen productions, which indicates that the limiting factor for this time period is the availability.

Fig. 10 compares the downtime for different component types and shows the downtime caused by a depending component in light colours and the downtime caused by a failure of that component type in the more saturated colour. The change in downtime for components which have less than 200 h of downtime is negligible. For the other components the downtime in scenario B is consistently lower than in scenario A and C. Moreover, a comparison of the overall downtime between scenario A and C for the PEMs, shows a difference of less than 1 %, while the downtime caused by a failure event decreased by 11 %. This further supports that the impact from the increased wave height threshold is more significant than the a 10 % decrease of the failure rate for the PEM.

5. Conclusions

Sustainable energy transition and geopolitical risks associated with fossil-fuel dependence result in the EU planing to increase its offshore hydrogen production. This study investigated the operation of an offshore hydrogen production platform by proposing a simulation model which includes various necessary components for a functional hydrogen platform. The model used a discrete event simulation approach and integrates failure and repair events with their resulting impact on other system components. The model includes the dependencies between the installed components on the platform and incorporates redundant design elements.

Based on this work, the choice of discrete event simulation to model the platform was appropriate. Solving the model, e.g. through analytical means would be impractical. Operations of individual components are highly dependent on each other. For example, in Fig. 2 even the sea water lift pump depends on power coming from a switch gear, the switch gear depends on cooling circuits and so forth. Furthermore, these components have redundancies. The dependency on the weather further causes an additional issue, because the repair time depends on season. This is highly relevant, as Fig. 6 shows that the weather strongly affects the platform availability. Moreover, discrete-event simulation allows combining elements from different modelling formalism resulting in a high expressive power needed for accurately representing the modelled system [43].

The results of this investigation show that the proposed system layout achieves a high availability for the PEMs. Furthermore, the data demonstrates that most of the downtime for the PEMs is caused by depending components, which suggests that a limiting factor for the PEM's availability is the platform layout. Our work shows that with reasonable assumptions on system redundancies one can reach high availability. Further optimizing platforms design in terms of reliability would require an assessment on capital expenditures needed to invest system redundancies. Without considering this trade-off, an assessment would result in ways to maximize the platform availability regardless if the resulting system is financially sound. So, further assessment must consider investment costs and loss of revenue due to unavailability.

The results from the sensitivity analysis revealed that increasing the possibility for human transfer from the SOVs to the platform by increasing the wave height threshold can decrease downtime for all components and has a bigger impact than optimizing the failure rate for the PEM. The issue of accessing the platform may become more relevant in future, as it is foreseen that the wave heights in the eastern North Sea may grow due to the climate change [64]. Additionally, the sensitivity analysis also showed that an increase in availability is not equally transferred to an increase in hydrogen production, since another major limiting factor is the actual electricity generated from the offshore wind farm.

Several limitations must be acknowledged. The simulation model assumes that the failure rate for the implemented components is constant and does not include possibly changing failure rates due to degradation. The result of ageing might be an increase of the failure rate over the time. Additionally, the maintenance model was based on a corrective maintenance strategy and did not incorporate scheduled maintenance, which could increase availability. To improve these limitations, future studies can integrate scheduled maintenance methods and a degradation of components into the simulation model.

Another limitation is the scarce available reliability data for the hydrogen equipment. Due to this limitation, we conducted a sensitivity assessment on PEM failure rates. It showed that 10 % increase in failure rate would have a limited effect on the platform availability. We further opted to use OREDA data [57] from oil and gas industry and other sources to compensate the lack of data.

Yet, this shortcoming may recede in future. There are efforts to collect reliability data from hydrogen equipment [58], and conduct pilot demonstrators on offshore production of hydrogen [4,5]. Hopefully,

they will result in a situation where this data would be more readily available. With such data, the question on how high operational availability an offshore hydrogen production platform could achieve, can be answered with higher certainty. Studying reliability of these platforms is important. As, we believe that it will be a major consideration on whether offshore production of hydrogen is financially feasible.

CRediT authorship contribution statement

Lukas Sepulveda Clasen: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Arto Niemi:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization. **Frank Sill Torres:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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