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Conceptual design of an offshore hydrogen platform

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ABSTRACT

Offshore green hydrogen emerges as a guiding light in the global pursuit of environmental sustainability and net-zero objectives. The burgeoning expansion of offshore wind power faces significant challenges in grid integration. This avenue towards generating offshore green hydrogen capitalises on its ecological advantages and substantial energy potential to efficiently channel offshore wind power for onshore energy demands. However, a substantial research void exists in efficiently integrating offshore wind electricity and green hydrogen. Innovative designs of offshore hydrogen platforms present a promising solution to bridge the gap between offshore wind and hydrogen integration. Surprisingly, there is a lack of commercially established offshore platforms dedicated to the hydrogen industry. However, the wealth of knowledge from oil and gas platforms contributes valuable insights to hydrogen platform design. Diverging from the conventional decentralised hydrogen units catering to individual turbines, this study firstly introduces a pioneering centralised Offshore Green Hydrogen Platform (OGHP), which seamlessly integrates modular production, storage, and offloading modulars. The modular design of facilitates scalability as wind capacity increases. Through a detailed case study centred around a 100-Megawatt floating wind farm, the design process of offshore green hydrogen modulars and its floating sub-structure is elucidated. Stability analysis and hydrodynamic analysis are performed to ensure the safety of the OGHP under the operation conditions. The case study will enhance our understanding OGHP and its modularised components. The conceptual design of modular OGHP offers an alternative solution to "Power-to-X" for offshore renewable energy sector.

1. Introduction

1.1. Net zero future and policy

The UK's dedication to the Paris Agreement underscores its commitment to limiting global temperature rise. The nation's ambitious net zero goals and emission reduction targets reflect its resolve. Fossil fuels' 5% contribution to 2019's GHG emissions of 26 Mt CO_2 equivalent underscores the need for change. With legislation enacting a 100% emission reduction by 2050, even amidst the challenges of the COVID-19 pandemic, the UK remains steadfast [1]. In this context, the August 2021 net zero strategy emphasises decarbonisation across sectors, with hydrogen gaining prominence. Setting goals of 5 GW and 15–60 GW low-carbon hydrogen capacity by 2030 and 2050 respectively, alongside substantial investments, showcases the UK's commitment [2]. The April 2022 revision of hydrogen goals to 10 GW by 2030 further exemplifies its dedication [3]. The maritime sector's alignment with emission-free shipping adds a noteworthy facet [4]. Embedded in maritime heritage and economic influence, the UK's investment in emission reduction technologies epitomises its commitment to sustainable practices.

1.2. Demand for hydrogen power supply development

Growing demand for wind energy and natural gas faces challenges due to net zero commitments, limiting natural gas production to 20% in 2040 and 15% in 2050 [5]. Natural gas consumption drops from 250 to 150 million TJ, with roughly half sourced from the North Sea. Importantly, the UK imports 2/3 of its natural gas from nations including Norway, Qatar, the USA, and Russia, making supply vulnerable to geopolitical factors and market forces [6]. This underscores the need for a clean, high-density energy alternative.

Wind power contributed 26.1% to the UK's Q4 2021 electricity generation, with onshore and offshore wind contributing 12% and 14% respectively [7]. As electricity capacity must cover 100% of future

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demand, surplus potential can drive clean energy growth. Traditional offshore wind energy transport through high voltage alternating current (HVAC) power cables becomes inefficient beyond 100 km due to losses [8].

Hydrogen is a key medium for transforming renewable electricity into stable chemical energy via an electrolysis device. The stored hydrogen releases power in fuel cells or other facilities forming a closed loop between renewable electricity and hydrogen. Alternatively, the electrolysed hydrogen can be used in the power, building, transport and industrial sectors [9].

1.3. Offshore green hydrogen prospect

Skyrocketing gas prices have elevated energy independence as a top UK priority post-2022. The surge in gas costs has positioned the price of green hydrogen below that of grey hydrogen, catalysing a surge in offshore wind and hydrogen deployment targets. Historically, fossil-fuelled hydrogen with emissions capture, known as grey hydrogen, faced carbon capture and storage challenges. However, recent strides in electrolysis and renewable energy production are reshaping this landscape. Presently, a mere 1% of manufactured hydrogen is green, and offshore production is non-existent, largely due to cost, infrastructure, innovation, and scaling hurdles [10]. Hydrogen production via electrolysis is a promising approach for hydrogen production in the coming decades. Electrolysis emerges as a promising avenue for hydrogen production, harnessing renewable sources like wind to split water into hydrogen and oxygen, leaving only heat and, in desalination, saline brine. Offshore hydrogen production, powered by renewable energy sources such as wind, aligns with carbon reduction goals and decreasing fossil fuel dependence [11]. Global wind power contributes about 5% of electricity, primarily onshore, though offshore capacity exhibited remarkable growth, surpassing 10-fold from 2009 to 2020 [12,13]. The UK's ambitious offshore wind goals, targeting 50 GW by 2030, coupled with a substantial project pipeline, further exemplify this momentum [14]. With ample offshore wind resources, the UK is poised to generate substantial green hydrogen, crucial for advancing its net zero strategy. An estimated 130 to over 200 TWhr hydrogen is requisite by 2050 to integrate 75 GW or more of offshore wind into the UK energy system.

The United Kingdom boasts a remarkable share of Europe's offshore wind potential, equivalent to thrice the nation's current electricity consumption [15]. The faster winds of Atlantic Ocean are offset by unfavourable environmental conditions for platforms [16]. UK's Hydrogen Council [17] illustrates electricity demand and supply fluctuations. While electricity generation often exceeds demand, times of generation shortfall necessitate supplementary capacity. Battery storage can bridge short-term gaps, but with renewable energy growth, excess power surges. Here, hydrogen storage outweighs battery storage due to cost-effectiveness, providing a robust solution for enhanced flexibility demands [18].

2. Overview of offshore hydrogen technology developments

Before embarking on the design of a hydrogen platform, a comprehensive review of crucial data is imperative. Factors such as wind sources, water depths, offshore wind capacities, and the distribution of offshore platforms must be meticulously assessed. Given the novelty of offshore hydrogen platform design in the realm of offshore engineering, prototypes are few. Therefore, the exploration of technologies employed in hydrogen production and storage, along with an examination of ongoing hydrogen projects and existing hydrogen platforms, is pivotal. This analysis aims to yield suitable solutions for the realisation of an offshore hydrogen platform. The platform configuration has been analysed from process and economic feasibility [11,19,20]. The proposed paper will focus on the hydrodynamic aspect to illustrate the feasibility of the centralised platform configuration.

2.1. Offshore hydrogen generation projects

European countries are displaying remarkable enthusiasm in leading offshore hydrogen initiatives, evident over the past five years [21]. Numerous projects dedicated to hydrogen production and storage underscore a collective commitment to sustainable energy. These projects span a capacity range from 10 MW to 10 GW, showcasing ambitious goals. Table 1 provides an overview of European hydrogen production platforms, concentrated notably in the North Sea region. The United Kingdom stands out in this movement with projects approaching 10 GW, reflecting leadership in green hydrogen. European countries together contribute to an approximate 20 GW capacity, highlighting a collaborative drive to reshape energy paradigms sustainably.

2.2. Offshore wind farm distribution

Compared to scaling up individual offshore wind turbines to increase capacity, offshore wind farms have the advantage of efficiently harnessing wind energy, and their overall cost is relatively lower. The distribution of offshore wind farms across the UK in 2020 is illustrated in [34]. Up until April 2022, a total of seventeen offshore wind projects had begun, with ten out of the seventeen projects utilising floating platforms. The majority of these wind farms are situated in the North Sea, while the remainder are located in the Irish Sea.

The cumulative installed offshore wind power capacity in the United Kingdom stands at 11.3 GW [35,36] in of 2022. This growth trajectory is expected to continue, with the UK aiming to achieve a wind capacity of 50 GW by 2030 [37]. Notably, the pipeline system holds the potential for a remarkable capacity of 90 GW. In alignment with the UK Government's targets, the goal for green hydrogen production is set at 5 GW by 2030 [38]. Given this context, a strategic allocation of a fraction of the offshore wind capacity towards green hydrogen production could facilitate the realisation of the UK government's ambitious targets outlined in its net-zero strategy. Wind energy generation predominantly occurred onshore in 2015. However, the UK government removed the restriction on new onshore wind farms from 2020, which led to a surge in offshore wind capacity, particularly in the east and southeast of England. Looking ahead to 2025, new wind capacities are anticipated to be predominantly offshore, concentrating in the northern North Sea [39]. By 2050, the collective offshore wind capacity is projected to reach 24.8 GW [40]. In a bid to centralise offshore wind capacity, new wind hubs are emerging, such as Aberdeen in Scotland, aimed at bolstering the development of offshore wind energy in the region. Considering these developments, the offshore area of Scotland emerges as a promising candidate for hosting new hydrogen platforms.

The scale of wind generators has been consistently growing, with a shift from 5 MW generators in 2016 to the current installation of 12 MW units, and projections indicating an increase to 20 MW by 2030 [41]. In the context of ongoing pre/under construction projects worldwide, a global trend reveals an expansion in primary wind farm dimensions. This expansion encompasses a 38% increase in distance from shore, a 21% rise in water depth, a 21% growth in installed capacity, and a 22% increase in the number of turbines within a wind farm [42].

3. Conceptual centralised offshore green hydrogen platform design

3.1. Centralised offshore green hydrogen platform

Economic and technical analyses are two critical aspects of any new design. While centralised hydrogen production systems have been explored extensively in the literature, often with preliminary economic assessments compared to decentralised approaches, this paper places its primary emphasis on the hydrodynamic design and analysis. By focusing on the hydrodynamic aspects, this paper aims to advance the design of centralised offshore green hydrogen platforms. Fig. 1 illustrates the

Table 1
Hydrogen production platforms in Europe.

Project name	Capacity	Site	Region	Operational time
Offshore Hydrogen Production of Lhyfe and Centrale Nantes [22]	10–100 MW	SEM-REV, Centrale Nantes' offshore test site	France	2022
OYSTER of ITM Power, Ørsted and Siemens Gamesa [23]	MW scale	Grimsby, UK	EU	2024
Esbjerg Offshore Wind-to-Hydrogen Project, Swiss energy company H_2 Energy Europe [24]	1 GW	Esbjerg	Denmark	2024
Hyport Oostende Hydrogen Project of DEME Group and H_2 Energy [25]	50 MW	Oostende	Belgium	2025
AquaVentus Project [26]	10 GW	Helgoland	Germany	2035
DOLPHYN Project [27,28]	4 GW	Northern North Sea	Scotland, UK	2035
PosHYdon of NEPTUNE Energy [29,30]	–	Dutch North Sea	The Netherlands	2023
Bantry Bay green energy facility of Zenith Energy and EI-H2 [31]	3.2 GW	Bantry Bay	Ireland	2028
Salamander Project [32,33]	5 GW	Peterhead	UK	2028

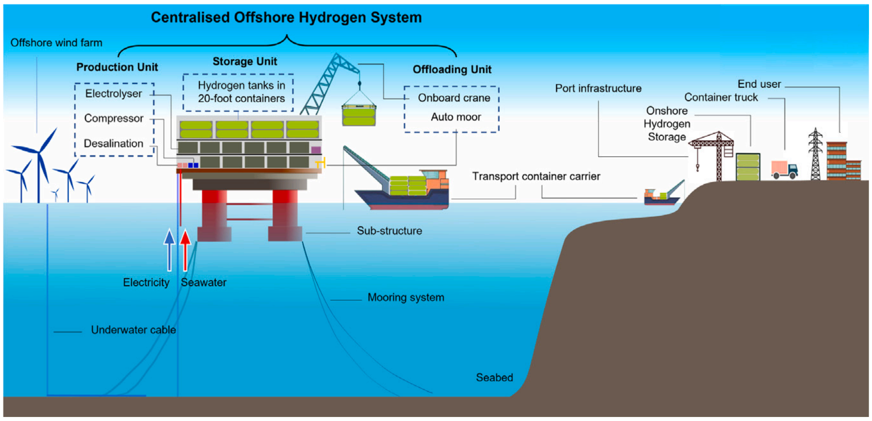


Fig. 1. Offshore centralised hydrogen platform in the hydrogen supply chain.

role of OGHP in the hydrogen streamline. The OGHP is integrated into the maritime hydrogen transformation as an offshore terminal. With the rapid expansion of offshore wind farms, the challenges associated with offloading hydrogen from these extensive facilities have grown in terms of cost and time. To address this, a centralised hydrogen platform is proposed, offering a more efficient approach to offshore renewable energy transition. Unlike the decentralised hydrogen units linked with individual wind turbines, the centralised system consolidates the electricity generated by multiple wind turbines onto a single offshore platform. This platform is strategically located in proximity to the designated wind farm, enabling the use of sub-sea cables for electricity transportation. As a result of this electricity aggregation, the volatility of input power is mitigated. In contrast to decentralised systems, the storage capacity of the centralised system is significantly larger. This enhanced capacity offers a greater degree of tolerance for hydrogen storage, accommodating larger quantities of hydrogen and reduce control frequency of the hydrogen production rate. This centralised offshore hydrogen platform boasts integrated equipment for hydrogen production, storage, and offloading processes. While situated at a considerable distance from ports, the system benefits from a streamlined approach to hydrogen transportation. Produced hydrogen is conveniently transported via hydrogen-powered ships in a regular routine to onshore storage tanks and to end-users, enhancing the overall efficiency and feasibility of the process.

3.2. Modularised system design

The proposed offshore hydrogen platform integrates production, storage, and offloading functions, featuring several modularised units including production, storage, offloading, additional units, and the platform sub-structure, as depicted in Fig. 1. The production unit comprises a desalination device for generating pure water from seawater, an electrolyser, a compressor for compressed hydrogen gas. The storage unit adopts containerised compressed hydrogen tanks. H_2 is compressed into cylindrical tanks which are integrated inside 20-foot TEUs [43]. The offloading unit facilitates hydrogen transfer from the platform to Autonomous Network Transport at Sea (ANTS) ship. The mooring device automatically docks the ship to the offshore platform. Additional components include a helideck, a control room, and emergency and safety equipment.

When the actual capacity falls below twice the design capacity, we have the option to upscale the dimensions of the platform. This increase in deck area allows us to accommodate more devices while ensuring platform stability. Conversely, if the actual capacity significantly exceeds twice the design capacity, we can increase either the number of deck layers or the quantity of platforms. Adding extra deck layers essentially duplicates the original design, which is highly detailed and well-illustrated. This duplication minimises the need for substantial design revisions.

3.2.1. Hydrogen storage

Compared with other fuels, hydrogen has a high mass energy density, but low volume energy density (1/3000 of gasoline). Therefore, a major prerequisite for building a hydrogen energy storage system is to store and transport hydrogen at a greater volume energy density. Considering the downstream of hydrogen transportation and hydrogen-powered vehicles, a higher mass density is also required. At present, the storage of hydrogen can be divided into high-pressure compressed

Table 2
Major properties of hydrogen fuels.

Property	CH_2 (@350 bar)	LH_2 (1 atm, −253 °C)	LOHC (DBT, 1 atm)	Ammonia (1 atm, −33 °C)
Low heating value, MJ/kg (kWh/kg)	120.00 (33.33)	120.00 (33.33)	7.42 (2.06 DBT)	18.6 (5.2)
Volumetric energy density, MJ/m^3 (kWh/m^3)	5040 (1400)	8500 (2361)	7000 (1945)	12,700 (3528)
Hydrogen storage density, kg/m^3	26	70.8	50–60	121
Carrier storage density, kg/m^3	26	70.8	910	600
Hydrogen release temperature, °C	N/A	−252	200–300	>500
Conversion rate, mol%	N/A	N/A	>95	65

Table 3
Results of the scoring for the five storage methods across the evaluation criteria.

Evaluation	Criterion	Weighting	CH_2	LH_2	LOHC	Ammonia
Technical evaluation	System complexity	0.15	1	4	5	2
	Technical maturity	0.15	1	4	5	2
	Size & Weight	0.1	5	3	4	2
	O & M requirements	0.05	1	4	5	3
Safety evaluation	Leaks	0.05	5	2	1	3
	Venting requirement	0.05	5	5	1	5
Economic evaluation	Overall efficiency	0.15	1	3	2	4
	CAPEX	0.1	1	3	5	2
	OPEX	0.05	1	3	5	4
	Integration complexity	0.15	1	2	4	3
Total		1.00	1.80	3.25	3.90	2.80

hydrogen (CH_2) storage, low-temperature liquid hydrogen (LH_2) storage and liquid organic hydrogen carriers (LOHCs) based on dibenzyl toluene (DBT), and ammonia. Other kinds of hydrogen storage options, such as chemically bound hydrogen storage, metal solid-state hydrogen storage and synthetic hydrocarbons are not discussed in this paper. The requirements for hydrogen storage technology are safety, large capacity, low cost, and easy access. The major properties of hydrogen fuel are listed in Table 2 [44].

The evaluation criteria for selecting an appropriate storage solution are organised into three main categories: technical, safety, and economic. Under the technical evaluation category, factors such as the complexity of the hydrogen storage format, technical maturity, size and weight of storage equipment, and operational and maintenance requirements are assessed. Safety evaluation encompasses considerations of leak risk and venting requirements as primary concerns. The economic evaluation considers overall efficiency, capital expenditures (CAPEX), operating expenses (OPEX), and integration with the ANTS transport or end-user network.

The storage formats were each ranked within the evaluated categories, with the results presented below. After applying the weighting for each category, a final score for each was calculated. The results are shown in Table 3 where 1 represents the best performing/most suitable option, and four represents the worst performing/least suitable solution. As a result of this analysis, CH_2 has been identified as the best option for the centralised offshore platform application. The selection of compressed hydrogen is beneficial to the simplicity of the process which leads lowest score of technical and economic evaluation.

Compressed hydrogen is efficiently stored and transported in standard containers, aligning with the container ship transport method. It eliminates the need for new port infrastructure. The chosen configuration of storage container is 20-foot standard-sized, housing nine hydrogen tanks at 350 bars [43]. This setup carries 356 kg of hydrogen gas within a total volume of 1480 l.

3.2.2. Hydrogen production

IonPRO LX MkII Model 4–10 [45] is selected as the desalination device to provide fresh water to electrolysers. An electrolyser, a pivotal component of hydrogen production, comes in four primary types: Alkaline Electrolysed Cell (AEC), Polymer Electrolyte Membrane (PEM), and Solid Oxide Electrolysis Cell (SOEC). Among these, AEC demonstrates mature technology, offering high hydrogen production capacity, low investment, and long lifespan. Following AEC, PEM has progressed through early marketisation, combining smaller footprint, higher current density, and output pressure. Advanced Anion Exchange Membrane (AEM) and SOEC are in experimental stages with lower technology readiness levels (TRLs). AEM blends AEC and PEM characteristics, delivering cost efficiency and high efficacy, while SOEC aims for up to 90% efficiency improvement. High energy consumption and low efficiency have historically hindered water electrolysis for hydrogen production [34]. Presently, AEC and PEM stand out as the most suitable choices due to their technological maturity. Moreover, [46] illustrates the advantage of PEM electrolysis that this technology has faster response to load change. The electrolyser used in the hydrogen production modular is NEL Containerized PEM Electrolyser illustrated in [47].

CH_2 is used as a demonstration which is the best option for entire green hydrogen storage process. The parameters of hydrogen compressor in the hydrogen production modular are selected as Z Type Diaphragm Air Compressor [48].

3.2.3. Hydrogen offloading

Stored hydrogen energy is poised for potential transportation via the ANTS ship. However, the relative motion between two types of floating structures can impact bunkering efficiency and even pose safety risks. In this context, both the platform and autonomous transport ship are envisioned to operate autonomously. Traditional mooring ropes might not be suitable for this automated system. An innovative solution lies in arm mooring mechanisms, employing pneumatic or magnetic arms to secure the ship to the terminal and mitigate motion effects. Arm dimensions and numbers will correspond to the weight of ANTS ship. Introducing active control into these mooring arms, while considering motion compensation, is a future possibility. After successful berthing, hydrogen energy stored in tanks can be transferred to the ANTS ship through onboard crane. The mooring device selected is AutoMoor unit developed by Trelleborg Group [49].

The crane facilitates the transportation of hydrogen storage tanks, akin to containers, between the platform deck and the ANTS ship. This design approach is drawn from standardised containers and carrier practices. Leveraging existing port infrastructure, this method minimises the need for constructing new facilities. The efficiency of hydrogen transport is enhanced through the utility of cranes. Should storage tanks on both ANTS ships and hydrogen platforms adhere to standardised dimensions, the transportation of hydrogen between offshore, ship,

Table 4
Areas and weights of the units of the offshore hydrogen platform.

System modular	Device unit	Device specification	Area per unit power (m^2/MW)	Weight per unit power (kg/MW)
Storage	Storage format Storage container	CH_2 (350 bar, 20 °C) H_2 Tank container (20-foot TEU)	28.40	36 595.45
Production	Desalination device Electrolyser H_2 compressor	IonPRO™ LX MkII Model 2–10 MC 500 containerised PEM Z-type diaphragm compressor	14.12	5056.53
Offloading	Mooring Transport	Trelleborg AM-T20–01 Crane (125-ton, 72 m)	0.41	39.00

and land will be notably streamlined. Given the prevalence of cranes in ports, the investment required for hydrogen transportation at port interfaces is anticipated to decrease.

3.2.4. Weight and area estimation

Regarding the device information of OGHP provided, the weights and footprints of the units for per unit power (MW) are calculated, as listed in Table 4. The footprint contribution of the production unit is also two times that of the storage unit. The majority of the weight and footprint can be up-scaled or duplicated independently based on the result in Table 4. Once input wind energy capacity is specified, the quantities of the devices can be calculated, and the area and weight of the whole hydrogen platform can be preliminary estimated.

4. Case study

4.1. Site selection

The capacity design of OGHP is highly dependent on the power capacity of the wind electricity generation. The equipment quantities, equipment locations and deck layers of the hydrogen platform are required to be determined by the capacity of the hydrogen platform. Therefore, the layout design of the hydrogen platform is sensitive to the input capacity of the wind farm. The proposed platform in the case study is designed based on a new-built floating wind farm, the Salamander project [32], which has a 100-MW capacity. The layout of the equipment is designed based on the wind capacity. The centralised hydrogen platform is located near to the wind farm to reduce the cost of electricity cable. The location of hydrogen platform is advantageous for minimising routine maintenance expenses associated with service ship transportation.

The Energy Transition Zone (ETZ) Ltd is selected as expected port terminal which is poised to develop into a hub for achieving net-zero emissions, seamlessly connecting with the North Sea coastline and harbor. It will serve as a prominent commercial gateway, effectively linking onshore renewable industrial activities with offshore infrastructure, particularly high-value manufacturing endeavors. The wind farm is situated approximately 75 km off the Port of Aberdeen. By 2030, The ETZ [50] sets to finalise a comprehensive multi-phase development adjacent to the Aberdeen South Harbour project. This visionary zone is poised to attract investments and catalyse innovation, playing a central role in advancing net-zero aspirations. During the meticulous planning and design of the ETZ, a key focus has been placed on ensuring the smooth integration of green hydrogen energy transport with the ongoing port operations. Stringent safety measures and comprehensive risk management strategies have been seamlessly incorporated to mitigate any potential risks associated with offshore renewable energy endeavors. The Energy Transition Zone offers prime investment prospects for energy transition-related projects and developing activities that will support the transformation of the supply chain. The location of the Energy Transition Zone is adjacent to the new £400-million development at Aberdeen South Harbour and the non-tidal harbour will provide new infrastructure [50]. It focuses on high-value manufacturing, marshalling, and assembly for renewable energy, including offshore green hydrogen. Equipped with cutting-edge facilities, the ETZ will offer specialised infrastructure for handling compressed hydrogen containers, ensuring smooth hydrogen transport even during peak shipping periods. The confluence of strategic location, advanced infrastructure, and resolute sustainability goals firmly establishes the Energy Transition Zone as an ideal hub to facilitate and advance offshore green hydrogen transport endeavors.

Table 5
Quantities of modularised units in the floating case.

Floating case design	Unit	1st round	2nd round
Wind capacity	MW	100	93
Electrolyser capacity	MW	50	46.5
Production modular	–	21	20
Storage modular	–	400	400
Offloading modular	–	6	12
Control room	–	1	1
Crane	–	1	1
Helideck	–	1	1
Area	m^2	4297.5	4450.9
Weight	ton	4292.2	4072.0

Table 6
Platform modular and hydrogen production calculation of the case study.

Power consumption per production modular	MW	2.3
H2 capacity per electrolyser	kg/day	5310.0
Quantity of electrolysers	–	20
Total H2 capacity	kg/day	21 240.0
Mass of hydrogen per tank	kg/tank	356.0
Quantity of tanks filled per day	tank/day	59.5
Quantity of tanks onboard	–	400
Days to fill half of the onboard tanks	day	3.4

4.2. Platform layout design

The power reduction factors from the wind farm to the electrolysis equipment are estimated as 0.5 for floating cases respectively. The designs went through two rounds of analysis, to avoid unfeasible designs of the system and the results are shown in Table 5.

The quantities of each device can be determined and the total weight and area can be specified preliminary. The input power required for one modular production set is approximately 23.5 MW. Given that the wind capacity is 100 MW, and accounting for a reduction rate of 0.5, the power input to the platform is 50 MW. This power input can support roughly 21 production modulars, which in turn determines the weight of hydrogen production. Regarding the transportation of hydrogen, the gas produced can fill 200 standard containers daily. To ensure an efficient transport process, the quantity of containers is doubled. Furthermore, the footprints of the devices are estimated to occupy about 140% of the actual area. This additional space is allocated to ensure that the deck layout is not too congested, allowing for smooth operations. The final values of the platform modules have been slightly adjusted to ensure an aesthetically pleasing layout. The detailed calculation result of the final design is shown in Table 6.

In the initial design iteration, the modular unit quantities were determined based on a precise electricity capacity of 100 MW for the

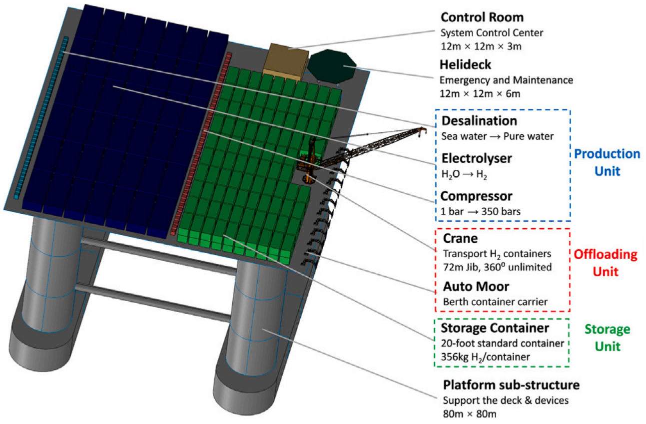
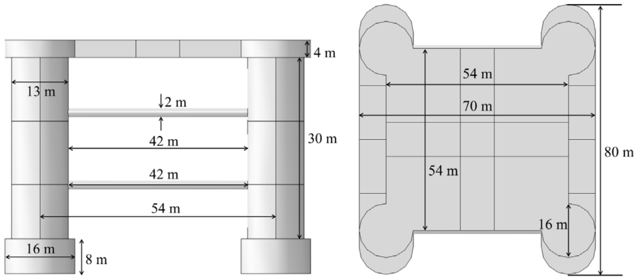


Fig. 2. Layout design of offshore hydrogen platform.



(a) Side-view profile.

(b) Top-view profile.

Fig. 3. Specific parameters of semi-submersible platform.

floating system. Subsequently, a second-round design further optimised the quantities while arranging the devices on the 80 m × 80 m deck. In this refined layout, the required electricity capacity is 93 MW, slightly lower than the Salamander's capacity. Table 5 presents the quantities, weights, and footprints of the units in both design rounds, all distributed on a single-layer deck. The production unit quantity was initially estimated at 21 units based on input power, later refined to 20 units for better distribution. The iterative design process ultimately identified an optimal quantity of 12 automoor facilities. Regarding the setup recommendation [51] of the automatic mooring devices on the guidance, the quantity is revised to 12 to provide sufficient mooring force. The conceptual design of the device layout for each case is shown in Fig. 2. Key devices are strategically situated onboard. Production units, encompassing electrolysers, compressors, and desalination equipment, are grouped for efficiency. Automatic mooring devices are positioned at one platform edge, while storage tanks are placed between production and mooring units. A helideck measuring 12 m × 12 m is designed atop the platform. Adjacently, a control room spanning 5 m × 10 m is allocated for device monitoring and crew accommodation.

4.3. Semi-submersible sub-structure design

The platform model is based on the Amirkabir semi-submersible platform [52]. The principal particulars of the sub-structure design will be subject to adjustments aligned with the weights and spatial requirements of the installed devices. The parameters of the newly designed sub-structure are illustrated in Fig. 3. The draught is 30 m, which means the equipment deck is 8 m above the water free surface. The size of the platform is 80 m × 80 m, which leaves sufficient residual footprint. The structure material is Q235 steel, and the thickness is 0.026 m.

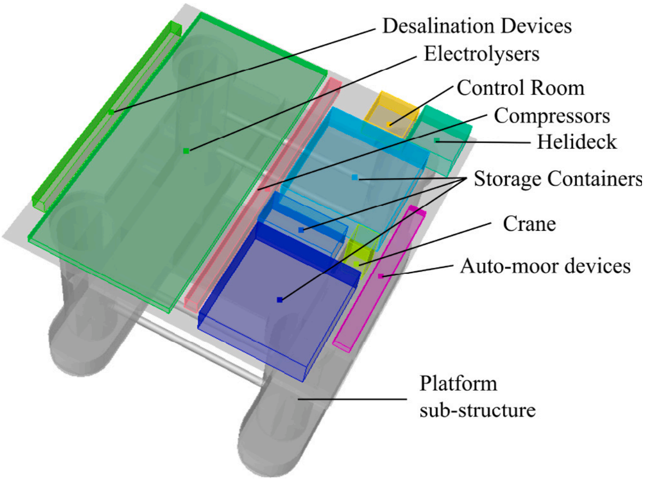


Fig. 4. Geometry of the offshore floating platform.

4.4. Stability analysis

Fig. 4 depicts the geometry of semi-submersible sub-structure and equipment deck layout of the newly designed platform. Devices are organised according to unit categories, and their weights are simulated as distributed loads on the equipment deck. Different devices are distinguished by colour-coded labels as displayed in the figure. Table 7 provides the loads corresponding to onboard devices. These loads are approximated as equivalent distributed loads, matching the sizes of actual devices in the respective specific areas. The original of coordinate is set at the centre of deck surface.

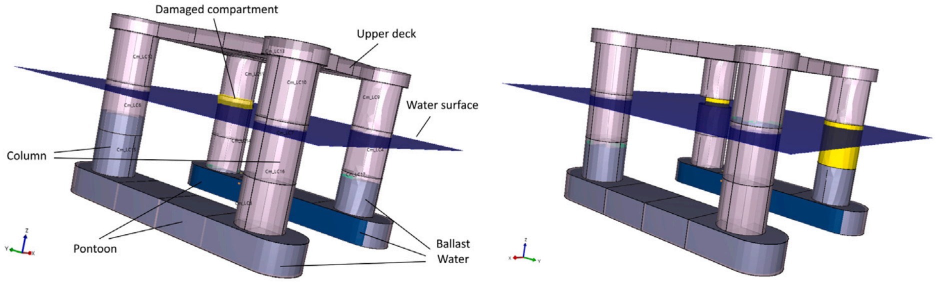
The pontoons and columns are compartmentalised for water ballast, with four compartments in each pontoon and three in each column. Water ballast fills these compartments to adjust the weight and buoyancy balance. Permeability is 70% for the upper deck and 100% for other compartments. The equilibrium is at the horizontal centre of platform. Fig. 5 depicts the ballast balance, while two damaged cases are defined: the damaged case 1 is based on the least size requirement of damage compartment at load case (CmLC), CmLC3 representing minor damaged condition and the damaged case 2 is costumised which includes a large, damaged column compartment CmLC6 representing extreme damage condition. The damaged case is defined as illustrated in [53,54]. The highlighted compartments in Fig. 5 represent the damaged compartments used in stability analysis for damaged conditions. The damaged compartment properties are shown in Table 8.

Table 9 shows the initial stability of the platform. The buoyancy and the total mass are balanced by the design of the compartment ballast, with the difference in weight and buoyancy being less than 1 kg. The dry mass is the summation of steel structure of the floating sub-structure and devices, and the metacentric height is found to be 8.62 m. The wind heeling moment is 326,953 kN·m. The results of the intact and damaged stability analysis are shown in Fig. 6. Floating offshore structures adhere to stability guidelines outlined in [53,54]. The assessment involves confirming compliance with Norwegian Maritime Authority (NMA) hydrostatic rules for both intact and damaged scenarios.

Table 10 presents the outcomes of the rule check for intact stability, confirming compliance with all five criteria requirements. Regarding the results of damaged case 1, the differences between the two conditions are less than 1%. The platform is of 80-meter scale while damaged compartment in the damaged case 1 is of 1-meter scale. The weight of the flooding water is 1% of the platform weight. The additional loads in damaged case 1 have insignificant impact to stability performance. Similarly, Table 11 illustrates the results of the rule check for damaged stability, affirming adherence to all eight criteria requirements.

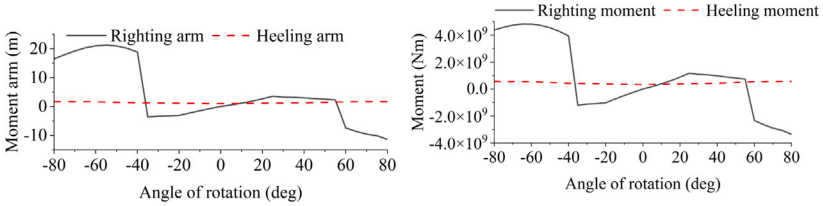
Table 7
Loads of the onboard devices on the OGHP.

Equipment	H × L × W (m × m × m)	Location (m, m)	Weight (ton)	F_z (kN)	M_x (kN m)	M_y (kN m)
Automoor	2 × 4 × 40	(36, −7)	51.0	500.3	3500.0	18,005.0
Compressor	4 × 2 × 70	(4, 0)	27.4	268.8	0.0	1074.8
Control room	5 × 10 × 10	(20, 32)	50.0	490.5	−15,690.6	9806.6
Crane	12 × 5 × 5	(30, −7)	140.0	1373.4	9610.5	41,187.9
Desalination	4 × 3 × 60	(−37, −0)	27.4	268.8	0.0	−9942.0
Electrolyser	2 × 35 × 70	(−17, 0)	3288.0	32,255.3	0.0	−548,153.0
Helideck	6 × 12 × 12	(32, 32)	22.5	220.7	−7048.2	7048.2
Storage 1	7 × 25 × 26	(20, 12)	218.0	2138.6	−25,654.2	42,757.0
Storage 2	7 × 18 × 8	(16, −7)	30.0	294.3	2059.4	4707.2
Storage 3	7 × 25 × 16	(20, −25)	218.0	2138.6	53,446.2	42,757.0
Total	–	–	4072.3	39,949.3	2,0334.1	−39,0751.0

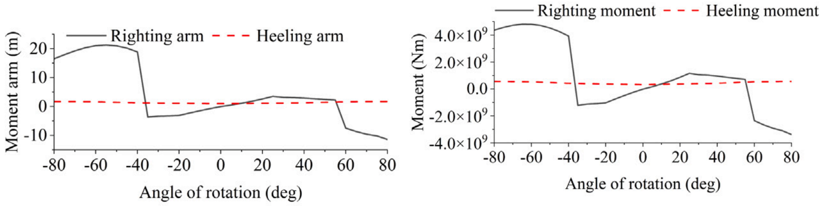


(a) Damaged case 1 (b) Damaged case 2

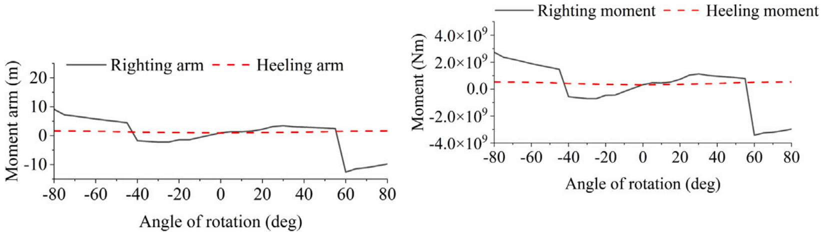
Fig. 5. The ballast condition and damaged compartments of the designed sub-structure.



(a) Righting arm of the intact case. (b) Righting moment of the intact case.



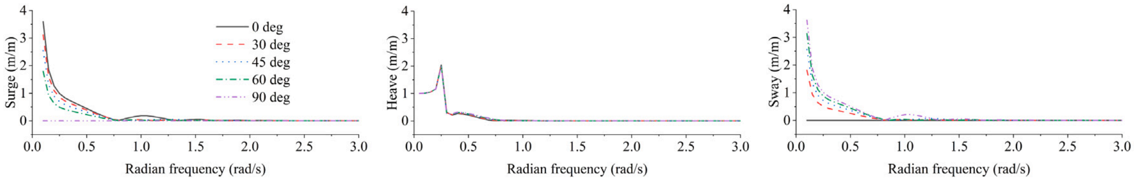
(c) Righting arm of the damaged case 1 (d) Righting moment of the damaged case 1



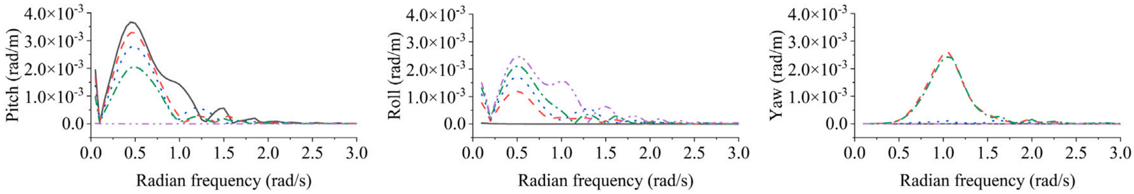
(e) Righting arm of the damaged case 2 (f) Righting heeling moment of the damaged case 2

Fig. 6. Stability analysis of the platform1. .

The meticulous design of the hydrogen platform, encompassing the distribution of equipment and the sub-structure layout, contributes to ensuring the stability of the floating platform through stability rule check. Regarding the results of damaged case 2, one huge column compartment close to free surface is filled by water with damage. The stability will be impacted remarkably. Under the extreme damaged condition, the design platform in the case study still pass meet the rules of MNA criteria.



(a) Surge (b) Heave (c) Sway



(d) Pitch (e) Roll (f) Yaw

Fig. 7. Motion responses of the floating platform in frequency domain.

Table 8
Damaged tank properties.

Compartment	Damaged	Filling fraction	Mass	COG
CmLC6	Case 2	100.00%	1671.2	(−27.0, 27. 0, −9.3)
CmLC3	Cases 1 and 2	50.83%	21.37	(−23.35, −23.35, −0.76)

Table 9
Initial stability of the platform.

Parameter	Unit	Value
Total mass	ton	33,955
COG (total)	m	(0, 0, −19.3)
Radius of gyration	m	(32.7, 33.2, 35.3)
Centre of buoyancy	m	(0, 0, −22.7)
Draft	m	33.5
Dry mass	ton	8720.6
COG (Dry)	m	(0, 0, 3.5)
Metacentric height	m	7.85

Table 10
Rule check of the intact stability analysis.

Criterion	Computed value	Required value	Result
Righting area	7.6	17	PASS
Metacentric height	41.6	30	PASS
Righting moments from upright to second intercept	True	True	PASS
Second righting/heeling moment intercept angle	8.613	1	PASS
Equilibrium inclination angle with wind	6E+08	3E+08	PASS

4.5. Hydrodynamic analysis

Wave directions ranging from 0° to 90° were considered, taking advantage of the structural symmetry of platform along the x-axis and y-axis. Calculations were performed for wave directions of 0°, 30°, 45°, 60°, and 90°. In Fig. 7, the hydrodynamic responses of the floating platform are depicted in terms of its 6 degrees of freedom (6-DoF) under wave-induced loads within the frequency domain. The hydrodynamic response results of the floating platform reflect the nature characteristics although the frequency-domain analysis is preliminary. Notably, substantial wave-induced drift motions are evident in the curves reflecting translational motion responses. These significant motions introduce safety concerns during offloading operations between the offshore platform and the transportation ship. The frequency-domain analysis will guide time-domain analysis under environmental loads. As a mitigation measure, implementing a mooring system is essential to curtail these motions. Conversely, rotational motions are relatively minimal due to the substantial weight of the floating platform. As such, the hydrodynamic loads exert a less dominant influence on these rotational motions.

5. Conclusion

The quest for harnessing offshore renewable energy sources is of paramount significance in addressing energy challenges. This study meticulously examines the landscape of OGHP and offshore wind farms within the UK, offering an insightful glimpse into their policy context and future prospects. By delving into the motivations and obstacles entailed in OGHP development, the study lays bare the technological and design intricacies that underpin offshore hydrogen endeavors. A pivotal stride in this trajectory is the introduction of a novel conceptual design methodology for a centralised floating hydrogen platform. This innovative approach dissects the system into three distinct yet interconnected modules: production, storage, and offloading. Notably, the modular nature of device layout ensures scalability, allowing for seamless expansion in alignment with offshore wind capacity. The study deftly employs this framework in a case study scenario, where a 100-MW wind project serves as the bedrock of energy input. Here, the site selection and platform layout are meticulously detailed, lending tangible substance to the proposed methodology. The selection of a floating sub-structure for the platform, coupled with the device arrangement of platform, is underscored by careful considerations. A rigorous stability analysis, compliant with NMA rules for both intact and damaged conditions, ensures the robustness of the proposed OGHP design. The simulation outcomes affirm the feasibility of the OGHP in the case study, while highlighting the necessity of a robust mooring system to counter the significant translational motions observed in low-frequency ranges. The trajectory of this study also extends into future work, as hydrodynamic analysis involving mooring lines is poised to take centre stage. In summary, this study charts a clear course towards a sustainable energy future by unveiling a comprehensive road map for the real-world deployment of Offshore Green Hydrogen platforms. This work demonstrates that the marriage of offshore renewable, hydrogen technology and hydrodynamic analysis to support the development of offshore hydrogen technologies based on the previous process and economics researches.

CRediT authorship contribution statement

Ming Zhang: Methodology, Software, Formal analysis, Data curation, Writing – original draft, Writing – review & editing.. **Longbin Tao:**

Table 11
Rule check of the damaged stability analysis.

Criterion	Computed value of case 1	Computed value of case 2	Required value	Result
Not flooded by any opening in the angular interval	True	True	True	PASS
Nonweathertight openings	True	True	True	PASS
Theta WA (Flooding angle)	29.36	31.21	55.71	PASS
Theta WA (second intercept)	29.36	31.21	55.33	PASS
Angular range from first to second intercept	46.01	55.64	10	PASS
Righting moment area to second intercept	7.25+E08	7.71+E08	3.88+E08	PASS
Equilibrium inclination angle with wind	9.31	0.30	17	PASS
Height of floodable opening	20.22	17.80	0	PASS

Investigation, Writing – review & editing. **Martin Nuernberg:** Conceptualization. **Aarvind Rai:** Investigation. **Zhi-Ming Yuan:** Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ming Zhang reports financial support was provided by MarRI-UK.

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