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A NOVEL CONCEPTUAL DESIGN OF MODULARISED OFFSHORE GREEN HYDROGEN SYSTEM

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ABSTRACT

As a signatory to the Paris Agreement, the UK is committed to contribute efforts to prevent global temperature increase. The UK set its policies and proposals to meet zero net strategy by 2050. Offshore green hydrogen is one promising approach to transfer offshore wind energy to onshore demand areas due to its clean and high-power density. The UK is accelerating towards offshore green hydrogen and has made the price of green hydrogen competitive in the marketplace. The bottleneck of offshore green hydrogen system (OGHS) is the cost of scaling up hydrogen production in the current stage. Innovate designs of hydrogen production system may bring breakthrough to the cost when scaling up the OGHS. This study proposed a centralised OGHS which integrates with modularised production, storage, and offloading units using electricity coming from offshore wind farms. The paper offers an overview of the current situation and development of hydrogen platform and offshore wind farm for supporting the design of offshore platform as well as highlights the key features of technologies used by the different components of the OGHS, through a thorough literature review, including state-of-the-art technical reports and journal papers. A conceptual design of the proposed modularised OGHS is illustrated with a recommendation of site selection. Equipment layout of the OGHS distributed on a floating supporting structure is designed based on a case study of a 200-MW floating wind farm. Stability of the OGHS floating platform is analysed to verify safety of the in the case study, and linear hydrodynamics analysis is simulated based on linear potential theory.

Keywords: Conceptual design; Modularised hydrogen system; Offshore green hydrogen; Offshore renewable energy.

NOMENCLATURE

EU	European Union
GHG	Greenhouse Gas
GOC	Center Of Gravity
H2	Hydrogen
NMA	Norway Maritime Authority
OGHS	Offshore Green Hydrogen System
PEM	Polymer Electrolyte Membrane
RAO	Response Amplitude Operator
UK	United Kingdom
PEM	Polymer Electrolyte Membrane

1. INTRODUCTION

As a signatory to the Paris Agreement, the UK is committed to contributing towards efforts to keep global temperature increase this century to well below 2 °C above preindustrial levels and to pursue effort that will limit temperature increase to 1.5 °C. At present, emissions are largely derived from fossil fuels which were further enforced in June 2019 by the UK government's introduction of a primary legislation that commits the UK to achieve a 100% reduction in GHG emissions by 2050. In August 2021, the UK government released its net zero strategy, laying out its plans for the decarbonisation of several key industries to meet a net zero emission target by 2050 . With regard to these plans, the interest in alternative green energy vectors has been increasing , with specific attention in the energy industry being given to hydrogen (H2) in recent years.

On April 7, 2022, the UK government announced a goal of up to 10 GW of H2 production capacity by 2030, subject to affordability and value for money, with at least half of this coming from electrolytic hydrogen . The capacity was doubled compared with the target set in August 2021. The strategy also set out our intention for up to 1 GW of electrolytic hydrogen (green hydrogen) to be operational or in construction by 2025. The current plans for the Net Zero Hydrogen Fund will materialize alongside private investments between 2022 and 2025 for green hydrogen projects.

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FIGURE 1 shows the hydrogen demand of 2050. The figure shows the system transportation of energy in the UK if the UK will be leading the way in net zero energy. All the natural gas, all the nuclear energy and part of the wind energy is transferred into hydrogen energy. The demand of hydrogen energy at the terminal will be 1/3 in 2050. Hydrogen demand increases 10-fold by 2050 compared with that of 2015 . Considering the tremendous increase in hydrogen demand, the development of hydrogen power supply should be accelerated to meet hydrogen demand in the future.

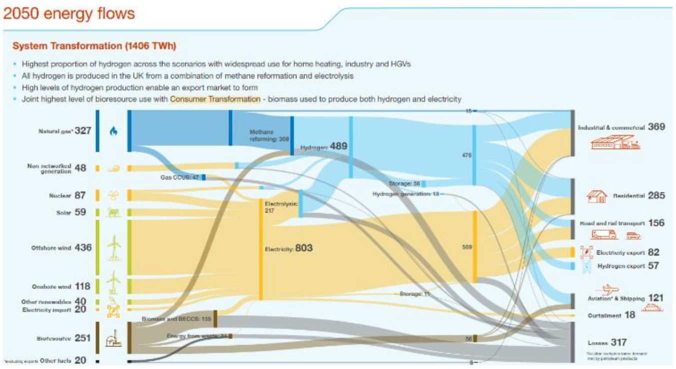


FIGURE 1: ENERGY FLOW OF THE UK IN 2050 .

Skyrocketing gas prices made energy independence the top priority for the UK after 2022. The rising price of gas made the price of green hydrogen already cheaper than that of grey one. This shock caused by gas price resulted in an increase of offshore wind and H2 deployment targets.

Although the biggest barrier is the cost, infrastructure, innovation and upscaling are also hurdled to overcome for green hydrogen . Hydrogen production via electrolysis is a promising approach for hydrogen production in the coming decades. Considering that the UK Government has increased the offshore wind installed capacity target to 50 GW by 2030 and Renewable UK estimated that the project pipeline in the UK equals 91 GW in 2022 , the UK has sufficient offshore wind for energy need pulsing substantial export. Therefore, offshore wind energy has enormous potential to generate green hydrogen that can accelerate the net zero strategy.

FIGURE 2 shows the time-history fluctuation of electricity demand and supply. The generation of electricity capacity is higher than the demand for electricity most of the time. Once generation becomes lower than demand, alternative capacity is required to balance the gap between generation and demand. Using battery storage is not a cost-effective approach to balance the gap with the growth of renewables. H2 is a good contender when a higher degree of flexibility is required.

This paper aims to describe the status and future perspective of offshore green hydrogen. The knowledge of existing offshore hydrogen projects, hydrogen system designs, technologies of oil and gas platform and technologies of offshore wind farm. A novel design of modularised offshore hydrogen platform is proposed to integrate production, storage and offloading units. The platform layout of the OGHS is designed based on the power supply of early-planning wind farm. A floating offshore platform is applied as the of the offshore system. Stability and hydrodynamic responses are simulated.

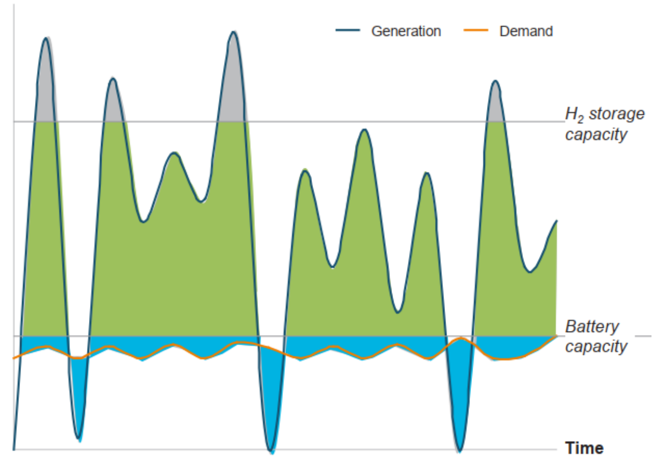


FIGURE 2: HYDROGEN STORAGE CAPACITY BRIDGES GAPS BETWEEN SUPPLY AND DEMAND (DATA IS FOR ONE WEEK) .

2. REVIEW OF HYDROGEN SYSTEM

2.1 Existing hydrogen projects

European countries exhibit huge enthusiasm towards developing offshore hydrogen platforms. Numerous projects on hydrogen production and storage have been proposed in the past 5 years. The target hydrogen capacity ranges from 10 MW to 10 GW. TABLE 1 lists the hydrogen production platforms in Europe. Production platform projects are distributed in the North Sea area, indicating the green hydrogen potential of the North Sea. The projects proposed in the UK have a scale of about 10 GW capacity while the total capacity is approximately 20 GW amongst the European countries.

2.2 Offshore Wind Farm Distribution

Compared with upscaling an offshore wind turbine to increase the capacity, an offshore wind farm can absorb wind energy sufficiently and the cost of a wind farm is relatively low. The distribution of offshore wind farms across the UK in 2020 is mapped in FIGURE 3. Seventeen offshore wind projects commenced until April 2022. Ten of the seventeen offshore wind projects are floating types . Most wind farms are installed in the North Sea, whilst the remaining ones are in the Irish Sea.

TABLE 1 HYDROGEN PRODUCTION PLATFORMS IN EUROPE.

Project name	Capacity	Site	Country	Operational time
Offshore Hydrogen Production of Lhyfe and Centrale Nantes	10–100 MW	SEM-REV, Centrale Nantes' offshore test site	France	2022
OYSTER of ITM Power, Ørsted and Siemens Gamesa	MW scale	Grimsby, UK	EU	2024
Esbjerg Offshore Wind-to-Hydrogen Project, Swiss energy company H2 Energy Europe	1 GW	Esbjerg, Denmark	Denmark	2024
Hyport Oostende Hydrogen Project of DEME Group and H2 Energy	50 MW	Oostende, Belgium	Belgium	2025
AquaVentus Project	10 GW	Helgoland	Germany	2035
DOLPHYN Project	4 GW	Northern North Sea, Scotland	UK	2035
PosHYdon of NEPTUNE Energy	-	Dutch North Sea	Netherlands	2023
The Salamander Project	5 GW	Peterhead	UK	2028

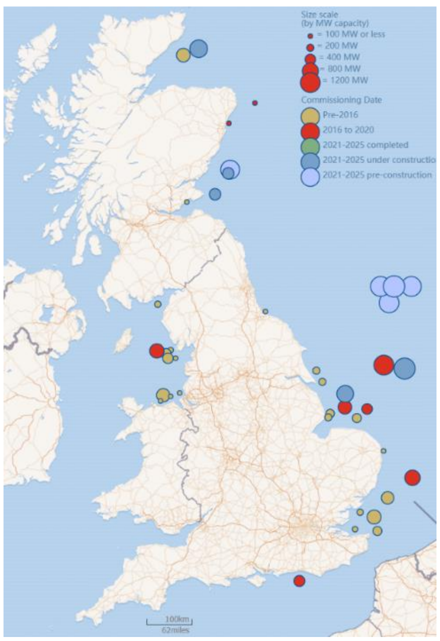


FIGURE 3: OFFSHORE WIND FARM LOCATIONS IN THE UK OFFSHORE WATERS IN 2020 .

2.3 Conceptual design of the modularised offshore hydrogen system

The floating offshore hydrogen platform in this study is designed as a standard unit. The offshore hydrogen platform gathers the renewable electricity of distributed wind turbines or wind farms in a specific location. The platform integrates H2 production, storage and offloading functionalities. The electricity is converted into H2 gas by electrolysers onboard. The produced H2 is transferred into compressed gaseous H2 through a pipeline and compressor and stored in the onboard tanks. The compressed H2 gas is transported by ships to the ports. Compared with collecting H2 production from localised wind turbines, the offshore platform serves as an offshore terminal which saves the cost of shipping transportation between wind turbines. The electricity generated from wind turbines can be gathered to the offshore terminal through underwater cables. The time-history fluctuation of electricity outputs of localised wind turbines is weakened when the power is gathered as a scale of dozens or hundreds. The accumulated electricity will be converted to H2 gas on a large scale. Therefore, the cost of shipping transportation can be reduced remarkably.

The capacity design of OGHS is highly dependent on the power capacity of the wind electricity generation. The platform can be bottom-fixed type or floating type which is dependent on the water depth. The equipment quantities, equipment locations and deck layers of the hydrogen system are required to be determined by the capacity of the hydrogen system. Therefore, the layout design of the hydrogen system is sensitive to the input capacity of the wind farm. The proposed platform is designed based on a new-built floating wind farm, the Salamander project , which has a 200-MV capacity. The layout of the equipment is designed based on the wind capacity.

When the input capacity of wind farms is larger than the design capacity, there are two strategies to match the system layout design with the input capacity. 1). When the actual capacity is less than two times the design capacity, dimensions of the platform can be upscaled to increase deck area to install more devices. 2). When the actual capacity is much larger than the two times, the quantity of the platform can be increased.

3. MODULARISED HYDROGEN PLATFORM CONFIGURATION

FIGURE 4 shows the conceptual design of hydrogen highway. The green hydrogen is eletrolysed from offshore wind energy and shuffled by hydrogen transportation ship to nearshore terminal. The hydrogen is then transported to onshore storage tanks and to end-users. The offshore hydrogen terminal is a major component in the maritime hydrogen highway.

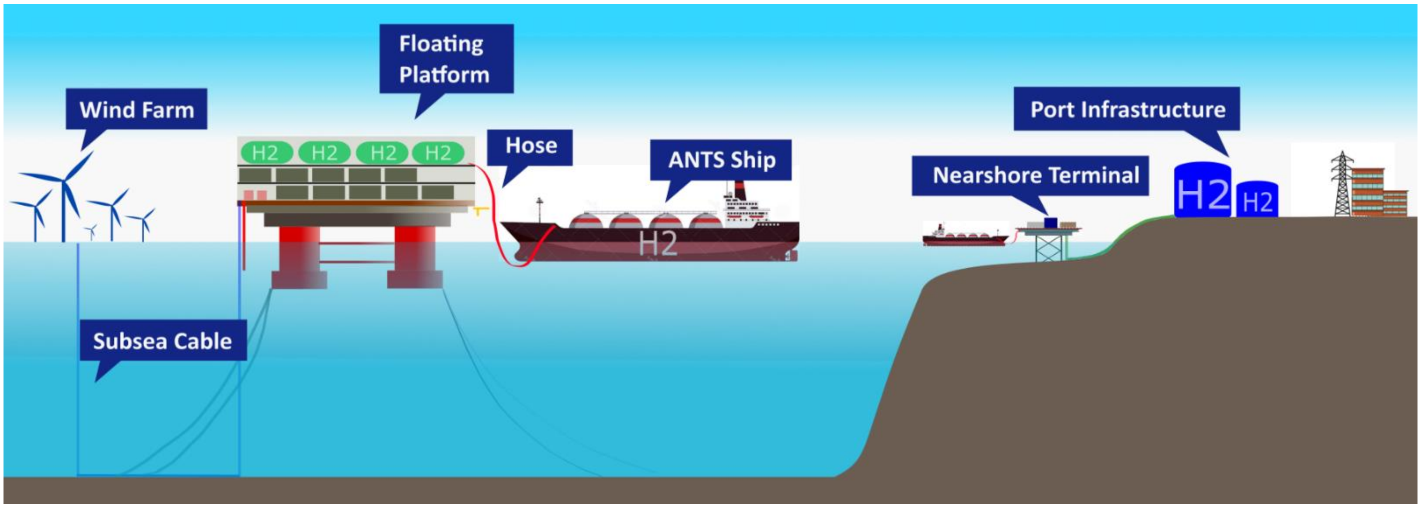


FIGURE 4: CONCEPTUAL DESIGN OF MARITIME HYDROGEN HIGHWAY.

3.1 Location selection and supporting structure

The Salamander wind farm is located in the Northern North Sea near Scotland. To reduce the cost of underwater electricity cable, the hydrogen platform will be located close to the wind farm. The location indicates the hydrogen platform's supporting structure is also floating type, which is the same as the wind farm. The water depth near the Scottish offshore wind farm is more than 100 m. The semi-submersible type of supporting structure is determined for the offshore hydrogen platform. The semi-submersible type is suitable for platform upscaling. The platform model is based on the Amirkabir semi-submersible platform as shown in FIGURE 5. The parameters of the designed floating supporting structure are based on the data shown in .

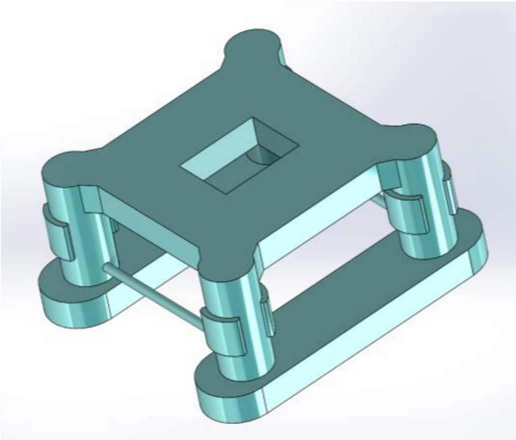


FIGURE 5: GEOMETRY MODEL OF THE AMIRKABIR SEMI-SUBMERSIBLE PLATFORM SUPPORTING STRUCTURE .

3.2 Functional modules of hydrogen platform

The proposed offshore hydrogen platform integrates production, storage and offloading functions; hence, the main modularised units include production units, storage units, offloading units, other units, and a platform supporting structure, as shown in FIGURE 6. The production unit consists of a desalination device for pure water production from sea water, an electrolyser and a compressor for compressed hydrogen gas and a liquefier for liquefied hydrogen. The storage unit has two categories: onboard and subsea. The subsea storage is used only for floating platforms. The offloading unit transports hydrogen from the platform to the transport ship. Flowlines are a major component of the offloading process, and automoor device berths the ship to the offshore platform automatically. A helideck, a control room and emergency & safety device are also installed on the platform. The minor components, such as the sea water storage, pump, etc. are not listed because the weights and footprints are not dominant.

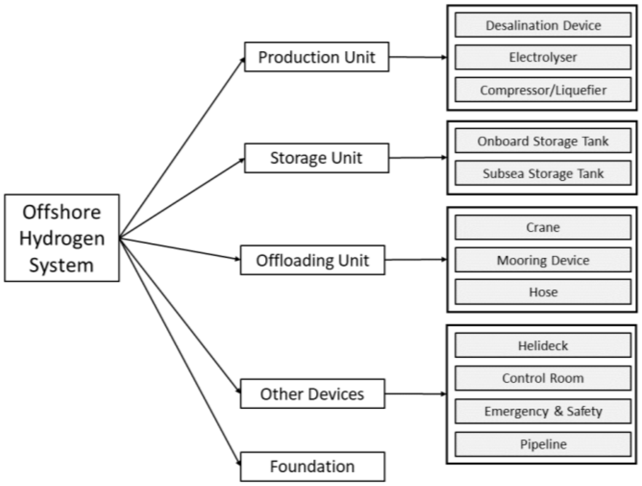
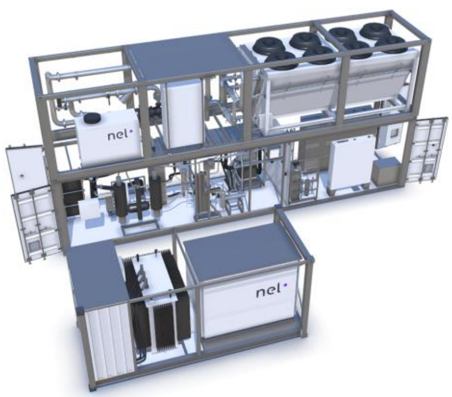


FIGURE 6: MODULARISED UNITS OF THE OFFSHORE HYDROGEN PLATFORM.

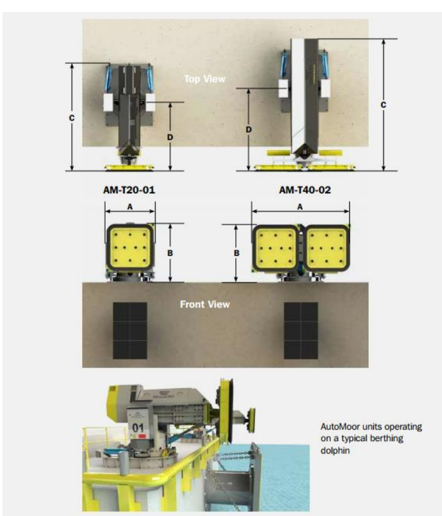
3.3 Devices on the platform

FIGURE 7 shows the devices of the three main functional units on the platform. Other additional devices are required to guarantee operation safety. A 12 m × 12 m helideck is designed at the top of the platform. A 5 m × 10 m control room is installed to monitor all devices and leave space for the crew. The control room can close and restart the devices remotely. Lifesaving equipment, such as emergency boats, is placed on each layer of the platform.

(a) Seawater desalination plant .

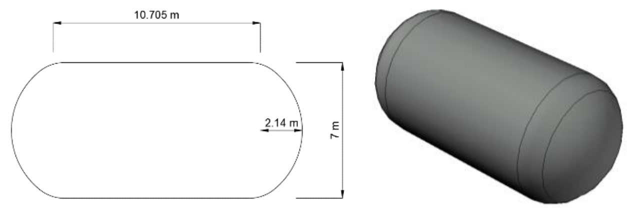


(b) Containerised PEM (Polymer Electrolyte Membrane) electrolysers for NEL hydrogen .



(c) Parameters of the AutoMoor device .

(d) Compressor plant .



(e) Compressed hydrogen storage tank.

FIGURE 7: DEVICES INSTALLED ONBOARD.

The parameters of the desalination unit, the electrolyser, the compressor, the storage tank and the auto-moor device are shown in TABLE 2 to TABLE 6.

TABLE 2 PARAMETERS OF THE SEAWATER DESALINATION PLANT .

IonPRO LX MKII Model			3-18	4-10	4-18
Nominal Flows	Feed	m^3/hr	1.1	1.5	1.5
@15℃ & 1 bar	Product Water	m^3/hr	0.75	1	1
Recovery		%			65-75
Dimension	Width	mm			800
	Depth	mm			1100
	Height	mm			1570
	Weight	kg	660	650	660

TABLE 3 PARAMETERS OF THE PEM ELECTROLYSER .

MC 500 PEM	
Net Production Rate	
Nm^3/h @ 0℃, 1 bar	492
Kg/h	1062
Production capacity dynamic range	10 – 100%
Average power consumption at stack	4.5 kWh/Nm^3
Purity	99.9995%
Delivery pressure	30 barg
Dimensions of process container	12.2m×2.5m×3m
Dimensions of rectifier container	12.2m×2.5m×3m
Ambient temperature	-20 to 40℃

TABLE 4 PARAMETERS OF THE HYDROGEN COMPRESSOR.

Z Type Diaphragm Air Compressor	
Piston travel	70 - 180 mm
Max piston force	10 - 90 kN
Max discharge pressure	70 MPa
Flow-rate range	0.5 - 500Nm^3/h
Motor power	2.2 - 45 kW

TABLE 5 PARAMETERS OF THE HYDROGEN STORAGE.

Tank shell	Carbon fibre composite T700
Tank liner	Polyethylene
Diameter of the tank	7 m
Length of the cylindrical part	10.7 m
Dome end extension	2.14 m
Thickness of the cylindrical part	145 mm
Thickness of dome ends	100 mm
Volume of one tank	477.33 m^3
Mass of one tank	71.12 t
Density of hydrogen@700bar	38.73 kg/m^3
Mass of hydrogen in one tank	18.48 t

TABLE 6 PARAMETERS OF THE AUTO-MOOR DEVICE.

Model	AM-T20-01	AM-T40-02
Quantity of pads	1	2
A (mm)	1780	3430
B (mm)	2400	2470
C (mm)	3845	4065
D (mm)	2450	2465
Quantity of anchor bolts	15	18
Shipping mass (kg)	8500	11000

4. CASE STUDY

4.1 Layout design of hydrogen platform

The weights and footprints of the units are calculated as listed in TABLE 7. The main contributor to the weight is the production unit. The footprint contribution of the production unit is two times that of the storage unit. Based on the parameters shown above, the area and weight for each one MW wind electricity can be estimated and the summation value of the area and weight can be calculated by multiplying the input capacity with reduction factor. The total area and weight is dependent on the input wind capacity. The platform can be easily upscaled with the proposed design approach.

TABLE 7 WEIGHTS AND FOOTPRINTS OF THE UNITS.

	Area per MW	Weight per MW
	m^2/MW	kg/MW
Production unit	28.40	36595.45
Storage unit	14.12	5056
Offloading unit	0.41	39

The design has two rounds to avoid unfeasible designs of the system as shown in TABLE 8. In the first round of design, the quantity of units is calculated when the electricity capacity is precisely 200 MW. The design in the second round slightly modifies the quantities of modularised units to the optimum whilst distributing the device on the deck. The deck area is 80 m × 80 m. The required electricity capacity of the second-round layout design of the floating systems is 202 MW, which is higher than the capacity of Salamander. TABLE 8 shows the quantities of the three units, weights and footprints in two rounds of layout design. The weight of the five largest oil and gas platforms ranges between 40, 000 tons to 200, 000 tons. The weight of offshore wind turbine tower of Scottish Hywind Project is only 670 tons. The weight of the necessary devices onboard has similarity to present offshore oil and gas platform. Moreover, the large required distributed area is much larger than the typical wind turbine supporting structure. Thus, the proposal design adopted the supporting structure of the oil and gas platform, Amirkabir, is reasonable. The devices are distributed on a 1-layer deck. The quantity of production units in the first round, 43, is estimated by the input power. Then, the power is updated to the accurate value, 197 MW which is generated by 42 sets of production units. The updated quantity of the production units, 42, is easier to distribute in a rectangle area than 43 units. The quantity of offloading units in the first round of design is underestimated. Regarding the standard setup of automatic mooring devices, the quantity is revised to 12.

FIGURE 8 shows the layout of the offshore floating hydrogen platform which matches with 200-MW wind farm. The devices are equipped onboard. A residual section is left for the future retrofitting. Additional devices not mentioned in the paper can be installed in the residual area. And the weight of residual is considered in the following simulation.

FIGURE 9 shows the geometry modelling of the newly designed platform. The devices are estimated as equivalent distributed loads on the deck as the same size of actual devices in the same specific area. Compartments of the pontoons and columns are divided to fill water ballast. The balance of weight and buoyancy is tuned by the water ballast.

TABLE 8 QUANTITIES OF THE MODULARISED UNITS.

Design	Unit	1st round	2nd round
Input power	MW	200	202
Production unit	-	43	43
Storage unit	-	18	18
Offloading unit	-	6	12
Control room	-	1	1
Helideck	-	1	1
Area	m^2	4297.5	4450.9
Weight	t	4292.2	4072.0

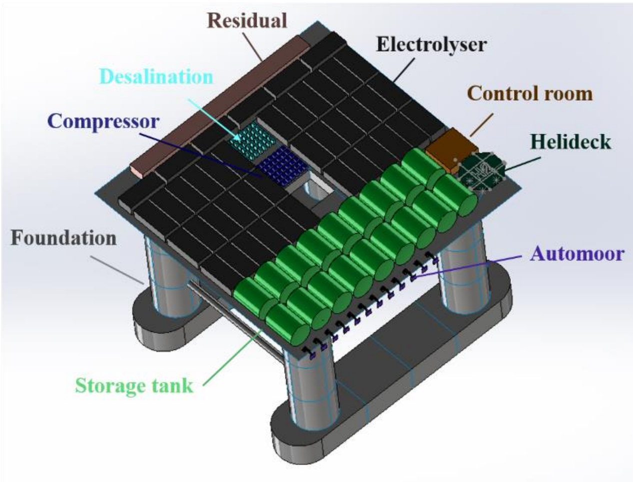


FIGURE 8: LAYOUT OF THE OFFSHORE FLOATING HYDROGEN PLATFORM.

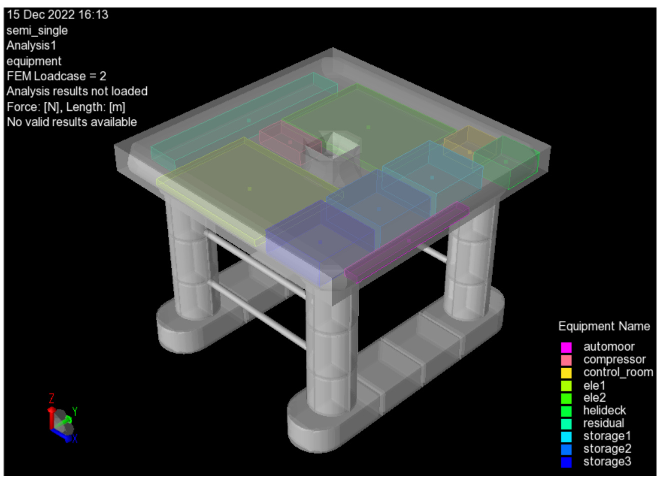


FIGURE 9: GEOMETRY OF THE OFFSHORE FLOATING HYDROGEN PLATFORM.

4.2 Stability analysis

The stability analysis of the floating platform is simulated by the stability module of commercial software, DNV-GL HydroD. TABLE 9 shows the initial stability of the platform. The buoyancy and the total mass are balanced by the design of compartment ballast. The distribution of water ballast in compartments is shown in FIGURE 10. The compartments of pontoons are fully filled with water which provides most of the weight. The columns are filled partially which balance the moments induced by the distributed onboard devices. The difference of weight and buoyancy is 1 kg. The size of the platform is 80 m * 80 m, which leaves sufficient residual footprint. The dry mass is the summation of steel structure of floating supporting structure and devices. The metacentric height is 8.12 m. Stability simulation is shown in FIGURE 11.

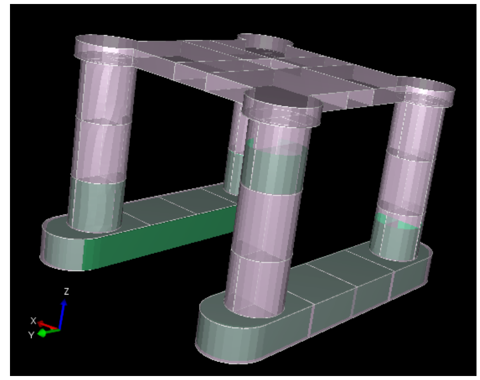
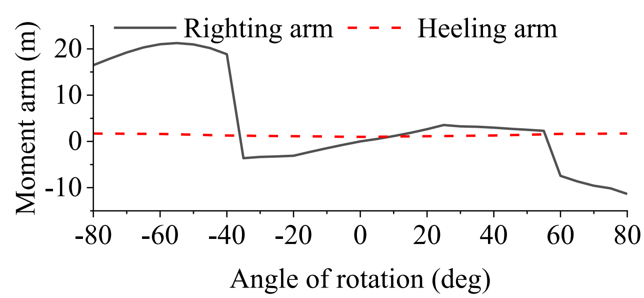


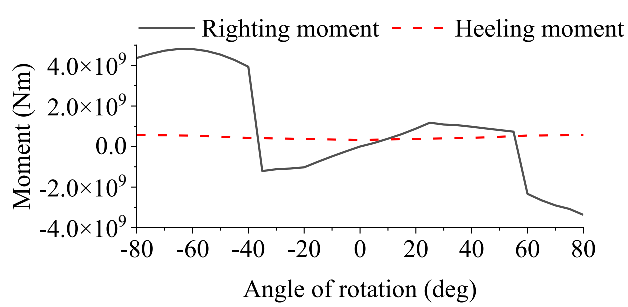
FIGURE 10: WATER BALLAST DISTRIBUTION OF THE SEMI-SUBMERSIBLE SUPPORTING STRUCTURE.

TABLE 9 INITIAL STABILITY OF THE PLATFORM.

Parameter	Unit	Value
Total mass	kg	39,496,079
Center of gravity	m	(0, 0, -23.1)
Displacement	kg	39,496,080
Center of buoyancy	m	(0, 0, -23.8)
Deck size	m*m	80*80
Draft	m	35
Dry mass	kg	8,693,781
Center of gravity (dry mass)	m	(0, 0, -1.51)
Waterline area	m^2	523.5
Metacentric height	m	8.12



(a) Righting arm.



(b) Righting moment.

FIGURE 11: STABILITY ANALYSIS OF THE PLATFORM.

TABLE 10 WATERLINE DAMAGE EXTENT ASSUMPTIONS FOR SEMI-SUBMERSIABLES.

Damage Extent	Unit	Value
Penetration	m	1.5
Vertical height	m	3
Damaged width	m	3
Damage zone	m	-1.5 – 1.5

The stability of floating offshore structures is guided by . The compliance to NMA (Norwegian Maritime Authority) hydrostatic rule is checked for both the intact case and damaged case. The damaged case is defined as illustrated in . TABLE 10 describe the damage extent for semi-submersibles. The damaged tank properties are shown in TABLE 11.

TABLE 11 DAMAGED TANK PROPERTIES.

	Filling fraction	Mass	COG
Intact	0.00%	0	-
Damaged	50.83%	21.37	(-23.4, -23.4, -0.8)

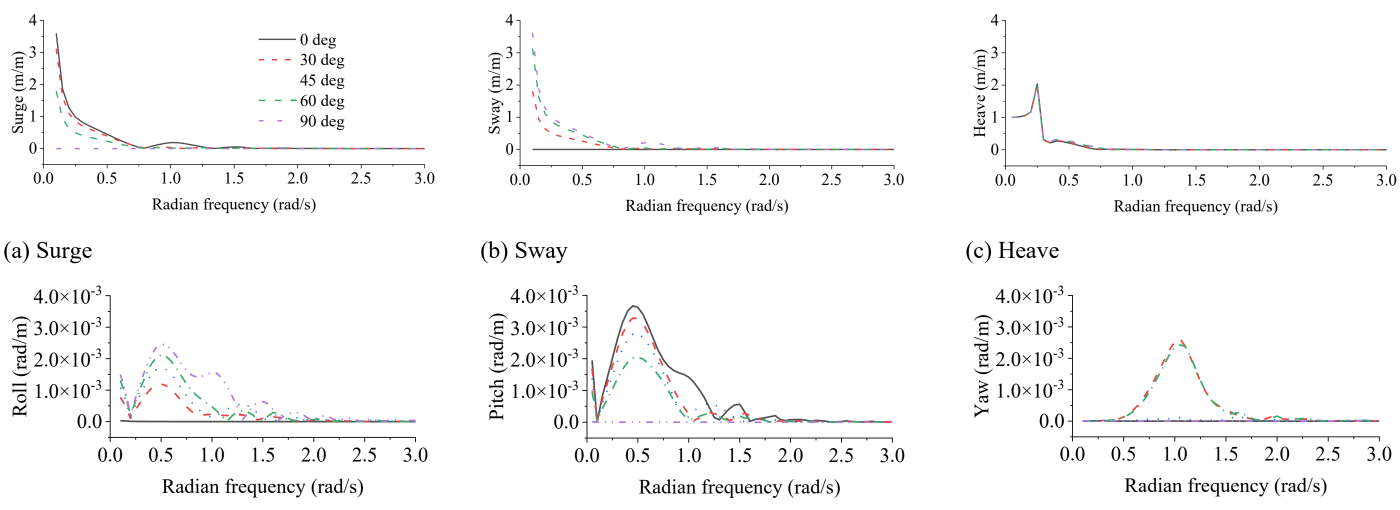
The five NMA intact stability criteria and eight NMA damaged stability criteria are met for the intact and damaged cases, respectively, as shown in TABLE 12 and TABLE 13.

TABLE 12 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

TABLE 13 RULE CHECK OF THE DAMAGED STABILITY ANALYSIS.

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



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

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

FIGURE 12: RESPONSE RAOS OF THE PLATFORM MOTIONS IN FREQUENCY DOMAIN.

4.3 Hydrodynamic analysis

The hydrodynamic analysis of the floating platform in frequency domain is simulated by the hydrodynamic module of DNV-GL HydroD. The numerical model is the same as that of stability analysis. Wave directions from 0° to 90° are considered because of the symmetry of the platform structure in the x-axis and y-axis. Cases of 0°, 30°, 45°, 60° and 90° wave directions are calculated. FIGURE 12 shows the 6-DoF hydrodynamic responses under wave loads in frequency domain. The response amplitude operators (RAOs) of surge motion and sway motion are of large values, which indicates large motions in these two directions. However, the corresponding wave frequencies of the peak values of the motion responses are significantly low. The wave components of such low frequencies are rare in the actual sea state. Regarding the curves of translational motion responses, there are large wave drift motions. The large motions are safety risks for the offloading operations between offshore platform and transportation ship. A mooring system is required for the floating platform to reduce the motions. The rotational motion is small because of the heavy weight of the floating platform. Therefore, the hydrodynamic loads are not the dominant factor.

5. CONCLUSION

The study illustrates the status and perspective of offshore green hydrogen systems and offshore wind farms. A 200-MW wind farm as the wind electricity supply and the OGHS is located near the wind farm. A centralised floating hydrogen system is first proposed in the study. The components of the hydrogen system are divided into three modules, production, storage and offloading. The device layout is modularised which makes the system flexible to scale up based on offshore wind capacity. The floating supporting structure is chosen considering the water depth and deck devices of the platform. The layout of the platform is designed, and stability analysis is simulated. The design passed stability checks of NMA rules for intact and damaged cases. A mooring system is required because of the significant translational motions in low frequency ranges. Hydrodynamic analysis of the hydrogen system with mooring lines will be studied in the next stage. Both frequency domain and time domain analysis will be implemented.

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