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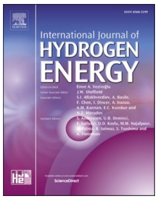

Design considerations and preliminary hydrodynamic analysis of an offshore decentralised floating wind-hydrogen system

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ABSTRACT

Despite the number of works on the techno-economics of offshore green hydrogen production, there is a lack of research on the design of floating platforms to concomitantly support hydrogen production facilities and wind power generation equipment. Indeed, previous studies on offshore decentralised configuration for hydrogen production, implicitly assume that a floating platform designed for wind power generation (FOWT) can be also suitable as a floating wind hydrogen system (FWHS). This work proposes a novel design for an offshore decentralised FWHS, and analyses the effects of the integration of the hydrogen facilities on the platform's dynamics and how this in turn affects the performances of the wind turbine and the hydrogen equipment. Our findings indicate that despite the reduction in platform's stability, the performance of the wind turbine is barely affected. Regarding the hydrogen system, our results aim at contributing to further assessment and design of this equipment for offshore conditions.

1. Introduction

The world commitment for the achievement of net zero carbon emissions goal by 2050, has allowed the rapid development and maturation of technologies to harness the vast potential of marine renewable energy resources. Currently, offshore wind turbines are the most mature and promising in terms of expected deployments in the short term. Indeed, the potential wind resource located offshore globally is estimated in at least 3.1 TW and deployment is expected to increase from around 25 GW–190 GW by 2050. Since 80% of this potential is in water depths greater than 60 m, where fixed bottom turbines are unpractical or uneconomical to install, floating support platforms are required. Although more onerous, floating offshore wind turbines can achieve greater capacity factors by accessing higher and more consistent wind speed patterns, especially in remote regions. However, as wind energy deployment areas move farther offshore, connection to the grid is usually not available using electrical cables as a means of energy transportation and become economically disadvantageous [1–3]. Onboard transformation of wind energy into an alternative energy carrier such as hydrogen can be a route to untap the vast far offshore wind energy potential. The integration of ocean renewable energy and hydrogen production is not a novel concept, with pioneer works being reported in Refs. [4–9] where, besides offshore wind energy, other sources of ocean renewable energy have been proposed such as ocean thermal gradient and wave energy. Only in recent years with the demand for energy transition to clean fuels, the integration renewable energy – hydrogen has captured increased attention. Most of these recent works are focused on the techno-economics aspects of hydrogen production from offshore wind energy as in Refs. [10–21] or on the selection of the electrolysis technology [22,23] or the transportation options to the market [1,14,24,25]. The Authors have performed a comprehensive and detailed review on the main concepts developed for offshore hydrogen production from marine renewable energy in Ref. [26]. Also, an extensive discussion on the main challenges in the design of those systems can be found in Ref. [27].

The integration of hydrogen production with offshore wind can take place in either of the following three configurations: onshore hydrogen production, offshore centralised production and offshore decentralised production [16,17,21]. For onshore hydrogen production, electrical cable transmission is required to transport the (offshore wind energy) electricity to the shore to then produce hydrogen in an in-land facility. This configuration may not be ideal for far offshore sites (e.g., distances

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greater than 100 km from shore) due to high electrical transmission costs and losses [1–3]. For offshore hydrogen production, the centralised configuration consists of a set of floating offshore wind turbines that only produce electricity and then transmit this energy to a nearby (floating) platform dedicated only to hydrogen production, to then export it to the market (via pipelines or ships). Examples of concepts under this type of configuration can be found in Refs. [20,28,29] and also in the 1-MW SeaLhyfe demonstrator [30]. On the other hand, the offshore decentralised configuration consists of set of floating offshore wind turbines platforms that have been adapted or designed to produce, besides the electricity from wind energy, hydrogen onboard. Examples of this configuration include the 2-MW and the 10-MW ERM Dolphyn [31] concepts or the 1-MW NereHyd [32] project.

There is still no consensus on which hydrogen production configuration is the best, although several techno-economics assessment have been performed exploring considering several scenarios, including hydrogen compression, liquefaction, storage, transportation, or even the transformation to other energy vectors such as ammonia or methanol [24,25]. A few studies claim that in terms of levelized cost of hydrogen (LCoH) a decentralised system, especially for far offshore and deep water developments, is a better option for the coming years [17,21], but several variables including geopolitics, market prices and governmental policies can significantly affect this scenario. As evidenced in our literature reviews [26,27], the techno-economics aspects of (floating) offshore hydrogen production has been extensively explored, but based on high level assumptions, especially in terms of technical aspects of the design and performance of the floating platform, where the common premise is that no major changes are expected – compared to a dedicated electricity generation offshore floating wind turbine (FOWT) platform.

The design of a FOWT is still an engineering challenge that currently demands significant research efforts to, for instance, design an optimum configuration [33]. The engineering complexity is associated to the coupled aero-hydro-elastic-servo dynamic behaviour of the FOWT subject to the stochastic character of the offshore ocean environment. As FOWT designs mature and new units are deployed, a few specific criteria have been developed to assess the performance of the floating structure under operational and survival modes [34,35]. For floating platforms dedicated to offshore hydrogen production from wind energy, hereafter referred as Floating Wind Hydrogen Systems (FWHS), no reference designs and no performance criteria exist, at least, for the offshore ***decentralised*** configuration. Indeed, only very recently, the first conceptual design of an offshore hydrogen platform for offshore ***centralised*** configuration has been published in Ref. [29]. While the main challenges in the centralised configuration are mostly related to the (large feasible) size of the floating facility, for the decentralised configuration the challenges seem greater. First, the hydrogen production equipment should be integrated within the limited existing space on the FOWT platform and, second, the performance criteria for both wind turbine and hydrogen equipment should be concurrently satisfied.

In that context, the aim of the present work is to perform a preliminary design of a FWHS for the decentralised configuration and address those challenges. The IEA 15-MW reference UMaine's FOWT semisubmersible platform [36] is used as a starting point for our design. The components and the main characteristics of a suitable hydrogen production facilities have been selected based on technologies available in the market, and then integrated to the reference UMaine's FOWT. Changes in mass distribution associated to the integration of the hydrogen facilities and their effects on equilibrium, floating stability and dynamics responses of the new floating platform (FWHS) have been investigated. The effect of the dynamics under wind and waves have been also analysed in terms of performance of the wind turbine, i.e., the generated wind power and nacelle accelerations. All those effects have been assessed by comparison with the performance indicators of the original FOWT. State-of-the-art numerical simulation tools have aided in the design of the decentralised offshore FWHS and allowed to obtain motion dynamics at (*ad hoc*) representative critical locations of the hydrogen production equipment, such as at electrolysers and hydrogen export pipe connection points. The latter results are expected to contribute to the assessment, test, adaptation or design of hydrogen production equipment for offshore ocean conditions – that will potentially lead to the development of operational limits and criteria, that, in turn, will drive the future designs of floating platforms for FWHS.

2. Materials and methods

2.1. Design premises

The design a floating platform dedicated to electricity generation from offshore wind energy (FOWT) is typically driven by the choice of the wind turbine generator and its performance under operational and survival conditions [33]. On the other hand, for a floating platform designed concomitantly for electricity generation and hydrogen production, i.e., a FWHS, additional requirements to the ones already in place for a FOWT need to be satisfied. In Ref. [27], the Authors have discussed in detail the challenges and design requirements for those floating platforms such as the availability of enough internal space to accommodate hydrogen production facilities, operational constraints for the electrolysis system and auxiliary equipment, or constraints related to the dynamics of the hydrogen risers and pipelines. Based on the findings of that work, the Authors have further advanced on research of FWHS and performed a multicriteria decision making (MCDM) analysis to assess different energy harvesting devices and their support floating platforms for an offshore decentralised energy hydrogen system. Barge and semisubmersible floating types have been identified resulted as the most suitable alternatives, with a preference for semisubmersibles due to its highest technological readiness level (TRL) and the number of FOWTs of this type already deployed at sea [26].

The present study aims at advancing on this research area by proposing a preliminary design of a FWHS for offshore decentralised configuration. Since the premise of that design configuration is to integrate hydrogen production facilities on an existing FOWT floating platform, the UMaine VolturnUS-S Reference platform for the IEA Wind 15-MW Offshore reference wind turbine [36] has been selected for the present study. This FOWT was chosen as starting point for the design of the FWHS due to its large wind turbine power rating and the availability of technical data. On the other hand, due to its vast offshore wind energy potential and the ambitious projects towards hydrogen production, the Scotland's lease site NE8 has been chosen as deployment site for the proposed FWHS design. The environmental characteristics of this site will be used to assess the performance of the FWHS under representative stochastic wind and waves.

Notice that despite the *ad hoc* choices in terms of type of semisubmersible or site location, the design process proposed here can be adapted to any FOWT semisubmersible intended for hydrogen production under decentralised configuration.

2.2. Offshore decentralised FWHS components

The offshore decentralised FWHS is envisaged as consisting of the Rotor-Nacelle Assembly (RNA), the tower, the hydrogen production equipment, the floating platform (also regarded as substructure or foundation), the station keeping system (mooring lines) and the hydrogen export line (riser), Fig. 1. In the following subsections, the main components of the FWHS are briefly described and discussed regarding their effects on the hydrodynamic and power performance of the whole system.

2.2.1. RNA

The RNA is exposed to aerodynamics loads that are induced by the incident wind, the elastic behaviour of the blades, the motions induced by the floating support platform, and the action of the controller of the wind turbine. Since the integration of hydrogen production facilities on

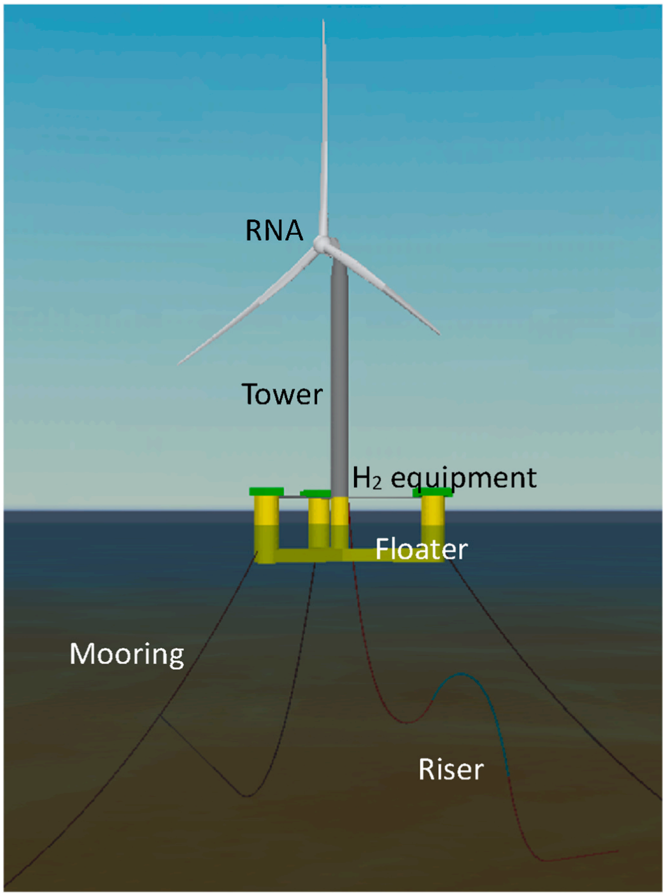

Fig. 1. Decentralised FWHS.

the floater changes the mass distribution of the reference condition, the motions of the support platform will be affected, thus, the performance of the wind turbine in terms of wind-induced loads and power production. For the present study, the IEA 15-MW offshore reference wind turbine and its ROSCO controller described in Ref. [37] are adopted, assuming that the set-up of the FOWT is kept the same.

2.2.2. Tower

The tower is exposed to aerodynamic loads from the incident wind and its structural response associated to the RNA loads on the tower top and the motions and inertial characteristics of the floating foundation on the tower base. With the integration of hydrogen facilities, the dynamics of the substructure is altered compared to the reference FOWT, thus, the structural responses of the tower are also expected to change, and with that, the induced motions on tower top, affecting the wind turbine induced loads and performance. The tower dimensions and properties originally described in Ref. [36] and the latest updates for the FOWT have been adopted for the FWHS.

2.2.3. Hydrogen production facilities

The term hydrogen production facilities will be used here to refer to all the structures and equipment necessary to install and produce hydrogen onboard, i.e., all the facilities that are not found in typical floating offshore wind turbine. Since hydrogen production systems for offshore conditions are not a mature technology, yet, i.e., are currently being tested/adapted to ensure compatibility with variable (wind) energy input and the harsh marine conditions, the layout and components considered for this study are based on the present understanding of the technology, as described in Refs. [31,38–40]. The facilities can be grouped in:

- Topside structure: additional structures on top of the platform to support the hydrogen production equipment and auxiliary systems;
- Topside equipment, consisting of:
  - o Seawater lift system (supplies seawater for water treatment and cooling systems)
  - o Water treatment system (supplies purified water to electrolysis system)
  - o Power distribution system (from wind turbine generator to electrolysis system)
  - o Electrolysis system, including its balance of stack (produces hydrogen)
  - o Back-up power system (supplies energy to critical systems during low/no wind conditions)
  - o Other auxiliary systems (chemical injection, drain, venting, etc.)

For the decentralised FWHS, proton exchange membrane (PEM) electrolyser is regarded as a better solution than alkaline electrolysers due to its compactness and faster dynamic response [40]. For this system, modular containerised units are available [41] and are the preferred solutions in some recent studies [29,31].

Assuming that the offshore FWHS is designed for off-grid operation, the wind turbine generator (WTG) should be able to power all the onboard systems, including not only the electrolysis system, but all the auxiliary and back-up power equipment – besides the inherent losses and efficiencies. Thus, a power reduction factor should be applied to obtain the nominal capacity for the electrolysis system. In Ref. [28], a power reduction factor of 0.83 is reported for a PEM electrolysis system powered by offshore wind turbines of 6.33 MW. The integration of hydrogen facilities introduces additional requirements and constraints associated to the performance of the components of the electrolysis system and the auxiliary equipment. Also, the mass distribution of the reference condition is changed, thus it is expected that the dynamic response of the floating foundation would be affected. In terms of loads, since the hydrogen facilities are located on the topside of the floating substructure, they are expected to be exposed mostly to wind loads. However, since the FWHS has deck equipment the occurrence of green water (eventual sea water washing the deck of the platform) and slamming (impact of waves) loads should be also assessed as part of later design criteria compliance.

2.2.4. Floating platform

The floating foundation should provide the necessary buoyancy and stability for the whole system and withstand the environmental (wind, waves and currents) loads under operational and survival conditions. For an offshore FWHS, the floating platform must satisfy criteria related to operational requirements of the hydrogen production equipment, besides those associated to the wind turbine performance.

The main dimensions of the substructure and estimates of the inertial properties (including solid and sea water ballast) reported in Ref. [36] will be used as basis for the present study. Due to the integration of the hydrogen production facilities, the draught, position of the centre of gravity and inertias of the original (reference) platform should be recomputed and updated. However, to keep the same airgap and hub height (relative to the calm sea water level) of the reference condition, the sea water ballast of the reference platform should be redesigned to compensate for the increase of mass, while trying to keep the centre of gravity as low as possible to ensure adequate stability.

2.2.5. Mooring system

As for a typical floating offshore wind turbine, a station keeping system should be adopted to limit the excursions of the platform and avoid damages to the hydrogen export riser/pipeline. The loads on the mooring system are governed by waves and currents, the motions imposed by the floating substructure in the line fairleads, and the stiffness characteristics of the mooring line material. To keep it simple, the same three-leg mooring system reported for the reference platform [36] will be used here.

2.2.6. Hydrogen export

Hydrogen will be exported to shore via pipeline composed by flexible riser attached to the floating substructure and connected to a rigid pipeline that then links to a nearshore tie-in-point. It is envisaged that the flexible riser shall use a lazy S configuration, like the currently adopted for electrical power export cable. Similar to the mooring system, the riser is exposed to waves and currents loads and the motions induced by the floating platform, but also to the internal hydrogen pressure. Riser integrity (for instance, in terms of minimum bending radius) is a crucial aspect and a key interface constraint with mooring system design, therefore riser flexibility and fatigue life should be carefully assessed. Since this verification is out of scope in preliminary design, it will not be performed here, however, the platform-induced excursions at the top connection points of the export pipe will be addressed.

2.3. Design methodology

Since there are still no design methodologies for FWHS, the global design methodology for FOWTs proposed in Ref. [33] will be adopted as starting point, together with the considerations outlined in previous subsections that impose additional requirements and constraints for the design of the offshore decentralised FWHS. As a result, the design of the FWHS for offshore decentralised configuration is highly constrained compared to the design of a typical FOWT. As a matter of fact, the design phase 1 [33,42] which involves the choice of the floater concept, the semisubmersible type (and its main dimensions) and the wind turbine properties are already predefined by the design premises. The next step on the design involves the definition of the hydrogen production facilities and main components, whose selection was based on the recommendations provided in the reports of the ERM Dolphyn project [31] and HyFloat project [43]. Once the main characteristics, dimensions and weights of the FWHS components are defined, their positions have been defined based on principles of naval architecture [44] and process engineering basic criteria regarding risk and compatibility of components [45]. The stability of the floating system has been investigated using the HydroD package [46] of DNV's Sesam suite. Then, the hydrodynamic characteristics of the system have been investigated by computing the response amplitude operators (RAOs), and then, using the representative sea spectra of the NE8 site, the significant responses in representative operational and survival conditions have been estimated, using Wadam [47] and PostResp [48] Sesam's packages. For the computation of the nonlinear dynamics and the generated wind power, OrcaFlex [49], which is a state-of-the-art numerical tool that simulates the time-domain aero-hydro-elastic servo dynamics responses of offshore structures, has been used.

Since, so far, there are no specific criteria for FWHS, the (few) existing performance criteria for FOWTs [34,35] is adopted for our preliminary assessment.

3. Results and discussion

3.1. General layout of the floating platform

Considering a 15-MW wind turbine capacity and the power reduction factor suggested in Ref. [28], an electrolysis system of 12.5 MW is envisaged. A single plant with such capacity can be found in the industrial market, but due to the inherent variable (wind) energy input, several smaller capacity units are preferred to maximise the electrolysers' operational windows. It should be noticed that the minimum load required for PEM electrolysers to operate is ~5% of their nominal capacity. Another constraint in the selection of the electrolysis units is the available deck area on the platform and the off-the-shelf modularised electrolysis units available in the market. As shown in Fig. 2, these units come as a stand-alone pair of containers: one for the chemical process equipment (green boxes) and the other for the input power conditioning, i.e., transformer & rectifier (orange boxes). To avoid formation of an explosive atmosphere inside the floating platform, the electrolysis units are placed on the top of the columns and separated from their main decks by a topside structure (grey boxes), thus providing blast isolation and green water & slamming protection. Two sets of 2.2 MW electrolysis systems are installed on top of columns 2 and 3, while on top of column 1, one set of 2.2 MW and one of 1.1 MW are installed. This smaller capacity set is aimed at ensuring minimum operation of the FWHS under low (wind) power conditions.

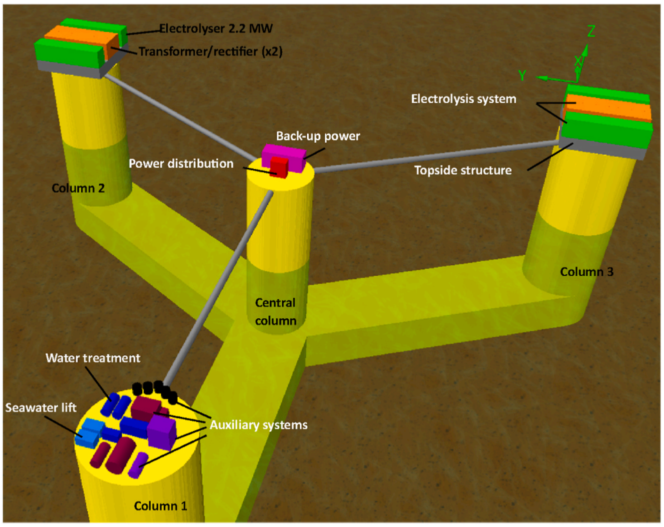

Fig. 2. Major components of the hydrogen production facilities. Tower, topside and electrolysis system on column 1 are hidden to facilitate the visualization of the balance of plant.

The other main components of the hydrogen production equipment (balance of plant) were selected based on the total electrolysis capacity, and were associated based on compatibility, ease of access, and weight distribution criteria. For instance, the bulk of power generation and its management & control (including back-up equipment) were installed inside the tower, while the water treatment, chemical and auxiliary

Table 1
Main characteristics of the electrolysis system for a 15-MW FWHS.

Component characteristics	unit	value
Wind capacity	MW	15.0
Electrolysis system capacity	MW	12.5
Electrolyser units (Nel MC500)		
H_2 Net volume rate	Nm^3/h	492.0
H_2 Net mass rate	kg/h	44.2
Power consumption	MW	2.2
Number of units	–	5
Water consumption	m^3/h	0.4
Process container - W x D x H	m	12.2 x 2.5 x 3.0
Weight process container	t	18.6
Power container - W x D x H	m	12.2 x 2.5 x 3.0
Weight power container	t	24.0
Delivery pressure	barg	30.0
Electrolyser units (Nel MC250)		
H_2 Net volume rate	Nm^3/h	246.0
H_2 Net mass rate	kg/h	22.1
Power consumption	MW	1.1
Number of units	–	1
Water consumption	m^3/h	0.2
Process container - W x D x H	m	12.2 x 2.5 x 3.0
Weight process container	t	17.3
Power container - W x D x H	m	6.1 x 2.5 x 2.6
Weight power container	t	18.0
Delivery pressure	barg	30.0

systems are installed centralised, within column 1' s topside.

Table 1 shows the main characteristics of the electrolysis system units adopted for the 15-MW wind turbine, and Table 2 summarises the whole hydrogen production facilities associated to the 12.5 MW electrolysis system. The values are just referential and representative of the main component of each system.

3.2. Hydrodynamic performance assessment

3.2.1. Equilibrium and compartmentation

As for a typical FOWT the first step in the hydrodynamic design of the floating system is the verification of its equilibrium condition. Thus, the weight and distribution of all the components of the floating system should be estimated/computed. In Ref. [36] some indications are provided for the (solid and sea water) ballast distribution for the reference FOWT. Based on those clues, first, a compartmentation layout for the UMaine semisubmersible was designed for the FOWT reference configuration and then, a re-arrangement of ballast was proposed for the FWHS to guarantee equilibrium at the same initial heel/trim conditions of the reference FOWT. Table 3 summarises the main inertial characteristics of the FWHS along with the corresponding values of reference 15-MW FOWT. The reference frame for the coordinates of the centre of gravity of the floating system are the tower centre (TC) and the still water level (SWL), while the inertias refer to the centre of mass. Since, by premise, the FWHS should keep the same draught and trim/heel of the FOWT, the first choice was to remove a seawater ballast amount equivalent to the mass of the hydrogen facilities (~765 t) trying to avoid significant trim/heel imbalance of the floating platform. The final ballast arrangement is presented in Fig. 3. Compared to the FOWT, the integration of the hydrogen facility on the FWHS has barely affected the inertial characteristics (hydrogen facilities represent less than 4% of the total displacement of the platform), except for the significant raise in the vertical position of the centre of gravity (VCG) of the platform, which can adversely affect the static stability characteristics, and the pitch and roll natural periods of the FWHS.

3.2.2. Floating stability

Since the decentralised FWHS is envisaged for uncrewed operation, according to IEC 61400-3-2 [35], damage stability analysis may not be required. Thus, the righting moment stability (RM) characteristics of the platform subjected to the overturning moment (OTM) produced by wind loads on the FWHS should be checked against the criteria in the applicable parts of the IMO intact stability code [50] or in equivalent specialised standards such as DNV-ST-0119 [34]. A quasi-static approach has been adopted to assess the intact stability of the FWHS. Fig. 4 displays the static stability curves of the reference FOWT and the FWHS for azimuths 0°, 30° and 90°, where azimuth 0° (A0) refers to inclinations around the x-axis of the floating platform (Fig. 3), and azimuth 90° (A90) refers to inclinations around the y-axis.

Table 3
Comparison of inertial properties of the FWHS and the FOWT.

Characteristics	units	FOWT	FWHS	diff
Platform mass	[t]	4014.0	4014.0	–
RNA mass	[t]	950.1	950.1	–
Tower mass	[t]	1483.1	1483.1	–
H2 facilities mass	[t]	–	765.6	–
Solid ballast mass	[t]	2540.0	2526.3	−0.5%
Seawater ballast mass	[t]	11071.0	10319.0	−6.8%
Total mass	[t]	20058.1	20058.1	–
LCG	[m-TC]	−0.34	−0.34	–
TCG	[m-TC]	0.00	0.00	–
VCG	[m-SWL]	−1.88	−0.52	72.3%
Roll inertia	[t.m^2]	4.45E+07	4.55E+07	2.1%
Pitch inertia	[t.m^2]	4.46E+07	4.55E+07	2.1%
Yaw inertia	[t.m^2]	2.61E+07	2.79E+07	7.2%

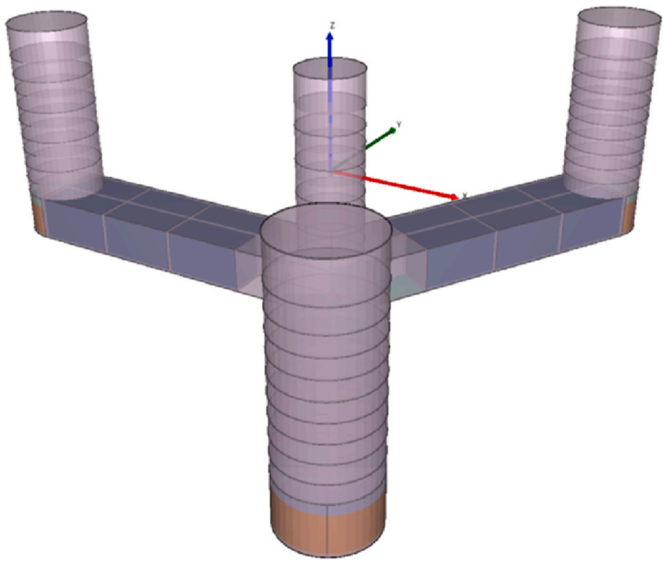

Fig. 3. Proposed compartmentation and contents (orange is solid ballast; blue is sea water ballast) for the FWHS. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Besides the strong variations of the stability with azimuth, the detrimental effect of the raise of the platform's VCG is evident, especially in terms of vanishing stability angles and maximum restoring moments. According to DNV-ST-0119, the criterion for quasi-static evaluation is based on a safety factor (γ_{stab}), defined as the area available for restoring (righting) and the area resulting from excitation (heeling), which should be ≥ 1.3. The main stability characteristics for the reference FOWT and the FWHS are summarised in Table 4. The outcome of the stability evaluation is that despite reasonably fulfilling the DNV criterion for the inclinations around y-axis (Azimuth 90°), for the other azimuths, the static stability may be deemed inadequate (even for the reference FOWT). However, it should be reminded that the quasi-static approach is more conservative compared to time-domain dynamic

Table 2
Main components of the hydrogen production facilities for a 15-MW FWHS.

Hydrogen Facilities	Main components	# units	Capacity per unit	Location	Footprint L x D x H	Weight [t]	Power [MW]
Topside structure	Stools, stiffeners, deck plates	3	148 m^2	main deck	12.2 x 12.2 x 2.0	155.0	–
Topside equipment							
Seawater lift system	Pumps, filter, strainer	2	416 m^3/h	topside 1	2.0 x 1.2 x 1.0	0.3	0.167
Water treatment system	Desalination, deionisation, storage	1	3.55 m^3/h	topside 1	1.8 x 0.8 x 1.0	1.0	0.084
Power distribution system	MV/LV transformer, LV transformer	1	1500 kVA	tower	2.4 x 1.5 x 2.5	3.9	–
Electrolysis system	Electrolyser stacks & balance	5 + 1	492 Nm^3/h	topsides 1 - 3	12.2 x 2.5 x 3.0	42.6	2.200
Back-up power system	Black start battery	1	2 MWh	tower	6.1 x 2.4 x 2.6	28.0	–
Other auxiliary systems	Instrument air, control & safety	1	760 Nm^3/h	topside 1	2.3 x 1.8 x 2.7	2.3	0.110

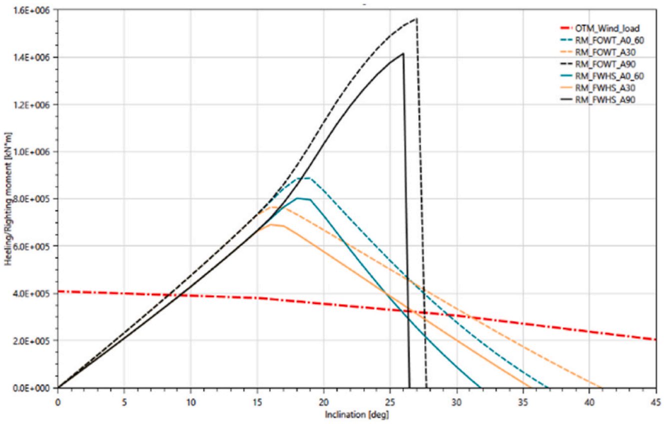

Fig. 4. Static stability curves for operational condition @ rated wind speed: FOWT vs FWHS.

simulations. Indeed, DNV-ST-0119 states that stability requirements are difficult to fulfil for the most critical load cases, for which time-domain analysis are recommended. Thus, instead of considering, at this stage, changes in the platform design or its mass distribution, which are out of the scope of the present work, the dynamics of the platform under wind and waves will be first verified.

3.2.3. *Wave-induced dynamics: frequency domain*

A key aspect in the assessment of the dynamics of the FWHS is to characterize the natural periods of the systems to identify potential resonances that may lead to excessive motions of the support substructure or preclude the operation of H_2 production equipment. A frequency-domain linear approach is adopted for the computation of hydrodynamic coefficients, wave-induced loads, and motions at critical points on the FWHS, such as at the locations of the electrolyser containers on columns 1 and 2 (or 3), at the hub of the RNA, and at the top connection of the H_2 pipe with the floating platform (see Table 5). The points chosen for the electrolysers correspond to the top, most outside (aft or forward) port corners of each, while for the pipe connection the point selected was located forward, port side of the central column. For the sake of simplicity and comparison with the FOWT results, the mooring system design of the reference FOWT has been adopted for the FWHS, i.e., a water depth of 200 m was assumed. Based on the characteristics of that mooring system, a linearized moored restoring matrix has been computed and used for the frequency domain calculations.

The obtained natural periods of the FWHS and the reference FOWT are shown in Table 6. The differences are negligible, except for roll, pitch and yaw, with an increase of ~1.5 s in the natural periods, reflecting the increase in VCG and inertias in the FWHS. Since these periods have moved further from the typical energetic periods of the sea, in principle, this effect could be beneficial for the wave-induced dynamics. Indeed, the Response Amplitude Operators (RAOs) of the associated platform motions show a shift of the peak towards higher periods and eventually a reduction of the amplitudes. For instance, Figs. 5 and 6 show the RAOs of pitch motion of the platform and the longitudinal acceleration at the RNA for their most critical wave incidence. Based on these RAOs, it could be preliminary stated that the influence of the integration of the H_2 facilities on the performance of the wind turbine is negligible, at least, for typical offshore wave periods (~5–20 s).

Still based on the frequency-domain approach, wave induced motions of the platform at selected locations of the electrolysers and the connection of H_2 pipe have been computed and expressed in terms of RAOs. Figs. 7 and 8 show the velocity components “felt” by the electrolysers while Fig. 9 shows the displacements in x, y, z directions experienced by the H_2 pipe upper connection to the platform. These results can be taken as indicative values to assess the feasibility of the operation or performance of the electrolysis equipment under wave-induced dynamic conditions. So far, to the best knowledge of the Authors, there is neither criteria to judge H_2 production equipment performance for floating offshore conditions nor design motion requirements for the support platform.

RAOs are typically the best way to characterize the inherent dynamics of a floating structure exposed to regular wave excitation. However, a more realistic assessment of the dynamics of the FWHS can only be obtained after applying actual (irregular) sea states. Thus, the metocean conditions of ScotWind Leasing site NE8 have been assumed to define the three representative design loading cases (DLCs) shown in Table 7. The environmental data was obtained from the ERA 5 reanalysis database [51] and the DLCs were selected from IEC 61400-3-2 [35]. For

Table 5
Locations of critical points for the FWHS.

Critical locations	x [m-TC]	y [m-TC]	z [m-SWL]
RNA hub	−13.64	0.00	150.17
Electrolyser col. 1	−58.00	12.50	21.00
Electrolyser col. 2	32.13	51.07	21.00
H_2 pipe connection	6.00	6.00	15.00

Table 6
Comparison of natural periods: FWHS vs FOWT.

Mode	Surge	Sway	Heave	Roll	Pitch	Yaw
FOWT	88.2	166.1	19.7	26.9	26.3	57.4
FWHS	88.2	166.4	19.7	28.4	27.8	58.7
diff	0.0%	0.1%	0.0%	5.7%	5.6%	2.3%

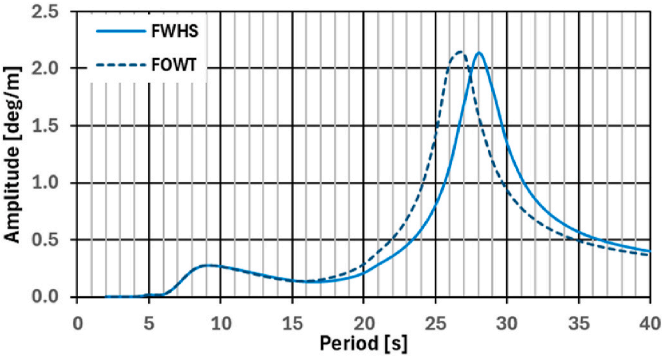

Fig. 5. RAO of pitch motion (0° incidence).

Table 4
Comparison of stability characteristics of the FWHS and the FOWT.

Stability parameters	units	FOWT					FWHS				
Azimuth →		0° & 60°	15° & 45°	30°	75° & 105°	90°	0° & 60°	15° & 45°	30°	75° & 105°	90°
Metacentric height	m	12.78					11.42				
First intercept	deg	8.3					9.2				
Second intercept	deg	29.3	30.7	31.1	26.9	27.6	25.8	26.6	26.8	24.2	26.4
Safety factor (γ_{stab})	–	1.4	1.3	1.3	1.5	2.0	1.2	1.1	1.1	1.3	1.7

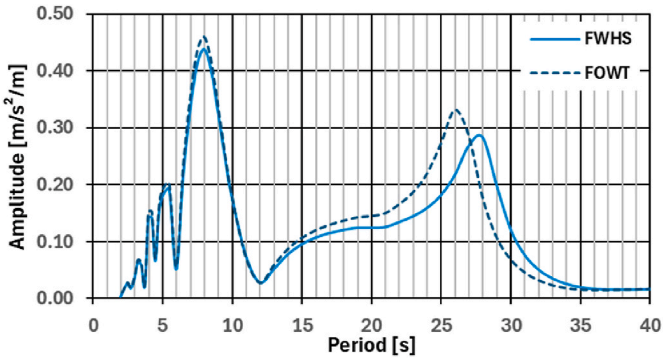

Fig. 6. RAO of x-acceleration at RNA (180° incidence).

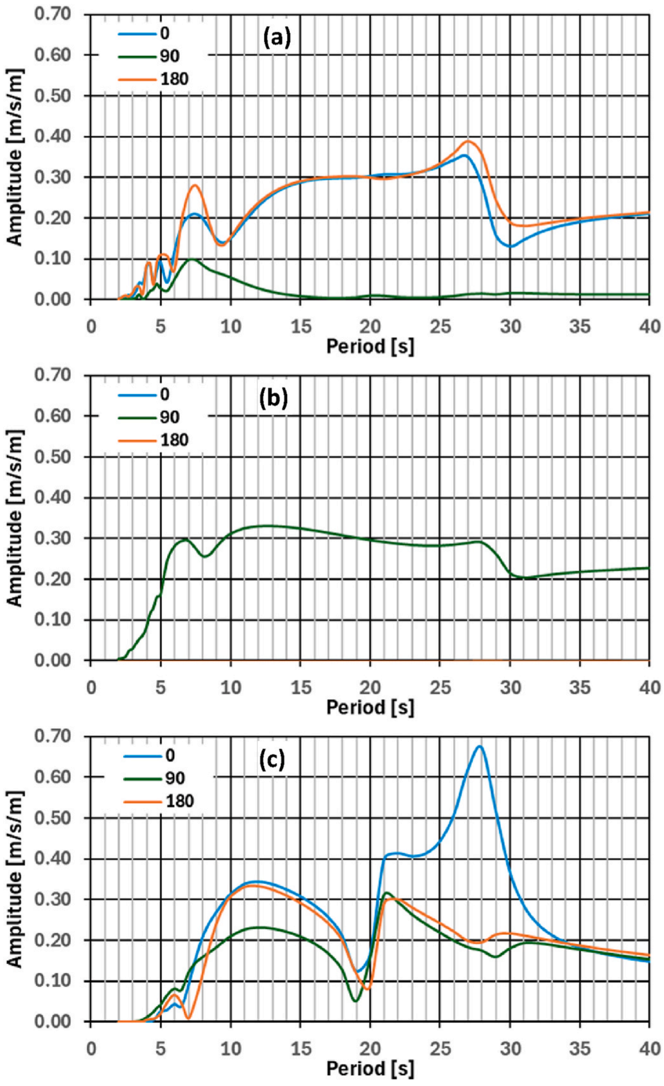

Fig. 7. RAO of velocity components: a) x b) y c) z at electrolyser on column 1 for three wave incidences. y-component is null for 0° and 180° directions.

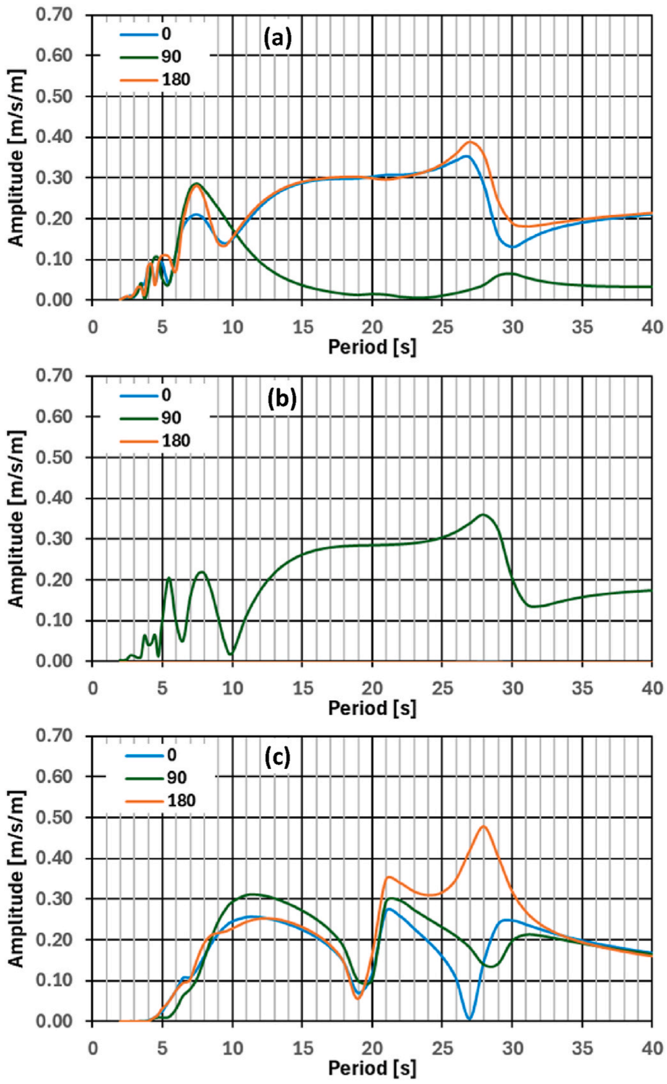

Fig. 8. RAO of velocity components a) x b) y c) z at electrolyser on column 2 for three wave incidences. y-component is null for 0° and 180° directions.

a sea state spectrum (S_ζ) of a given DLC and the RAOs of a dynamic characteristic j (heave motion, x-acceleration, etc.) of the FWHS, its response spectra (S_j) can be been computed, according to Ref. [52]:

$$S_j = |RAO_j|^2 S_\zeta$$

The representative statistical values of a response j, such as significant amplitudes (*Sig. Amp*) and mean average zero-crossing periods (T_z), can be obtained from the following relationships [52]:

$$Sig.Amp_j = 2.0\sqrt{m_{0j}}$$

$$T_{zj} = 2\pi\sqrt{m_{0j}/m_{2j}}$$

where: $m_{nj} = \int_0^\infty \omega^n S_j(\omega)d\omega$.

And ω represents the wave-frequency components of the sea spectrum. In Table 8, a summary of the wave-induced responses of the FWHS for the most critical wave incidence directions (Wave Inc) is presented. For the sake of comparison, also the FOWT platform's pitch and the RNA x-acceleration have been computed for the same conditions. In terms of significant pitch amplitude, the FOWT displayed 0.12° and 1.06° for DLCs 1.3 and 1.6 (or 6.1), respectively, i.e., the differences with the FWHS values (0.11° and 1.07°) are very small. However, in terms of x-acceleration, the differences seem significant, with the FOWT giving 0.32 m/s^2 and 2.78 m/s^2 for DLC 1.3 and 1.6, respectively, while the FWHS reached 0.19 m/s^2 and 0.88 m/s^2 for the same corresponding conditions. These differences have been already evident in the x-acceleration RAO curve (Fig. 6), especially for the longer wave periods, where extreme waves could still have energy. Notice that the results shown in

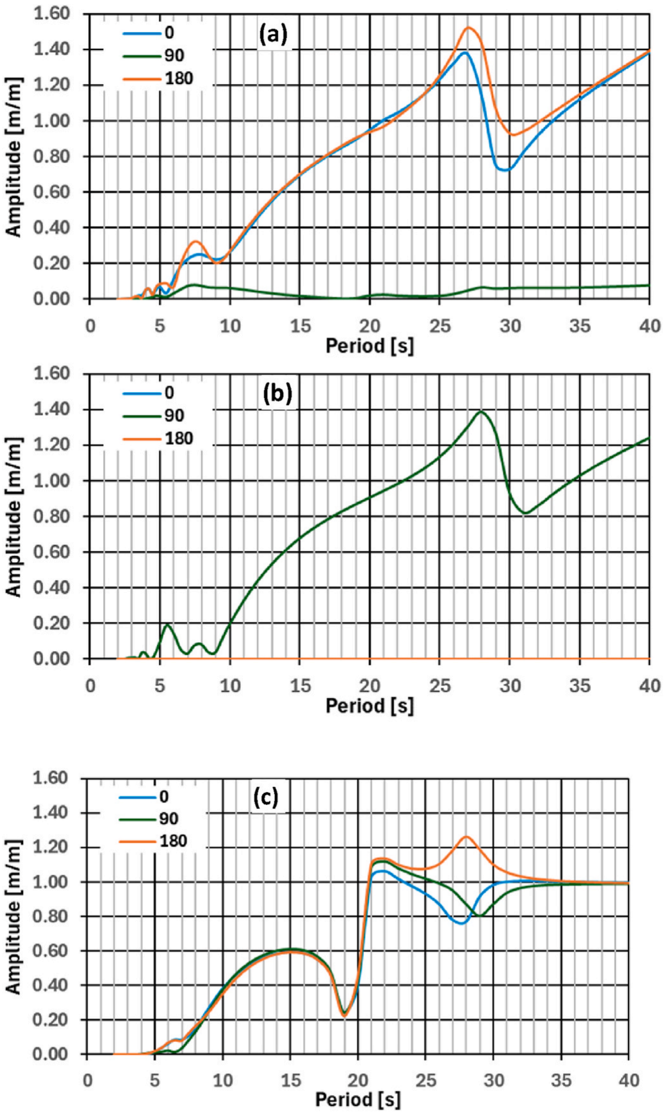

Fig. 9. RAO of displacement components: a) x b) y c) z at top of H_2 pipe connector for three wave incidences. y-component is null for 0° and 180° directions.

Table 7
Representative DLCs for the FWHS for NE8 site.

DLC	WT Mode	Wind		Sea state		
		Type	V_{hub} [m/s]	Hs [m]	Tp [s]	γ [−]
1.3	Power Production	ETM	10.59	1.40	8.09	1.00
1.6	Power Production	NTM	10.00	11.08	13.71	2.75
6.1	Parked	EWM	50.00	11.08	13.71	2.75

Table 8 do not consider wind excitation, i.e., those response amplitudes account only for the oscillatory motions induced by waves, and amplification or cancellations wind/wave effects may still occur.

Table 8
Statistical spectral (wave) responses of the FWHS.

Wave inc	Parameter	Units	DLC 1.3		DLCs 1.6 & 6.1	
			Sig. Amp	Tz [s]	Sig. Amp	Tz [s]
0°	**Platform's pitch**	**[deg]**	0.11	8.6	1.07	11.1
180°	**RNA_AccX**	**[m/s^2]**	0.19	7.4	0.88	8.5
180°	**Elec1_VelX**	**[m/s]**	0.13	7.3	1.37	12.2
90°	**Elec1_VelY**	**[m/s]**	0.18	7.1	1.75	11.6
0°	**Elec1_VelZ**	**[m/s]**	0.12	8.8	1.68	12.2
180°	**H2pipe_X**	**[m]**	0.15	7.8	3.00	13.4
90°	**H2pipe_Y**	**[m]**	0.08	7.3	2.81	13.9
180°	**H2pipe_Z**	**[m]**	0.12	9.0	2.70	13.1

3.2.4. Wind- &waves-induced dynamics: time domain

To assess the performance of the FWHS, the dynamics associated to the wind turbine generator in operational and survival modes should be simulated under realistic (time- and spatial-varying) wind and wave scenarios. Thus, a nonlinear numerical model has been implemented in OrcaFlex, a state-of-the-art package for the dynamic analysis of offshore marine systems. This time-domain model allows a more complete description of the performance of the FWHS by considering aero- and hydro-dynamic loads, coupled effects of the mooring system, tower flexibility and the RNA dynamics governed by the IEA 15-MW ROSCO controller. Thus, also allowing the computation of the generated power, among other WT's performance indicators.

Based on the wind and sea states parameters described in Table 7 and assuming aligned wind and wave directions of 0°, 90° and 180°, a set of simulation conditions with 1 h duration have been defined for the FWHS. For the sake of comparison, the FOWT have also been modelled and simulated for the same wind and wave conditions.

Compared to the reference FOWT, the FWHS clearly exhibit larger platform's pitch for DLCs 1.6 and 6.1, especially in the extreme (maximum and minimum) values with differences reaching 40%. However, in absolute values, among all the simulated conditions, the maximum, mean and maximum standard deviation of the pitch responses did not exceed 7.5°, 4.3°, and 1.9°, respectively. For the x-acceleration at tower top, among all the simulations, the differences between the FOWT and the FWHS did not exceed 15%, with maximum and maximum standard deviation values of 1.72 m/s^2 and 0.46 m/s^2, respectively, both for DLC 6.1. Thus, in the context of DNV-RP-0286 and within the scope of a preliminary design, the FWHS satisfies the recommended values for the maximum and mean platform's tilt angles and maximum acceleration at the tower top, for operational and non-operational loading cases. On the other hand, since there are still no criteria for the performance of offshore H_2 production systems, the time series of the motions (velocities) at the electrolysers locations are provided for the simulated conditions where the maximum values have been identified (Fig. 10). Likewise, the X–Y trajectory of the top connector of the H_2 pipe for the most critical simulated condition is shown in Fig. 11.

3.3. Wind energy and H2 production assessment

Despite the reported differences in the FWHS pitch response and the tower top acceleration relative to the corresponding motions of the reference FOWT, the wind turbine performance of the FWHS was negligibly affected in terms of generated power, with differences (relative to the FOWT) in the maximum and mean values of less than −0.5% and in the standard deviation of less than 0.7%, among all simulations in operational mode, perhaps reflective the effectiveness of the wind turbine controller.

Based on the instantaneous generated power of the FWHS and assuming a power reduction factor of 0.83 with an energy consumption of 4.5 kwh/Nm^3 of H_2, the average (nominal) amount of produced H_2 for the (1-h) duration of each simulated operational condition has been estimated. In general, the results show that since the influence of the wind/direction is negligible in the generated WT power, the average (nominal) H_2 production is also barely affected. Thus, for all simulated directions in DLC 1.3 and DLC 1.6, hydrogen productions of ~229 kg/h and 205 kg/h have been obtained, respectively. Since the performance

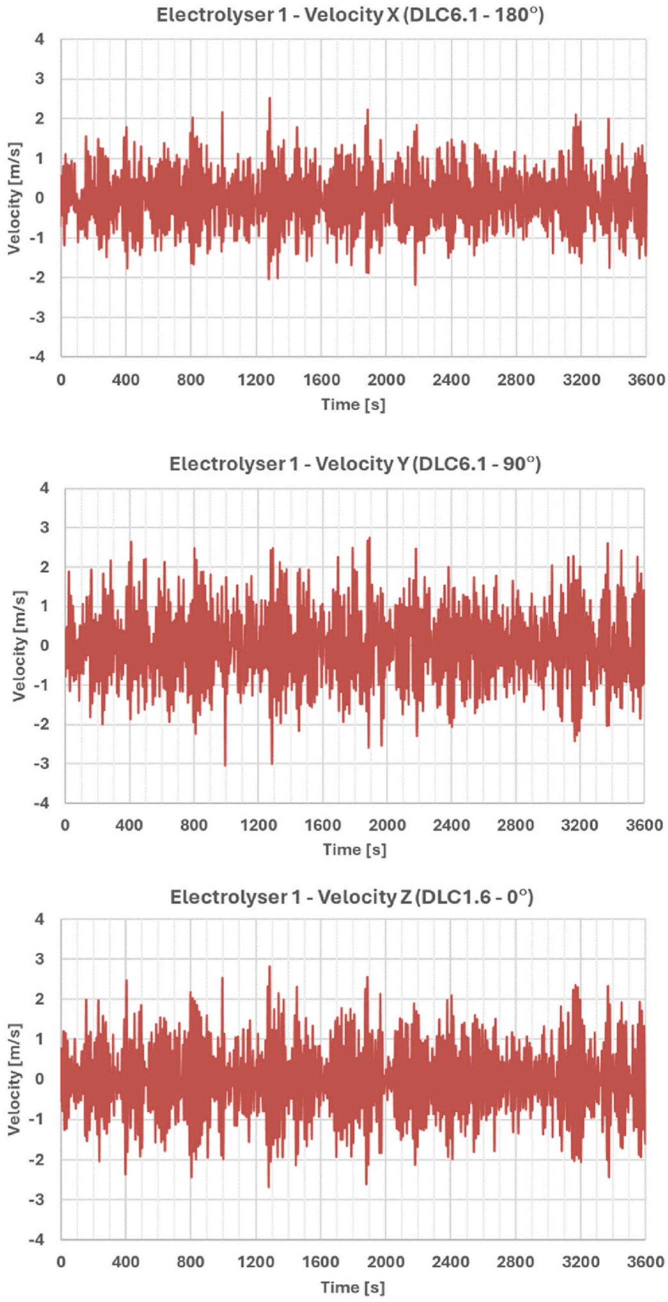

Fig. 10. Velocity components at electrolyser locations for most critical cases.

of the hydrogen system could change depending on the instantaneous loading of the electrolysers, these values should be taken only as high-level indicators – but may be more realistic than nominal rated values.

4. Conclusions

A preliminary design of a floating wind-hydrogen system (FWHS) for decentralised configuration has been proposed, providing some key details on the typical required components, its characteristics and expected locations onboard. The main premise was to start with an existing concept of a floating offshore wind turbine (FOWT) and integrate the hydrogen production facilities onboard trying to avoid significant changes in the design of the floating foundation. The UMaine semi-submersible concept with the reference IEA 15-MW reference wind turbine has been used as a case study. The FWHS has been extensively analysed in terms of equilibrium, stability and its dynamic motion characteristics. Also, to assess how the integration of hydrogen facilities could affect the performance of the floating foundation, the reference FOWT has been also modelled, analysed and compared for the same conditions of the FWHS. The main outcomes from these comparisons are:

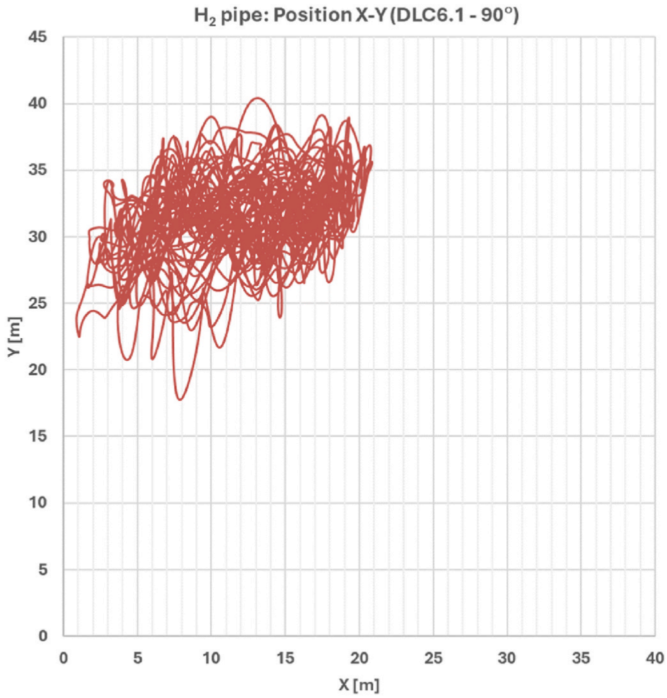

Fig. 11. Horizontal excursion at the top of H_2 pipe for most critical case.

- The floating stability of the FWHS underperforms the FOWT, failing the stability criteria for some azimuths directions.
- Pitch response is the most affected motion compared to the FOWT, especially for extreme survival conditions. However, the differences do not exceed 1°.
- All other platform's motion responses are negligibly affected by the presence of the hydrogen facilities onboard.
- The WT performance is even less affected, perhaps evidencing the effectiveness of the WT controller.

In summary, the design of the FWHS proposed here is in line with the performance of typical floating wind turbine foundations, i.e., wind and wave induced motions of the floating platform are within the recommended serviceability limits, for both operational and survival modes, even under extreme environmental conditions. Nonetheless, since the starting point of the proposed FWHS design is an existing floating platform, eventually optimised for power generation, future research should explore optimisation of FWHS aiming at ensuring continuous (reliable) H_2 supply, by avoiding disruptions associated to low (wind) power conditions.

Concerning the effects of the floating platform dynamics on the hydrogen equipment, velocities and motions at specified critical locations of the electrolysers for representative design conditions have been calculated. For these values, no criteria are still available to judge, for instance, the electrolysers performance. However, it is expected that the results here provided may aid in the design of hydrogen production equipment and in the assessment of feasibility of the electrolysis process under offshore dynamic conditions.

CRediT authorship contribution statement

Claudio A. Rodríguez Castillo: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maurizio Collu:** Writing – review & editing, Supervision, Investigation. **Feargal Brennan:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

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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