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OFFSHORE RENEWABLE ENERGY

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Angelos N. Findikakis
Hydrolink Editor

Guilherme Moura Paredes
Guest Editor

EDITORIAL

In early August, the Intergovernmental Panel on Climate Change (IPCC) released the Sixth Assessment Report (AR6) of its Working Group I on the physical science basis of climate change. The report is a stark warning of the consequences under some potential future scenarios, which prompted the United Nations General Secretary António Guterres to tweet that "the evidence is irrefutable: greenhouse gas emissions are choking our planet and placing billions of people in danger". This adds to the urgency to expand the use of all forms of renewable energy, including offshore energy production which is the theme of this issue of Hydrolink. In addition to four articles on this subject, this issue includes also a set of notes by Roberto Ranzi, Chair of IAHR technical committee on Climate Change Adaptation, summarizing some key points from the recent IPCC report.

Offshore renewable energy includes the generation of electricity from wind, waves, currents, tides, and floating solar photovoltaic plants, and ongoing research on exploiting salinity and temperature differences in the ocean. The current issue of Hydrolink includes four articles on different aspects of offshore renewable energy structures.

Wind turbines, either on fixed or on floating platforms, are the dominant source of offshore renewable energy today. Introduced few years ago, floating platforms make it possible to access sites at depths greater than 50 m, and at greater distances from the shore. Advances in floating platform design allow the deployment of larger units, such as the 11 MW wind turbine of the Aqua Ventus demonstration project off the coast of Maine in the United States. Even though offshore wind is only a small part of that of all wind-generated electricity, it is increasing steadily, reaching around 5% of the total wind capacity in 2020. According to one projection, the offshore wind capacity is expected to grow from 23 GW in 2018 to 228 MW by 2030, and to about 1,000 GW by 2050.

A large portion of the cost of offshore wind energy is that of operation and maintenance. The article by Langiano *et al.* describes a project aiming at reducing these costs using robotic assets. These new technologies are being tested at the WindFloat Atlantic platform, the largest fully operational floating turbine in the world, located 20km off the coast of Portugal, in waters about 100m deep. The article discusses the use of autonomous surface and underwater vehicles, unmanned aerial vehicles, and remotely operated vehicles with advanced features for non-destructive testing, cleaning of subsea assets for welding inspection and other underwater maintenance.

The utility of offshore wind renewable energy structures can be increased, and the cost of generated energy reduced, by designing them to accommodate several services. The article by Gao *et al.* discusses the design of a multi-purpose offshore platform that combines aquaculture and energy generation by a wind turbine and a set of wave energy converters. The aquaculture system with floating net pens will be located within a rectangular-shaped, concrete-caissons-based platform. The performance of the proposed design has been tested using a combination of computational analysis and physical modeling in a hydraulic laboratory.

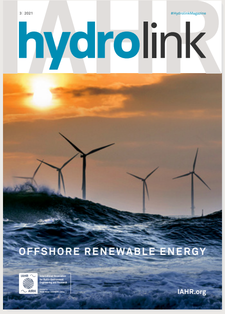
Wave energy has great potential, but the technology to capture it at scale is still under development. In 2020 its global installed capacity was only 2.3 MW. The deployment of wave energy converters in the ocean has been limited to prototype testing, mostly in Europe, with some important installations in Brazil, the US, Japan and India. Research is under way also on generating electricity from ocean currents which, in some locations, have relatively high energy density and constant velocity, making it possible to generate energy most of the time.

The methods to capture tidal energy fall into two general categories: tidal range (which involves the construction of a barrage); and different tidal current technologies, using submerged turbines or other devices. Even though tidal range power stations are not located at any distance from the shore, they can be considered offshore energy because they use the flow of the ocean tides. Tidal range power is dominated today by two projects: the 240 MW Rance barrage in France and the 254 MW Sihwa Lake scheme in South Korea. Other larger tidal range schemes, such as the Severn Barrage in Wales, have been proposed over time. Tidal current schemes are much smaller but promising. An example is the 1.2 MW tidal power array installed at the Eastern Scheldt storm surge barrier in the Netherlands. Another interesting recent development in this field is the deployment of a 2 MW floating tidal turbine unit in Orkney, Scotland.

The article by Ahmadian and Hanousek provides an overview of the potential of tidal range energy schemes and their range of benefits, as well as how to address concerns about their environmental and ecological impacts. Some of the options for enhancing energy production by these schemes include the creation of energy parks, by including quasi-offshore wind turbine arrays within them, or placing tidal stream turbines to capture some of the energy in the water plume exiting through the turbines and sluices. The potential for co-located industries, such as aquaculture, recreation, or containment of fresh water as a coastal reservoir is also discussed.

Floating solar panels have been installed and operated successfully for some time in reservoirs and lakes in many parts of the world. Operating floating solar photovoltaic plants in the ocean is far more challenging because of the many special problems caused by the waves and winds in offshore environments. which exert mechanical stresses to the many moving parts of these installations. The article by Baderiya *et al.* discusses an innovative conceptual design of such offshore plants aimed at addressing these problems.

The four articles mentioned above offer just a glimpse into the rapid progress towards capturing the vast potential of different forms of offshore renewable energy sources. There are great expectations that progress in this direction will accelerate in the coming years.



IAHR
International Association for Hydro-Environment Engineering and Research

IAHR Global Secretariat
Madrid Office
Paseo Bajo Virgen del Puerto, 3
28005 Madrid, SPAIN
T +34 91 335 7908 | F +34 91 335 7935

Beijing Office
A-1 Fuxing Road, Haidian District
100038 Beijing, CHINA
T +86 10 6878 1128 | F +86 10 6878 1890

iahr@iahr.org
www.iahr.org

Cover picture: Wind turbines off the North East coast

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GUEST EDITOR

Guilherme Moura Paredes

Civil engineer, specialised in coastal and offshore structures. He worked for over 12 years in the development of wave energy converter, floating wind turbines, and offshore aquaculture. It helped him in creating a healthy relation between engineering and nature. He worked and studied in Portugal (FEUP and INEGI), Sweden (Chalmers University of Technology) and Denmark (Aalborg University) and collaborated with professionals from countries such as China, USA, Indonesia, Italy, India, Belgium, Austria, and France.

Notes on the August 2021 IPCC Summary for Policymakers

By Roberto Ranzi

Last 6 August 2021 the Intergovernmental Panel on Climate Change (IPCC), during its 54th Session finalized the first part of the *Sixth Assessment Report (AR6), Climate Change 2021: The Physical Science Basis*, prepared by the Working Group I. The publication of the reports on Impact and Adaptation and on Mitigation is scheduled for spring 2022. The 3949 pages WGI full report is accessible at the www.ipcc.ch web site and it will take time to study it in detail, although browsing the full report and its Summary for Policymakers (SPM) already provides a sound basis for an up-to-date approach for the assessment of the impact and design adaptation measures in water engineering, a topic of high interest for IAHR.

Below is a summary of key conclusions related to water.

The current state of the climate:

It is indisputable that human activities are causing climate change, making extreme climate events, including heat waves, heavy rainfall, and droughts, more frequent and severe.

- The likely range of total human-caused global *surface temperature* increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C.
- Human influence is very likely the main driver of the global *retreat of glaciers* since the 1990s and the decrease in *Arctic sea ice* area between 1979–1988 and 2010–2019. However there has been no significant trend in Antarctic sea ice area from 1979 to 2020 due to regionally opposing trends and large internal variability.
- It can be stated with high confidence that global *mean sea level* increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018. Thermal expansion explained 50% of sea level rise during 1971–2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land water storage 8%.
- In 19 out of 45 macroregions of the world an increase of *heavy precipitation* (drawn from one to five days precipitation) is observed, in 8 a low agreement is reached on the type of change and in none of them a decrease is assessed.
- In 12 out of 45 macroregions of the world an increase of *agricultural and ecological drought,* due to increased land evapotranspiration, is observed, in 28 a low agreement is reached on the type of change and just in one of them a decrease is assessed.

Possible climate futures

A set of five new illustrative emissions scenarios (named SSPx-y 'Shared Socio-economic Pathway' differently from the RCPs in the 5th Assessment Report) labelled with x=1,..,5 with radiative forcing, y, set to y=1.9, 2.6, 4.5, 7.0 and 8.5 Wm-2, is considered in AR6.

- In the mid-term (2041-2060) and long term (2081-2100) the very likely range of mean *global surface temperature increase* compared to 1850-1900 ranges from 2.0°C to 2.4°C and 2.7°C to 4.4°C, respectively, according to the SSP3-4.5 and SSP5-8.5 scenarios.
- It is virtually certain that the Arctic will continue to warm more than global surface temperature, with high confidence above two times the rate of global warming. Additional warming is projected to further amplify *permafrost thawing,* and loss of *seasonal snow cover,* of *land ice* and of *Arctic sea ice* (high confidence). There is low confidence in the projected decrease of Antarctic sea ice.
- It is virtually certain that global *mean sea level will continue to rise* over the 21st century. Relative to 1995-2014, the likely (with medium confidence) global mean sea level rise by 2100 is 0.28-0.55 m under the very low GHG emissions scenario (SSP1-1.9), 0.44-0.76 m under the intermediate GHG emissions scenario (SSP2-4.5), and 0.63-1.01 m under the very high GHG emissions scenario (SSP5-8.5).
- *Precipitation* is projected to increase over high latitudes, the equatorial Pacific and parts of the monsoon regions, but decrease over parts of the subtropics and in limited areas of the tropics.
- Increases in frequency and intensity of *hydrological droughts* become larger with increasing global warming in some regions (medium confidence). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming.
- It is very likely that *heavy precipitation events* will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events, with return period of 10 years, are projected to intensify by about 7% for each 1°C of global warming (high confidence).
- There is strengthened evidence since AR5 that the global water cycle will continue to intensify as global temperatures rise (high confidence), with precipitation and *surface water flows* projected to become more variable over most land regions within seasons (high confidence) and from year to year (medium confidence).
- Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in carbon dioxide ($CO2$) and other greenhouse gas emissions occur in the coming decades.

The IPCC AR6 report depicts scenarios consistent with, but, to some extent, even more severe than the AR5 and poses responsibilities to the decision makers on the active measures to be taken to mitigate the effect of the projected global warming.

The water engineering community including IAHR is also challenged in order to properly address the assessment at the regional and local scale the impact of combined climatic and anthropogenic changes in the water cycle and revision of the design and management criteria in the water sector.

Prof. Roberto Ranzi
PhD Roberto Ranzi is Professor of Hydraulic structures and River basin monitoring and restoration at the University of Brescia, Italy.
Professor Ranzi is Chair of the IAHR Technical Committee on Climate Change Adaptation.

http://roberto-ranzi.unibs.it

ATLANTIS
Shaping future robotised O&M in offshore wind

By Serena Langiano, Christian Verrecchia, Miguel Marques and João Formiga

Operations and maintenance (O&M) constitute a significant part of the total costs for offshore wind power, accounting for up to 30% of the total cost of energy with the current technologies[1]. Cost reduction comes through structured and innovative solutions. The ATLANTIS project, which includes ten partners from six different EU countries, aims at establishing a pioneer pilot infrastructure, capable of demonstrating key enabling robotic technologies for inspection and maintenance activities in offshore wind farms.

Figure 1 | Windfloat Atlantic. Courtesy of the Windplus consortium.

Introduction

The offshore wind energy projected market value for 2024 is around EUR 54B: it is one of the fastest growing green energy sources and expected to be one of the main energy sources in the near future as for the end of 2020[2], Europe is currently the leader of this market thanks to the high wind potential already exploited in the North Sea (almost 79% of the whole European installed capacity) distributed among: the UK (around 10.5GW), Germany (7.7GW), Netherlands (2.6GW), Belgium (2.3GW) and Denmark (1.7GW). Other European waters have been less exploited (the Irish Sea accounts for 12% of the offshore wind farms capacity, while the Baltic Sea and the Atlantic Ocean stand at 9% and less than 1% respectively[2]) mainly due the higher water depths and harsher environmental conditions. With the continuous development of floating technologies, future wind farms are expected to be installed farther from the shore. In 2020, in Europe the average water depth[2] of new installed wind parks was 36m, slightly higher than the previous year (34m). In this sense, the WindFloat Atlantic (WFA) shown in **Figure 1**, the largest floating windfarm fully operational in the world (25MW), represents a pioneer infrastructure for the floating wind sector. The WFA is located 20km off the coast of Viana do Castelo, in Portugal, where the water depth reaches 100m.

Offshore wind is an emerging sector facing economic pressures due to the uncertainties and high costs associated with O&M activities of the offshore assets, which significantly contribute to an increase of the Levelised Cost of Energy (LCoE) from - 56-76EUR/MWh for land-based wind parks to 99-175EUR/MWh for offshore windmills[3]. Safety is a fundamental concern for O&M activities, particularly when taking place at sea. Offshore operations must guarantee a high level of occupational safety by minimising the probability of workers being exposed to major hazards. ATLANTIS tackles this goal by replacing and/or supporting human operators with robotic assets.

ATLANTIS' objectives and targets

The ATLANTIS project aims at fostering robotic assets in the offshore wind energy supply chain, by demonstrating their benefits in terms of improving the efficiency of O&M activities and reducing the costs associated with the same. The pioneer infrastructure to be deployed in Viana do Castelo will shorten the time-to-market of new technologies, creating new business opportunities for Small and Medium Enterprises (SMEs) and local communities.

The pilot will be made available free-of-charge for technology developers for demonstrating their own technologies and it will establish an international O&M network for the offshore wind energy sector to increase the adherence of robotic solutions for O&M activities by at least 25% by 2025. The decision support tools in the planning of support vessel operations will contribute to lower the O&M costs up to 15% by minimising fuel consumption and downtime. Robotic-based operations ensure regular and less invasive interventions, which will reduce the need for divers and expensive support vessels. This translates into cost savings of up to 50%.

ATLANTIS technologies allow more accurate and faster activities with consequent lower downtimes and loss of profitability. The development and integration of the ATLANTIS' approach into operating offshore wind farms could bring a general reduction of O&M costs up to 10% and consequently a LCoE reduction of around 2%. ATLANTIS will provide guidelines for a harmonised certification approach towards a common standard for robotic-based O&M activities that can be more reliable, safer and environmentally friendlier, reducing the exposure to risks and hazards for workers and the marine ecosystem.

ATLANTIS represents an optimal trade-off between economic competitiveness and decarbonisation of the energy sector providing an important step forward towards the achievement of the Paris Agreement targets: ATLANTIS will encourage the offshore wind energy to embody robots in the O&M value chain as a mean for minimising the externalities of offshore wind.

The Atlantic Testing Platform for Maritime Robotics (Coastal and Offshore testbed)

The ATLANTIS project will demonstrate the concrete benefit that robotic technologies can bring to O&M activities performed in offshore wind farms. The Testing Platform (**Figure 2**) will be installed in the Atlantic Ocean, in the coast of Viana do Castelo in Portugal where the WindFloat Atlantic is located. This pilot will be demonstrated and operated by a strong collaboration between R&D institutes and industrial players, which will cooperate strictly with the aim of bringing together end-users' expectations and technology maturity level, facilitating the market roll-out of maritime robotic technologies through real-world demonstrations. The ATLANTIS project embraces all the value chain, grouping stakeholders from the maritime robotics and wind power industry, SMEs, R&D institutions and energy operators, bringing them together into a test centre.

The ATLANTIS philosophy foresees a long-term deployment and integration of robotic assets in offshore wind farms, to accomplish significant improvements in the LCoE, by the elimination or minimisation of supporting vessels for O&M tasks, as well as specialised workforce. A group of robots (underwater, surface and aerial) will be deployed to conduct less invasive, more frequent and effective O&M activities. These robots will perform the needed activities autonomously, by taking off from their base, travelling to the working spot and returning in autonomous mode. This autonomy strongly diverges from conventional strategies, which resort to divers or remotely-operated vehicles, where launch, recovery, and many times travelling to site still require great assistance from the operators.

The ATLANTIS Test Center is the core of the project, and it will be installed on the Portuguese coast to facilitate the roll-out of robotic-based O&M strategies through real-world demonstrations. The large pilot will include a Coastal Testbed and an Offshore Testbed, to host demonstrating campaigns in environments with increasing complexity and risks.

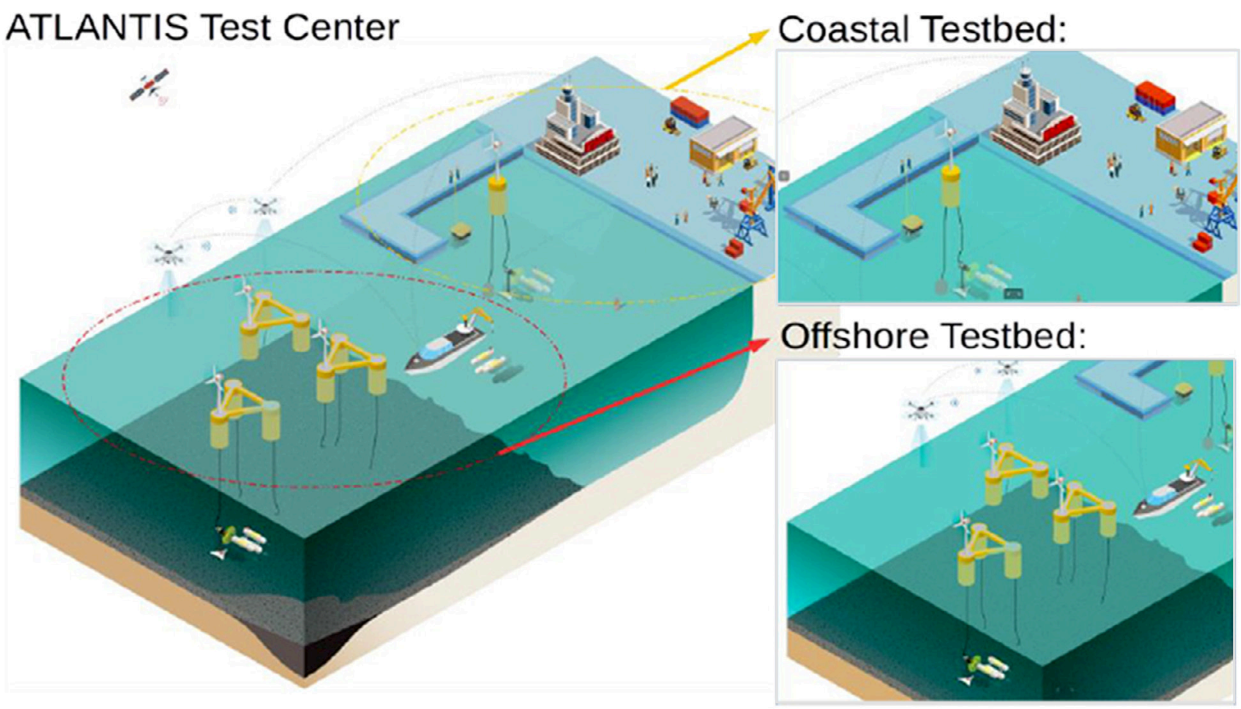

Figure 2 | The ATLANTIS Test Center formed by the Coastal and the Offshore Testbeds.

The **Coastal Testbed** will serve for technology developers to test and rehearse their robotic technologies in a de-risked environment, through cost-efficient, staged and rigorous testing campaigns in a near-real scenario. This testbed will be set-up in the harbour of Viana do Castelo and it will comprise a Shore Control Center (SCC) and a Floating Structure System (FSS). The FSS will be a semi-submersible platform anchored to the seabed through mooring lines. Both mooring lines and the structure will be inspected by the ATLANTIS robots to detect cracks and defects which represent one of the major concerns and which nowadays are spotted by divers via time-consuming work that includes the removal of marine growth from the welding seams. This task becomes notably important as offshore foundations are moving farther from the shore in deeper waters where stronger loads by waves and wind, and the impact of saltwater are present. The Coastal Testbed, besides being available for the robotic developers of the ATLANTIS consortium, will be at disposal of SMEs, R&D entities and academia that intend to test their own technologies. All experimentations inside the ATLANTIS Test Center will provide a common control framework where users can request, monitor and manage the validation or demonstration in a controlled replication scenario of harsh marine conditions and face the technical O&M challenges for both fixed and floating offshore wind turbines. After the close-to-shore testing phase, the robotic assets that have proved to be ready for the demonstration stage will be given the opportunity of testing and collecting performance data in a real-world environment, to enable the achievement of a higher technology maturity level.

The **Offshore Testbed** encompasses a commercial wind farm, the WFA, owned by the Windplus consortium (Ocean Winds: 85.2%, Repsol: 13.6% and Principle Power: 1.2%). The WFA, to date, is the largest floating offshore wind farm in operation, comprising three wind turbines supported by a floating structure based on WindFloat technology (Principe Power France-PPF patent). It provides unique wind, wave and weather conditions of the Atlantic waters to prove the reliability, feasibility and effectiveness of robotic solutions. The data gathered throughout the offshore test campaigns will be benchmarked against those related to standard strategies, thus allowing a direct comparison. The novelty of the ATLANTIS Test Center is the demonstration of complex offshore robot-based activities in a multi-domain environment that can be operated remotely or autonomously, encompassing but not limited to: survey of the foundations (underwater); survey of the mooring systems (underwater); survey of the biological growth (underwater and surface); survey of the export and array cables; survey of the turbines (aerial) and the floating structure (underwater and surface).

In terms of robots, the ATLANTIS project will make it possible to perform O&M activities by *Autonomous Surface Vehicles (ASVs), Unmanned Aerial Vehicles (UAVs), Autonomous Underwater Vehicles (AUVs)* fostering the ***vessel-less*** approach through experimental research. In addition to this, *Remotely Operated Vehicles (ROVs)* with advanced features for Non-Destructive Testing (NDT), cleaning of subsea assets for subsequent inspection of weldings and/or underwater light works for maintenance purposes will also be deployed.

Three communication modalities are foreseen in this operations context: an underwater acoustic modem; a local wireless communication system which will be used to communicate mission updates from the SCC to the robots and a main satellite-based link between the docking platform and the onshore SCC (see **Figure 3**).

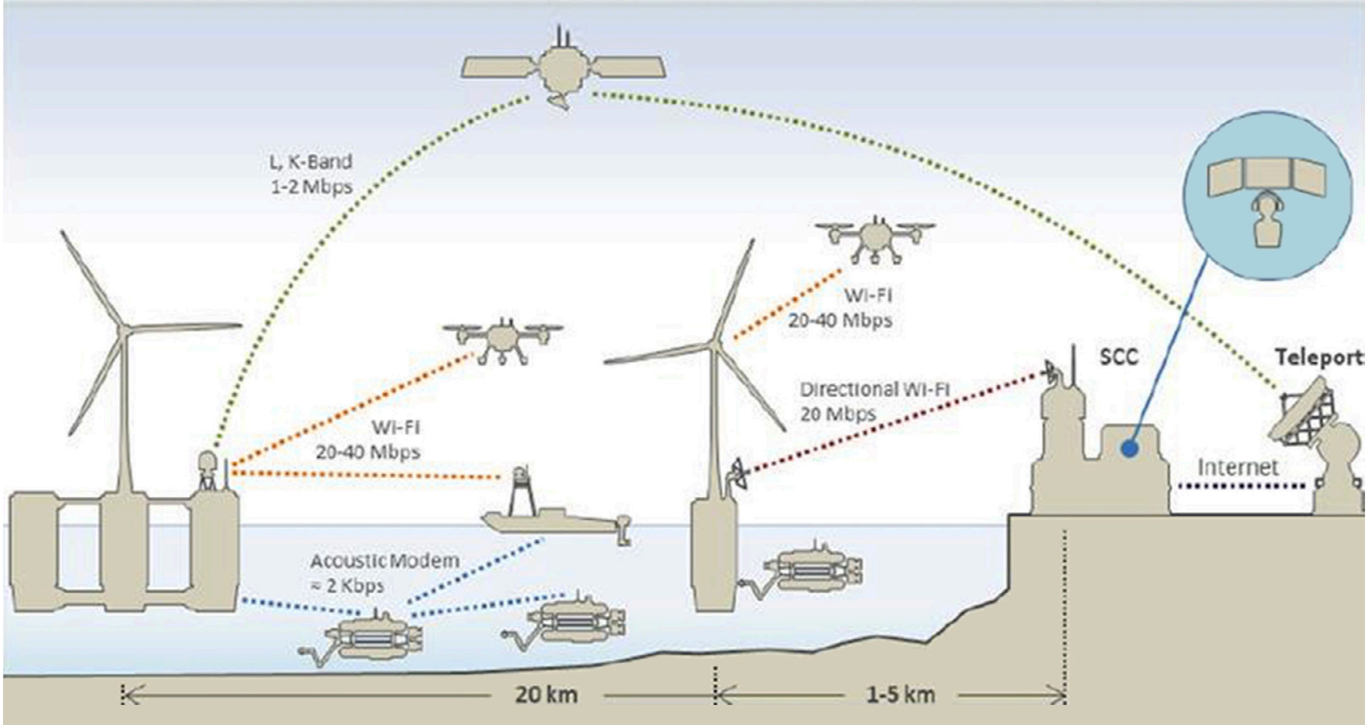

Figure 3 | ATLANTIS Communication architecture.

Scenario description

The ATLANTIS project established four showcases that it can leverage with the adoption of robots, which are representative of key areas of the O&M offshore wind value chain. Each showcase addresses sensitive topics of the different components of the offshore wind park.

The first showcase addresses the inspection and maintenance of the wind turbine. Currently, maintenance activities entail mainly visual inspection and remedial work when needed. Blades and tower, in ATLANTIS, will be inspected through UAV with advanced inspection capabilities, with the scope of identifying cracks, delamination, fatigue and extreme loading of blades, which are the major concerns for the offshore wind industry. O&M activities will be dedicated to the submerged structure, where marine growth cleaning is paramount to avoid over-loading effects as well as to allow NDT. Both cleaning and NDT will be performed by AUVs and ROVs properly customised.

The second showcase deals with the maintenance of both export and array cables that are exposed to tides and sediment flows, whose consequence is the movement of the cable. Waves and tides, vortexes, scour pits and storms can damage the cable protection system, exposing the cable to harsh conditions. ROVs and AUVs will be used within ATLANTIS to inspect the cable protection systems as well as to perform some interventions such as cleaning and/or rock removal. ATLANTIS aims at establishing a new methodology for cables inspection, by employing AUVs and ASVs with long endurance capabilities that will allow a constant and long-term inspection of the system.

The third showcase addresses the maintenance of the foundations and scour protection. The atmospheric, splash and submerged zone will be inspected via AUVs and ROVs with close-range navigation capabilities.

The fourth and last showcase aims at enhancing the planning of offshore activities through more accurate weather forecasts and multiple robotic-based operations. ATLANTIS' main objective is to establish vessel-less strategies by putting in place autonomous robotic operations supported by crewless vessels, such as ASVs, with the capability to transport, deploy and recover robotic assets in a real-environment. These assets will be demonstrated in this showcase. Moreover, within this use case optimised robotic-based operations will be performed in a multi-domain environment where robots will be (co)operating simultaneously.

Robotic-based operations will be complemented by two more solutions:

- A predictive maintenance supporting tool (developed by Teknologian tutkimuskeskus VTT Oy-VTT) which, by gathering and processing operational data, will be able to predict defects and fault in an early stage and
- A planning tool that will allow to schedule the activities considering environmental conditions at the scope of minimising costs and downtime (developed by ABB).

What's in it for EDP

The EDP group, as indicated through the just recently launched strategic plan for the five-years period 2021-2025, aims to be a leading global player in offshore wind via its joint venture Ocean Winds. Currently 6.6GW of offshore wind capacity are envisioned through eleven different projects which are already in place (e.g. Windplus in Portugal and SeaMade in Belgium), under construction (Moray East in the UK) or under development (in France, the UK, the US, Poland and South Korea). Some of these projects have already been secured by Power Purchase Agreements (PPA) or Feed-in Tariff mechanisms. It is then remarkable that further investments in offshore wind energy go through a more affordable, reliable and durable technology that can compete with well-established energy assets, such as onshore wind or Photovoltaic (PV) parks, and that can be better positio-ned in the energy market without or via less-intensive incentive mechanisms.

In this sense, the ATLANTIS project is key to bringing offshore wind technologies several step forward by allowing a more secure and economically viable operation and management of these energy plants. EDP, which participates in the ATLANTIS project through its R&D centre EDP NEW, envisions to: i) expand the company's skills in the O&M sector of offshore wind by sharing knowledge and contributing to the development of solutions, ii) foster the development of novel solutions for autonomous O&M enabling important reductions of OPEX and thus lowering the LCoE, with the result of increasing the financial attractiveness and ultimately improving the industry's business case.

Acknowledgment

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Serena Langiano
Serena Langiano graduated in Electrical Engineering from University of Cassino in 2018. Her background is namely in renewable energy, electrical machines and electrical systems. She joined EDP NEW in 2020 to contribute to projects focused on offshore wind and ocean energy. At EDP NEW, she performs economic analysis (LCoE, NPV, IRR) for energy power plants and designs business models for O&M applications in the context of offshore wind. She also contributes to the verification and validation of design tools for ocean energy systems aiming at supporting plant planning, performing economic assessment and system performance evaluation.

Christian Verrecchia
Christian Verrecchia graduated in Electrical Engineering from University of Cassino in 2018. His background is in renewable energy, power electronics and smart grids. He joined EDP NEW in 2020 as researcher in projects related to renewable energy and smart grids. At EDP he works in numerical modelling for RES technologies, namely PV and offshore wind, developing software for the computation of the power output, LCoE and O&M costs. He also supports real-world demonstrations of smart grids, focusing on storage integration and operation. Before joining EDP, he worked as a power electronic designer for the Italian Railway Network manager, designing and prototyping power converters.

Miguel Marques
Miguel Marques is the Head of Business Development at EDP NEW, whose main activities comprise the screening of new funding opportunities and the support of the development of R&D projects, namely in the areas of flexibility, hydro power, offshore wind and ocean energy. Before joining EDP NEW, Miguel worked in modelling and numerical software simulation of electrical power systems and as a field engineer in electrical grid maintenance in Portugal's main Distribution System Operator, EDP Distribuição. Miguel holds a master's degree in Electrical Engineering from the Lisbon Technical University, Portugal, with a major in Power Systems and minor in Telecommunications.

João Formiga
João Formiga is the Head of Renewable Energy Technologies at EDP NEW. His responsibilities focus on the coordination and development of R&D projects in RES technology and the establishment of new partnerships worldwide. Between 2013 and 2019, he worked for EDP Labelec's Energy Consulting department, on innovation and development projects, from the root development to the implementation and maintenance phases. João graduated in Electrical Engineering, with a major in Energy Systems and a minor in Systems, decision and control, focusing on Power Electronics.

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An innovative multi-purpose offshore platform concept for the blue economy proposed by the Blue Growth Farm Project

By Yan Gao, Maurizio Collu, Fabrizio Lagasco, Giulio Brizzi, Felice Arena, Carlo Ruzzo and Anita Santoro

The combination of energy generation devices and aquacultural systems is a smart way to improve the economic efficiency of integrated renewable energy systems and enlarge the application field of offshore platforms. An environmentally friendly multi-purpose offshore platform is proposed by the EU H2020 funded project 'the Blue Growth Farm' (www.thebluegrowthfarm.eu), which accommodates an aquaculture system within a rectangular-shaped concrete-caissons-based platform, which includes a wind turbine and a set of wave energy converters, producing renewable energy for its own operations. By integrating and engineering the aquaculture and renewable energy production systems, this efficient, cost-competitive and environmentally friendly multi-purpose offshore platform design is well suited for applications in the open sea.

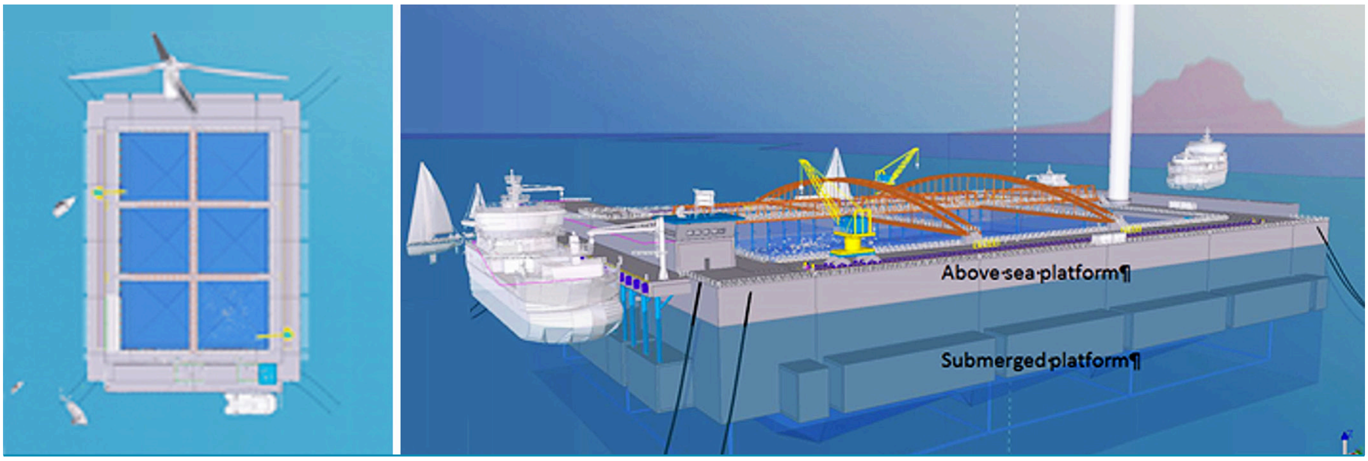

Figure 1 | The Design of the full-scale multi-purpose offshore platform 'The Blue Growth Farm'.

The background and targets of the Blue Growth Farm Project

The 2016 Paris agreement and the following related initiatives have pushed countries worldwide to set ambitious targets in terms of cutting greenhouse emissions (in terms of CO_2 equivalent tonnes). To achieve these targets, countries are largely relying on the use of renewable energy sources, transitioning from fossil fuels to these sustainable energy resources. Offshore renewable energy such as offshore wind, wave, current and tidal, is a favourable green energy resource that is plentiful, predictable, and environmentally friendly. The development of wind energy has been a hot topic in the realm of the blue economy field, especially after the successful operation of Hywind[1], which is the first full-scale floating offshore wind turbine in the North Sea in 2009. Wave energy is another kind of ocean renewable energy and much research has been conducted to convert the wave energy into reliable power via wave energy converters (WECs) such as oscillating-water-column (OWC) WEC[2].

The further expansion of marine fish farming in coastal waters is limited by a lack of suitable sites, as well as by concerns about pollution, sustainability and, in many cases, missing regulatory issues, and local community opposition. The integration of the different sub-systems into one complex infrastructure, the shared use of assets, and the combination of various offshore energy generation resources make the multi-purpose offshore platform an economic and efficient solution for both the offshore renewable energy and the marine fish farming industry.

For these reasons, the Blue Growth Farm (BGF) project's aim is to propose an efficient multi-functional offshore platform that 1 | combines fish production with the generation of renewable energy from wind and waves, 2 | operates with advanced automation and remote control capabilities, 3 | provides extra produced electric energy to the grid and sea electric station service to platform shipping operations[3].

The design of the BGF multi-purpose offshore platform

Given the nature of the problem it is addressing, key platform design requirements are that it must be able to withstand offshore conditions, including wave significant heights of up to 6m, whilst offering the highest standards of fish welfare, efficient use of resources, minimal environmental footprint and visual impact and, at the same time be commercially viable. If all these goals are met, the system should be an attractive option for commercial investors, and much less likely to attract opposition for its deployment from regulators or local communities.

Whilst various designs for offshore fish farming systems have been proposed over the years, so far none has had widespread uptake due to various concerns including their real ability to withstand harsh offshore conditions, insufficient technology maturity, the inherent difficulties in managing units to which access may be limited in adverse conditions, security and, not the least, cost. All these concerns have been taken into account in the design of the BGF platform.

The fish will be grown in floating net pens, much as currently practiced, so fish farming technology used is well proven. However rather than being exposed to the open sea, the net pens will be held within rectangular open-bottomed "pool" formed by floating, prefabricated concrete caissons joined together on site. The caissons, which also act as the collar for the pens, have a draught of 20m, thereby affording the cages protection from most of the incident wave energy and currents. Water exchange within the pool is facilitated by surface openings at the aft of the platform, which allows the outflow of water upwelling from the bottom of the pool due to the motion of the platform and the effects of sub-surface currents. The large open areas over and within the caissons will be used to house the feed silos, automatic feeding system, and other infrastructures such as a net store, ensiling system and workshop. The design of all these facilities is based on requirements dictated by the fish production programmes which have been developed for three different species (salmon, sea bream and sea bass) at three selected sites within territorial waters in Europe. Each programme has been tailored to give maximal production from the cage volume available, whilst ensuring all environmental parameters remain within set limits for best stock welfare.

The renewable energy systems comprise a 10MW wind turbine on the forward deck of the platform, and an array of wave energy converters (WECs) devices which form an integral part of the structure of the forward caissons. The energy produced will be used to power all the on-board equipment, and the excess energy may be dispatched to the local grid via umbilical cable. All systems on the platform, which include an automated feeding system, biomass estimator, under water and deck cameras, water quality sensors, security/surveillance systems, meteorological sensors, and structural health monitoring systems, will be managed and supervised by a central control room on the platform which will in turn be linked wirelessly to an onshore remote control room, allowing the system to be operated and monitored remotely when sea conditions are not suitable or safe to access the platform.

Scaled model tests at the Ecole Centrale de Nantes and NOEL

Various designs for the platform have been studied by means of computational analysis to determine its behaviour under a wide range of sea conditions. The selected configuration was planned to be studied also via experimental testing. A 1:40 scale model of the selected design was then built and tested in a wave tank trial at the Ecole Centrale de Nantes (FR), as shown in Figure 2, in order to validate the computer model assumptions and the coupled dynamics[4,5].

A higher scale 1:15 scale prototype, called 'AURORA', was built and is now in place at the Natural Ocean Engineering Laboratory (NOEL) open sea test site at Reggio Calabria in Italy, as shown in Figure 3. This prototype is fitted with an array of sensors to monitor its performance and behaviour for the entire duration of the experimental campaign (7 months) before its decommission by the end of 2021. This 1:15 scale model is constructed by categorizing the building blocks, such as the steel caissons-based platform assembly and its technology components, the ballasting system, the aquaculture prototype, the scaled energy harvesting devices, and the automation and control prototype, etc. For the installation of the aforementioned sub-assemblies, the wind turbine and WECs are both installed on the front side of the floater platform. An offshore camera is located in the mid aft side with the purpose to provide the remote-control station with the information for the entire duration of the experimental campaign. The experimental data collected will provide valuable information on the aero-hydrodynamic behaviour of the platform, the net pens and the wind and WEC systems, and will be used to optimise the models for predicting the behaviour of all sys-tems at full scale, thus enabling reliable virtual testing before any investment being mobilised.

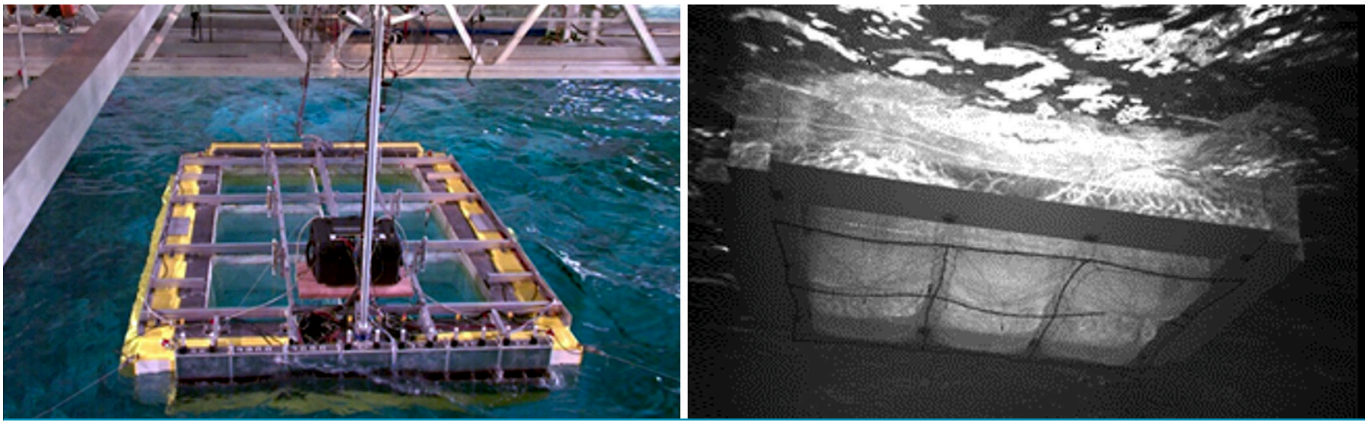

Figure 2 | 1:40 scale model test at the Ecole Centrale de Nantes (FR).

Figure 3 | The 1:15 scale model 'Aurora' at Reggio Calabria in Italy.

Social Impact, economy and business planning

Parallel to the engineering design work on the platform, the project has also looked at the social acceptance of multi-use platforms by holding workshops and meetings with stakeholders and local communities in two selected locations, Reggio Calabria (Italy), and Islay (on the west coast of Scotland). This interaction has provided valuable information on the key factors that most strongly influence public perception of such offshore systems which could be helpful in guiding potential investors on how best to win local approval and support for their proposed activities. Regulatory aspects related to Marine Strategy Framework Directive (MSFD) and compatibility with Marine Spatial Planning Directive (MSPD) of BGF Multipurpose Offshore Installations (MOI) have been investigated and the BGF contribution to best practise for the management of sea space multiple uses is expected to be delivered by the end of March 2022, thus contributing to the implementation of the EU Integrated Maritime Strategy, as well as to the Marine Strategy Framework Directive.

Conclusion and outlook

The EU H2020 funded project 'the Blue Growth Farm' aims to develop a multi-purpose offshore platform design which provides both green energy and fish farming. By combining different offshore energy generation devices such as the wind turbine and wave energy converters, this multi-purpose offshore platform meets the increasing demand of renewable energy production and at the same time decreases the environmental pressure on oceans exerted from fishing. Besides, the internal pool is used for a number of efficiently managed aquaculture fish cages, which also demonstrates its commercial feasibility. The aim of the Blue Growth Farm project of producing advanced industrial knowledge with a fully integrated and efficient offshore multi-purpose floating platform can be thus achieved, providing a practical solution for the blue economy.

Yan Gao
Dr. Yan Gao is a research associate at the University of Strathclyde, UK, at the Department of Naval Architecture, Ocean & Marine Engineering. Her research interests are ocean engineering with a focus on offshore platforms, computational mechanics on nonlocal material modelling, fluid-structure simulation with structural failure.

Maurizio Collu
Dr. Maurizio Collu is a reader in Offshore Renewable Energy Systems, and he joined the Naval Architecture, Ocean & Marine Engineering Department of the University of Strathclyde in 2018. His area of expertise is applied mechanics, focusing in particular on multidisciplinary, coupled model of dynamics for offshore renewable energy systems. He applies this expertise to develop conceptual and preliminary design methodologies for offshore renewable energy systems.

Fabrizio Lagasco
Mr. Fabrizio Lagasco is R&D Corporate Special Projects responsible in RINA Consulting S.p.A. and he acts as the coordinator of the Blue Growth Farm Project. Based on a leading (> 30 years) multidisciplinary experience matured through national and international industrial projects of high technology content applications, Mr. Lagasco is currently heading transversal and added value initiatives in the R&D projects and he is promoting exploitation of company R&D output towards new industrial capabilities to create value for the company and its industrial clients.

Giulio Brizzi
Dr. Giulio Brizzi is a senior aquaculture scientist. He is expert in offshore aquaculture and impact assessment of aquaculture and other human activities on the marine ecosystem, notably on benthos. Within the Blue Growth Farm Project, he participates as Chlamys srl researcher, and has been in charge of platform siting, after establishing the fish welfare criterion for under exposed marine conditions, as well as the assessment of the environmental impacts of platform.

Felice Arena
Felice Arena is professor of Ocean Engineering at the Mediterranea University of Reggio Calabria, where he is director of the Natural Ocean Engineering Laboratory NOEL. Fields of interest of his research activity include: mechanics and statistics of ocean waves, offshore engineering, wave energy converters, wind energy offshore. He is author of more than 250 papers. He is in the Editorial Board of Probabilistic Engineering Mechanics, by Elsevier; an associate editor of ASME Journal of Offshore Mechanics and Arctic Engineering. He has been scientific supervisor (principal investigator) of many R&I projects on offshore engineering and marine energy (including FP7 and H2020 projects).

Carlo Ruzzo
He is a staff member of Natural Ocean Engineering Laboratory (NOEL) and a post-doc in Ocean Engineering at the Mediterranea University of Reggio Calabria. His research topics include wave mechanics, extreme waves, wave-structure interaction, floating offshore wind turbines, multi-purpose floating platforms, etc. In this context, he is involved in numerical studies, and arrangement and management of experimental activities. His contribution within the Blue Growth Farm project mainly involve the study of the coupled dynamics of the structure and the realization of the outdoor experimental campaign at NOEL.

Anita Santoro
Anita Santoro is the CTO of Wavenergy.it limited company. She obtained her Master Degree in Environmental Engineering at the Mediterranea University of Reggio Calabria in 2010. Thanks to a joint program agreed by the Mediterranea University and the Instituto Superior Tecnico of Lisbon (PT), she obtained her PhD in Ocean Engineering at both universities in 2014. Her interests include wave data analysis, wave modelling and coastal engineering. She joined Wavenergy.it in 2018. Since then, she started working at the Blue Growth Farm project, with particular reference to the aspects related to the patented wave energy converters REWEC3.

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Exploring broader benefits of tidal range schemes

By Reza Ahmadian and Nicolas Hanousek

Tidal range energy has long been considered a reliable source of predictable low-carbon energy. Over the recent decades multiple new schemes have been proposed and discussed. Historically a major detractor to the development of new schemes has been their environmental and ecological impacts as well as high capital costs. Understanding the adverse impacts of such schemes and consequently planning to limit them at the early stages of their design could reduce any adverse impacts. As large marine hydraulic structures, tidal range schemes could provide various functionalities and a wide range of other benefits to the region they are built in, beyond generation of electricity. Such benefits could enhance the economic viability of these schemes, as well as improve their public acceptability and subsequently play a key role in the development of these large marine structures.

Introduction

With the increasing pressure to mitigate the effects of climate change, both societal and political, low-carbon energy sources are in ever-greater demand. To meet this demand, and develop a sustainable energy market, expanding the "cleaner" resources at hand is crucial. Tidal range energy has been considered as a source of reliable-predictable electricity for over a century, with Severn Barrage proposals dating back to the 1920s[1]. Tidal range schemes are marine hydraulic structures which create an artificial head difference between the water impounded within their basin and the tidal environment outside through their operation strategies. The head difference is utilised to operate the turbines and generate electricity. **Figure 1** illustrates electricity generation at tidal range schemes based on two-way generation, one of the most common types of operation of such schemes[1].

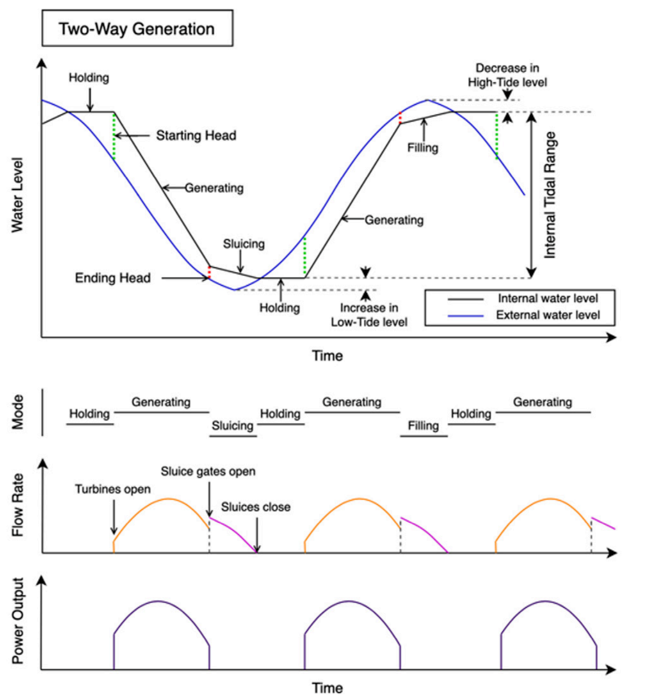

Figure 1 | Operational diagram, two-way generation.

Tidal range energy has been used to generate reliable and predictable low carbon electricity since the Rance Tidal Power Station (**Figure 2**) was connected to the French national grid in 1967. The Rance barrage was the largest tidal barrage in operation producing ~500 GWh of energy per year, until the Sihwa Lake scheme was constructed in South Korea, surpassing it, and generating ~550GWh of energy per year. The Annapolis Royal barrage in Nova Scotia produced ~50GWh of energy per year between 1984 and 2019, making use of a location that experiences the largest tides in the world[2]. Beyond these schemes, there are a variety of smaller schemes operating around the world. The energy potential of different locations depends primarily on the tidal range. Besides areas with very high energy yield, there are large areas around the world with ostensibly smaller tidal ranges and in turn, smaller average annual energy yield potential (see **Figure 3**) that could support a viable scheme. The benefits of a tidal range scheme beyond just electricity generation become more significant in areas with lower energy yields.

Expanding the energy potential

The operation of tidal range schemes, which directly affects the power generation and hydro-environmental/ecological impacts, has evolved significantly over the years. Early work such as by Prandle assumed that the head difference which triggers the start and end of generation would be constant, and the same over the neap-spring cycle. Zero-dimensional models have been widely used for the optimisation of tidal range schemes due to their limited requirements on input data, when compared to physically-based models, low computational cost, and ease of connection to optimisation tools. Optimisation methods such as gradient-based, grid searches, or evolutionary algorithms are aided by the expansion of computing capabilities, with Xue *et al.* reducing their computational cost by 95% by switching from a grid search to an evolutionary search algorithm to find optimal design parameters. Enhancements in computing facilities and optimisation methods have

Figure 2 | The Rance Tidal Barrage.

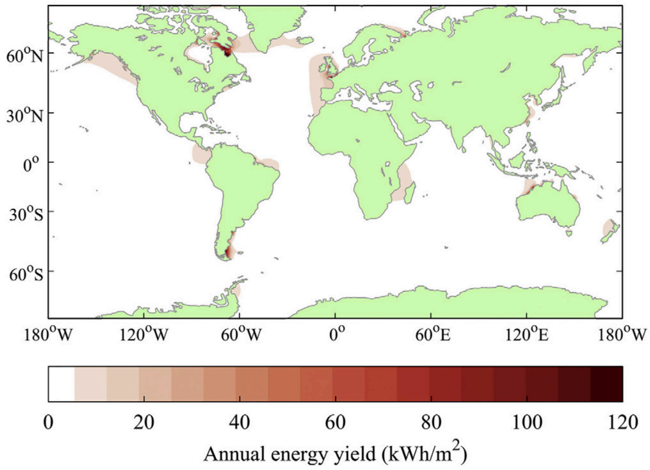

Figure 3 | Global tidal range resource potential[2].

led to the implementation of flexible operation in tidal range schemes. Under flexible operation, variable and independent start and stop head difference for each tide is used, which is dependent on the characteristics of that tidal cycle and preceding and subsequent tides in question[3]. This allows for better utilisation of the potential energy of a given tide based on the tide characteristics, resulting in an increased electricity generation of >15%, or >29% with the use of pumping water across the structure to increase the water level difference across the structure, compared to the base fixed case.

Energy storage and baseload generation

Pumped storage schemes offer the potential to compensate for the output variability of renewable sources. Energy storage and flexibility were identified as a priority area in a 2020 UK Government White Paper, with required storage capacity increasing with the further deployment of wind power in particular. An appropriately designed lagoon would have the potential to operate as an energy storage facility considering the forecast of demand and tidal conditions. Using tidal range schemes to store energy, as a tidally assisted pumped storage system, could provide significant further revenue for the scheme while providing a dispatchable renewable energy resource to contribute to the energy needs of a low-carbon power network. The energy from a tidal range scheme could also be utilised to power electrolysis and produce hydrogen for energy storage systems, similarly to the principles employed by the Orbital Marine Power O2 project in Scotland. Furthermore, research has shown that multiple lagoons can be utilised synchronously to generate close to continuous electricity by delaying or accelerating generation at different schemes. This could provide the opportunity for tidal range schemes to contribute to the baseload.

Energy parks

Significant marine structures such as tidal range schemes create a large impoundment. The internal area within the structure provides a space that can be physically controlled, is well sheltered from the elements and has in-built grid connection possibilities. Bridging the gap between offshore and onshore structures and to reduce the installation and maintenance costs of operation. A quasi-offshore wind turbine array can be built within such a scheme, particularly where there are high wind resources, such as in North Wales, where the Rhyl Flats and North Hoyle wind farms would likely fall within the bounds of a tidal North Wales lagoon. This would have the advantages of being able to utilise offshore technologies, whilst mitigating some of their drawbacks. For example, the physical proximity to land would reduce cabling. The reduced wave-climate within a tidal range scheme (where the fetch is limited to the size of the lagoon), would allow for less demanding designs for floating, bed-mounted turbine supports, or floating solar modules whose design can provide also water quality benefits through shading and mitigation of evaporative losses[13].
The Jiangxia Tidal Power plant in China notably generates more energy per year from the attached solar photovoltaic array than the turbines. Tidal range schemes typically produce some degree of flow plume when expelling water, visible in **Figure 4**. This effect could be utilised to extract the energy from this plume by placing tidal stream turbines in it. Swansea bay lagoon was found to have generated plumes of approximately 1-2 m/s velocity in the proximity of the turbines (depending on the method of momentum conservation) roughly 150 m long. This increase in velocity moves the hydro-environment of the region, where most hydrokinetic turbines are designed to operate in 2 m/s or greater flows. This could also reduce the environmental impact of this facility by removing some of the potentially adverse energy in the plume.

Benefits beyond electricity generation

Although the production of energy is typically the primary goal of a tidal range scheme as considered here, the construction of a high-capital and physically large marine infrastructure project, can and should provide additional benefits. A key to making a tidal range project attractive to key stakeholders and the broader public is being able to explain the wider benefits of the scheme beyond energy generation. For example, Petley *et al.*[4] considered the additional societal benefits that could be offered to the Liverpool area by a barrage across the Mersey

Figure 4 | Plume of water visible at Annapolis Royal.

estuary including transport, tourism, and engineered wetlands; all based about a re-imagined structural concept.

Flood protection

Various hydraulic structures have been used for the purpose of flood mitigation and protection across the world, such as the Thames Barrier and the Delta Works project, and this trend is expected to increase because of in the greater frequency and severity of coastal and fluvial flooding with rising sea levels and climate change. Areas wherein tidal range schemes are typically proposed are inherently tidal, and in some cases, these tides could significantly harm the local communities through flooding. In North Wales, proposals have been developed with the express benefit of mitigating the flooding experienced in the region. The Lake Sihwa scheme in South Korea was developed by modifying an existing land reclamation and flood alleviation scheme, with the water level inside being limited to a fixed maximum level. Such schemes can provide a significant degree of long-term savings to an area that is suffering from both tidal and fluvial flooding, in terms of insurance and prevention measures, particularly with this issue being likely to increase in severity in the coming years due to sea-level rise.

Impacts on ecosystem

Through the design of the internal landscape of a scheme, and appropriate scheduling of the generation plan, a wetland area can be established that matches the desired characteristics of a habitat. This habitat can be specifically tailored to suit the needs of a specific species or recreate an area previously lost in the locale. This philosophy redirects the conventional position of a power plant being damaging to the ecosystem around it, and places it as a part of the rejuvenation of a space, allowing the electricity generation to provide financial backing to an ecosystem project. The effects of a tidal range scheme on the ecosystem have in the past been significant, but if this change is accounted for from the design stage it has the potential to provide a mitigating influence on the adverse impacts, making tidal range energy more appealing to an increasingly environmentally conscious society.

Aquaculture

An infrastructure project such as a tidal range scheme has a large physical footprint, and co-location with other sources of energy and industries can offer both economic and social benefits. For example, by devoting both spaces within and around the site to aquaculture, fish, shellfish, seaweed, algae farming etc. can provide a local industry built around a tidal scheme. This can provide employment and opportunities through the full production and distribution chain, with farming, processing, hospitality and contribute to Blue Economy. Along with the solar panels, the Jiangxia tidal power plant is made commercially viable by the use of aquaculture and shellfish farming around the reservoir.

Coastal reservoirs

A tidal range scheme with a freshwater inflow, such as a river, becomes a briny impoundment of water. Through modelling of the flushing capacity, the salinity and water quality within a tidal range scheme can be pre-determined and controlled. This volume can be used to store higher quality water, for industrial, agricultural, or social needs, by monitoring the inflow water quality and flushing characteristics. This water source can be maintained and used to generate energy at times of peak demand. A coastal reservoir can also be a site for artificial wetlands, recreation, and cultural benefits. This has been seen tangentially from projects such as the Cardiff Bay development which can be considered as a coastal reservoir. The Cardiff Bay Barrage (**Figure 5**) and regeneration project transformed a formally industrial region into an attractive area of the city[5]; where sailing, hospitality, housing and outdoor activities have all flourished since 1999. The project does not generate electricity yet, but electricity generation could be considered as a part of the scheme, demonstrating that the intrinsic value of its wider benefits can outweigh energy generation. The Annapolis Royal and Rance barrages both also attract tourism to their respective areas, with visitor centres and educational facilities to draw in and educate visitors, the visitor centre at La Rance is estimated to admit 70,000 visitors per year.

Figure 5 | Cardiff Bay Barrage coastal reservoir. From: Falconer *et al.* Coastal reservoirs and their potential for urban regeneration and renewable energy supply, 2020.

Conclusions

Tidal range energy schemes have historically been seen as hydraulic structures that generate reliable, predictable, low-carbon energy over their long lifetime. The tidal energy potential could be harnessed to provide long term – deployable energy storage to keep up with the increasing use of less predictable renewables. Through increased understanding, holistic design, and expanded awareness, the benefits can far outreach the energy output alone. Through an appreciation of the space being acquired, and the structure constructed, platforms for offshore wind and floating solar arrays can increase the power generation potential of a tidal range scheme by connecting to well-developed renewables technologies. Well-positioned tidal stream turbines could be used to capture some of the energy contained in the mass of water exiting through the turbines and sluices, boosting the capacity and reducing the environmental impacts caused by the jets through the structures. The potential for co-located industries, such as aquaculture, recreation, or containment of fresh water can offer diverse opportunities for regeneration and socio-economic growth in an area where a large infrastructure project is being built. The environmental impacts often seen as detrimental could be prioritised in the design of the operation, to develop conditions suitable for a specific ecological system, be it wetlands, flood mitigation, or marine habitats. The change in perspective from tidal range schemes as power stations alone, to schemes whose design and construction add value to the region, can deliver more attractive schemes to the stakeholders and the wider public.

Reza Ahmadian
Reza Ahmadian is a reader, and the director of International at School of Engineering, Cardiff University. He has over 15 years' experience in developing and refining hydro-environmental computational models to investigate hydrodynamic, flood modelling as well as simulating water quality and sediment transport processes. He is a prior chair and member of the leadership team of the IAHR UK Chapter. His research is mainly focused on hydro-environmental modelling motivated by reducing the risk to humans' health and sustainable use of water.

Nicolas Hanousek
Nicolas Hanousek is a doctoral researcher at Cardiff University with the WISE Centre for Doctoral Training (EPSRC EP/L016214/1). He received his Masters in Civil Engineering at Cardiff University, with a placement year at HR Wallingford. His research interests include numerical modelling of tidal range schemes with respect to both optimisation and hydro-environmental impacts, and application of smoothed particle hydrodynamics.

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A novel concept for a floating solar photovoltaic power plant in an offshore environment

by Naman Baderiya, Luciana das Neves, Zafar Samadov, Damián Villaverde Vega and Ralf Bucher

The hybridisation of offshore renewable wind and solar energy resources is one of the emerging trends in ocean energy technologies. Said hybridisation is expected to become an integral part of the world's energy transition. Accordingly, floating solar photovoltaic (FSPV) power plants, in which photovoltaic modules are deployed on large water surfaces, have recently been attracting much interest. Along these lines, adding FSPV to the offshore energy mix is one of the new frontiers of offshore technologies with promising growth trends.

How FSPV help to diversity the offshore energy mix and its challenges

Floating solar photovoltaic in offshore environments brings additional benefits compared with fixed onshore systems or FSPV systems deployed in lakes and dams:

- Does not take up valuable space on land.
- Virtually unlimited surface area for deployment.
- Deployment in offshore environment prevents dirtying from dust and leaves.
- Bodies of water exert a cooling effect, which improves the performance of solar photovoltaic panels.

Combining floating solar panels with e.g., wind generation or hydrogen production can yield promising results towards the world's energy transition. It can also be exceptionally beneficial for remote islands and the development of the marine farming sector. However, floating solar systems come with great challenges, which are the reason why presently there are no designs that are either technically feasible, or commercially viable for installation in offshore environments.

FSPV power plants have a large number of moving parts that are subject to constant friction and mechanical stresses due to hydrodynamic loading caused by water level fluctuations, wind, waves and currents. They are also at risk of degradation and corrosion due to salt and moisture in offshore environments. Therefore, systems need to be properly designed and maintained to endure such harsh operating environmental conditions. Anchoring and mooring FSPV power plants in place brings about additional challenges. The long-term impact on marine ecosystems is another critical consideration, as the partial or total shading effect of the water column by the solar panels can potentially have negative effects.

Site selection

Site selection is critical for developing floating solar projects as it influences environmental conditions and hydrodynamic loading. Site selection must consider the seabed morphology, local morphodynamics, and the balance between competing uses, which ultimately determine engineering and construction costs and, thereby, the overall technical feasibility, and commercial viability of an FSPV project.

The Hollandse Kust (Noord) wind farm zone (HKN) which is 18.5 km off the west coast of the Netherlands was selected as prototype case site to perform the mooring design analysis of a novel FSPV power plant in an offshore environment. Metocean and environmental site conditions for different return periods of interest were obtained from a study by the Danish Hydraulic Institute (DHI)[5]. To optimise the power production per occupied surface area, the ocean surface area selected for the installation of the FSPV systems is located in the wind farm zone between the floating wind turbine (FWT). The illustrative arrangement of the system is shown in **Figure 1**. Because it is a concession area, the wind farm zone is also preferred as it does not affect and is not affected by any navigation route. Furthermore, it is easier to connect the FSPV plants to the grid within this zone.

Novel FSPV power plant in offshore environment

In this section, the essential, general, and additional, functional requirements of the floaters and mooring system of the novel FSPV power plant and their conceptual design are presented. It should be noted that the conceptual design proposed herein is site-dependent and follows the guidance of the international accredited registrar and classification society for maritime shipping Det Norske Veritas (DNV) standards[6,7,8,9]. The mooring system analysis considers two design limit states: the Ultimate Limit State (ULS) and the Accidental Limit State (ALS), as proposed in the DNV guidance[6]. Safety factors to consider in these limit states are taken from the American Bureau of Shipping (ABS) guidance[1] and then used to compute the factors of safety and allowable breaking loads for catenary and hybrid mooring chain layouts. The factor of safety for the anchors is based on guidance and recommendations for FWT by the Bureau Veritas (BV)[4], as there is nothing specific for FSPV.

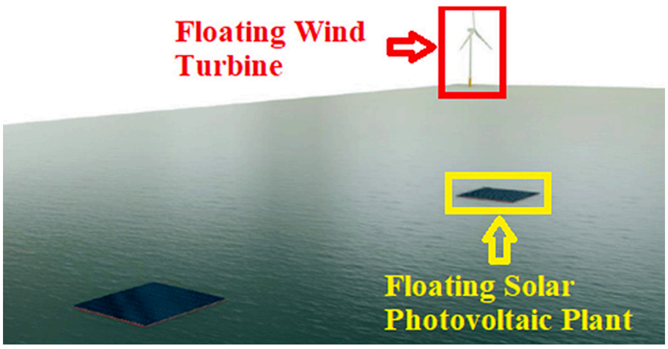

Figure 1 | Illustrative arrangement of FSPV and FWT.

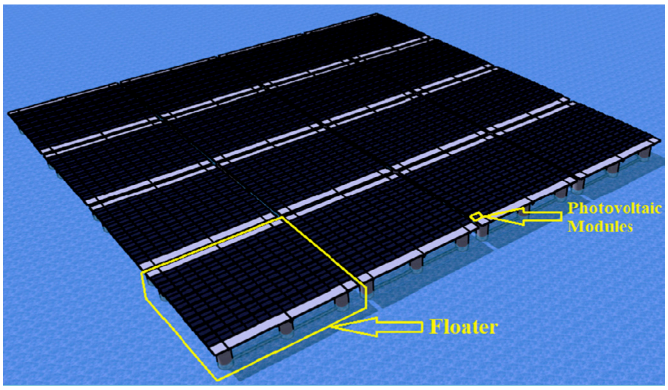

Figure 2 | Sketch of the novel FSPV 1MW power plant.

Floaters

Essential requirements	General requirements	Additional requirements
• Energy requirement • Articulation • Follow the wave slope	• Space requirement • Sufficient air gap	• Standardization of floater

For a reliable design, the floaters had to comply with the following essential requirements:

- The aim was to design the standard modular plant FSPV of 1 Megawatt (MW) capacity which can be used for scaling up power capacity for the project by using multiple plants.
- An articulation should be provided between the floaters to ensure that the array of floaters can easily follow the waves. Said articulation will be a flexible joint.
- The floater should follow the wave slope to reduce wave slamming as well as to reduce wave forces on the structure.

The following generic requirements should be followed while designing the floaters for the FSPV plan:

- A utility corridor of approximately 2 m should be provided on either side of the top part of the floater (**Figure 5**) for the cable routing, inverter and maintenance purposes. Similarly, a passage of 0.5 m is provided between the rows of photovoltaic modules for maintenance purposes. A spacing of 0.02 m is provided between adjacent photovoltaic modules.
- A minimum air gap between the water level and the lowest edge of the floater should be provided to avoid slamming from the maximum individual wave height expected to break on the floater.

An additional requirement to optimize the floaters design process is that:

- The design of the floater should be standardised to optimize the cost required for the production and installation.

Mooring system

Essential requirements	General requirements	Additional requirements
• Limiting the excursion of plant • Providing enough flexibility to plant for flowing slope of the wave • Avoiding resonance • Reducing the mooring footprint	• Keeping loads within the safety limits • Optimizing mooring slackness • Avoiding out of plane loads • Avoiding clashing of mooring lines and power cables • Allowing adjustment of cables and future intervention • Reducing fatigue damage	• Optimizing the cost of mooring and mooring equipment • Reducing the cost of installation of anchor and mooring line • Minimizing vertical loads on the mooring line • Reducing the impact on marine ecosystem

A good mooring design for the FSPV should comply with the following requirements:

- The excursion of the plant should be limited in all environmental conditions even in the case of an accident. This requirement is necessary to ensure that the plant does not collide with other structures.
- To comply with a basic principle of the floater design, the mooring system provided for the plant should be compliant enough to allow the floater to follow the slope of the wave and still maintain the limited excursion of the floater.
- Design of the mooring system should be carefully done to avoid the resonance of the moored system with the cyclic environmental loads such as wave frequency, slow-drift and wind loads.

The general requirements that the mooring system should comply with are:

- The maximum tension/load generated at any point on the mooring line should be below the breaking load of the respective line taking into account the factor of safety in it.
- The slackness of the mooring line should be optimized to avoid snap loads and compression in the lines.
- The mooring lines should not clash with anything including the power cables going from the plant to the shore.
- The design of the mooring line should be done in a way that allows future adjustments in the cables for elongation, creep, and settlement.
- The mooring system should have adequate life that exceeds the overall life of the project including the fatigue safety factor since fatigue is one of the main failure modes.

Additional requirements for optimizing the mooring system are:

- The design of the mooring system should be optimized to reduce the cost of the system (including the lines, anchors, and other equipment) as well as the installation cost.
- The planning of the mooring lines should be done in a way that reduces the impact of the lines on the marine ecosystem and any associated hazards.

Conceptual design

Floaters

The basic idea for the floater was inspired by the movement of attenuator type wave energy converters on waves as they follow the waves to extract energy from them. Similarly, the array of floaters was designed to follow the waves. The design of a floater is itself a compromise, or an optimization of the number of photovoltaic modules and the dimension of the floater. It is intended to maximize the number of photovoltaic modules on the floater keeping its dimensions small enough to follow most of the waves. Maximizing the number of photovoltaic modules on each floater makes it possible to reduce the number of floaters and the articulations used for joining them. Keeping the dimensions of the floater small enough to follow the waves results in the reduction of the air gap between the water level and the lowest edge of the floater leading to an increase in the stability of the system.

The number of photovoltaic modules considered in the design was based on previous experience. A conservative number of photovoltaic modules, 3072 was considered (1.2 MW) to allow room for modifications at the top of the floater for additional needs, like access between the rows of solar modules and other essential functions or pieces of equipment. The total number of photovoltaic modules was divided into smaller groups placed on the floaters. The plant of 1 MW consisted of 16 floaters, each of which containing 192 photovoltaic modules (**Figure 2**).

The dimensions of the typical floater were selected in a way that it can travel over the slope of the wave instead of the waves slamming on it. For acquiring it, the dimensions of the floaters are taken such that its size is less than half of the minimum wavelength of predominant waves. Significant wave heights and peak wave periods at HKN selected site vary, respectively, from around 2.3 m and 5.8 s – for wave directions within 30°N to 150°N – up to 7.2 m and 12.1 s – for 330°N wave directions. Wavelengths vary from about 47 to 240 m.

The floater was designed to align either in north-south direction or east-west direction. Therefore, only the design sea state with significant wave height of 2.2 m, for a peak period of 5.5 s, coming from 90°N and below this wave height will slam on the panel. Accordingly, and based on the guidance provided by ABS[1], the air gap between the lowest edge of the floater and the calm sea level was designed to be 3.5 m high, considering the maximum individual wave height in that sea state which is 4 m to avoid the slamming on the floating structure. A conservative air gap value, which does not consider the relative motion of the floating structure that can result in the reduction of the air gap, was considered in the conceptual design. In later design stages, this deck clearance must be re-examined and optimized based on more rigorous theory, or physical model testing. **Figure 3** shows the minimum air gap required to avoid slamming from the maximum individual wave height from all design sea state directions, when considering all waves are breaking on the floaters.

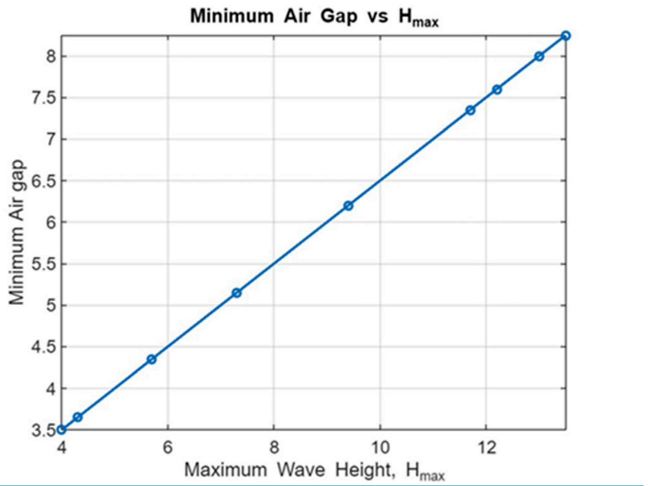

Figure 3 | Minimun air gap for different maximun individual wave height (H_{max}).

Figure 4 and **Figure 5** show the general arrangement and sketch of the unit floater, with dimensions of 24.32 by 23.7 m. The floater columns are cylindrical and made of mild steel, or low carbon steel, (density = 7,800 kg/m³) 6 mm thick. The selection of the shape of the columns was based on the consideration of having minimum drag and drift forces in all directions. The arrangement of the columns is such that it can be utilized directionally and provide sufficient strength and buoyancy to the structure. The radius of the corner columns is 1 m; the radius of centre column of the floater is 1.19 m; and that of those in the middle of the two sides is 0.95 m. The total height of the columns is 4.5 m, allowing 3.5 m of an air gap and 1 m of draft. The draft of the floaters is decided based on the required buoyancy and stability of the structure.

The beams are made of mild steel, selected based on bending analysis considering the self-weight of the plant; Finite Element Method (FEM) analysis was required for verifying the scantling for the hogging and sagging loads. The module's beams were calculated assuming uniform loads on the photovoltaic modules. The main transverse beam was calculated assuming uniform loads on the module s beam (an additional 20 % load is considered for the inverters and passageway). Circular beams of same strength were placed at the bottom of the cylinder to provide sufficient strength to the floater. The floater at the edge of the plant will have additional side walking space and taffrail for personnel protection.

Articulations are used to connect the unit floaters and enable them to follow the slope of the wave easily. At this stage, the state of knowledge in support of the design of the articulation is limited due to the lack of data on the forces involved. Therefore, the articulation was designed just to be flexible enough to follow on the slope of the wave. The top frame is connected to the adjacent floaters at the center of each side using articulations, as shown in **Figure 5**. The gap between adjacent floaters is set to 0.8 m for ease in crossing the floaters during maintenance operations. In designing the articulation, the maximum individual wave height that the floater is expected to follow should be considered and the analysis to be done based on it, as this will be the most critical scenario, as shown in **Figure 6**. It must be ensured, in this scenario, that the angle made by the articulation be restricted when the articulation centre is just above the crest of the wave to avoid collision and to have a minimum horizontal distance between the lower tip of adjacent floaters.

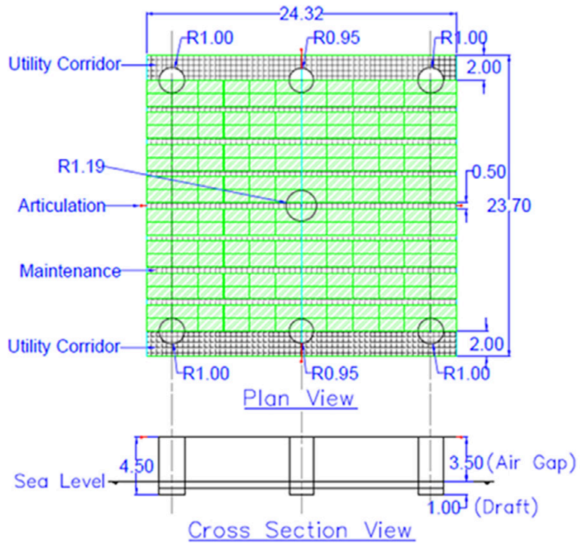

Figure 5 | General arrangement of the novel FSPV floater.

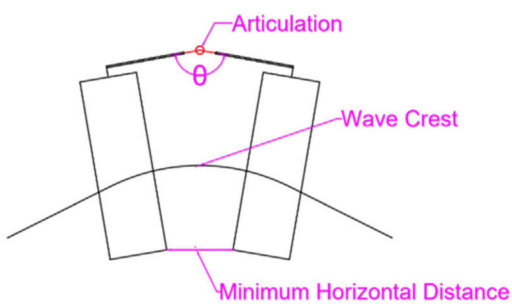

Figure 6 | Worst scenario for the novel FSPV articulation.

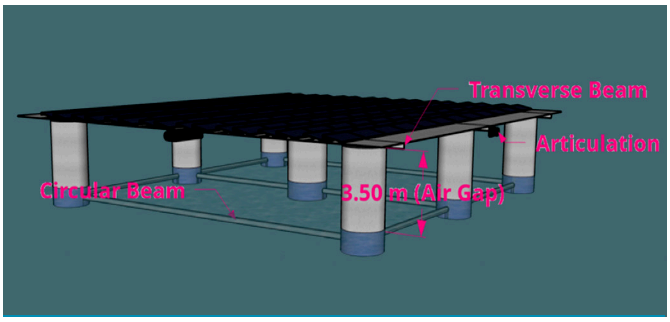

Figure 4 | Sketch of the novel FSPV floater.

Advantages	Disadvantages
• Modular design • Site dependent design • Optimising the surface • High energy density • Easy accessibility for operation and maintenance	• Complex articulation design • High fatigue loads on joints • Heavy weight of floaters

Mooring system and analysis

Ansys Aqwa software[2] was used for calculating radiation-diffraction loadings represented by the response amplitude operators (RAOs) and the quadratic transfer functions (QTFs), which were then used as input to the OrcaFlex software[10] for performing the dynamic mooring analysis of the novel FSPV power plant. First, the diffraction analysis was performed to investigate the hydrodynamic properties of a single floater. Then, the analysis considering the whole FPSV power plant was done. Finally, these results were used in the dynamic mooring analysis performed with OrcaFlex considering catenary and hybrid mooring layouts. The purpose of this dynamic mooring analysis was to optimize the mooring layout and compute the required anchor sizes. Figure 7 shows a 3D graphical picture of the mooring arrangement of the 1MW FSPV plant taken from the OrcaFlex simulation. Here the local axes in between of the floater define the degree of freedom allowed for the articulations. Details on the simulated cases and results can be found in the thesis by Baderiya[3].

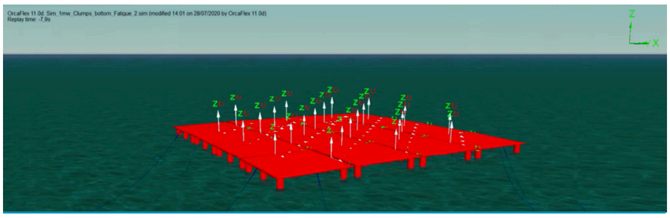

Figure 7 | Model of floating PV system in OrcaFlex. The arrows in the figure represent the local coordinate system of the articulations connecting the panels.

Conclusions

Floating solar photovoltaic power plants have recently been attracting interest. In offshore environments, adding FSPV to the offshore energy mix is one of the new frontiers of offshore technologies with promising growth trends. However, FSPV in offshore environments comes with great challenges.

To overcome these challenges, a novel FSPV power plant concept for deployment in offshore environments is proposed. The basic idea for the floater in this novel FSPV system is inspired by the movement on waves of an attenuator type wave energy converter, in the way that the attenuator follows the wave to extract its energy. Similarly, an array of floaters is designed to follow the waves. The lower part of the novel FSPV system is inspired by semisubmersibles, which are a proven design, and provides stability to the floaters. Furthermore, the novel FSPV system is designed taking into account modularity and ease of operation and maintenance. Earlier benchmark testing indicates that the cooling effect of water bodies improves the performance of solar photovoltaic panels.

Moving forward in the technology development of this novel FSPV power plant concept, the next steps will focus on the articulation as it is a critical component to the reliability and survivability of the system in aggressive offshore environments and to its overall technical feasibility. Furthermore, the weight of the floaters can still be optimised and the assessment of the structural safety of the FSPV electrical systems still needs to be performed.

Naman Baderiya
Naman Baderiya graduated in naval architecture and ocean engineering. He obtained a masters in advanced design of ship and offshore structures with specialization in hydrodynamics from Université Liège and École Centrale Nantes (EMship). He is currently working as an R&D Engineer at SolarinBlue, where he is part of the project that works towards developing the design of floaters for the FSPV plant (especially related to its hydrodynamics), and mooring system.

Luciana das Neves
Luciana das Neves holds a PhD in civil engineering (University of Porto). She is a Senior Engineer – Project Manager at IMDC nv and a visiting professor in the fields of coastal and offshore engineering at the University Porto. Luciana is a long-time advocate for sustainability and specialises in strategies for effectively managing risks and adapting to climate variability and change in coastal areas. In recent years, her R&I interests have also been revolving around ocean energy, namely the integration of wave energy conversion in multi-purpose breakwaters and hybridisation of offshore renewables.

Zafar Samadov
Zafar Samadov graduated in civil and industrial engineering. He obtained a masters in international construction management and engineering from the University of Leeds. Zafar has been project manager for different engineering studies assisting offshore wind farm developers, subsea cable projects, wave energy and floating PV. Prior to joining IMDC, Zafar promoted multilateral energy cooperation at the International energy charter secretariat. His passion is bringing together technology, services and digital solutions across the entire spectrum of offshore energy development.

Damián Villaverde
Damián Villaverde is a civil engineer with more than ten years of experience in multi-disciplinary and international marine and offshore projects. He holds a master in Civil Engineering (University of A Coruña) and a master in Integrated Management of Coastal Areas (University of Cantabria). Presently, Damian is working for SENER as Offshore Engineer for Floating Offshore Wind Projects. Prior to SENER, he had work for IMDC in coastal and offshore engineering projects in several countries worldwide, particularly Australia and Colombia.

Ralf Bucher
Ralf Bucher graduated in electrical power engineering, obtained a MSc in environmental engineering, and holds a PhD in engineering and electronics (University of Edinburgh). Presently, he heads the Power Grids & Systems department at Tractebel Engineering Germany and is project director for the Ethiopia-Kenya HVDC link. Prior to Tractebel, Ralf had work in Voith Siemens Hydro and Lahmeyer International. He has been project manager and plant specialist for several 1 GW+ (pumped-)hydro schemes.

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Machine learning for early stage piping design

By Ilker Telci

The design and construction of pipeline systems consist of several steps beginning from before Front-End Engineering Design (Pre-FEED) to Engineering-Procurement-Construction (EPC). Pre-FEED and FEED stages involve the initial conception and feasibility assessment of the systems. Their detailed design is finalized in the EPC stage of a project. In the early stages (e.g. Pre-FEED) of a project the main concern is the estimation of the project cost. These design stages have high impact on the sustainability, performance, and the cost of the final product[1]. Although the design is at a conceptual level at this stage, an accurate cost estimate is crucial for the success of the overall project. The cost of piping systems mainly depends on the pipe class (pressure capacity) to be used and the piping supports. The decision on the pipe class requires information on the expected maximum pressure in the pipe segments; the support capacity can be determined based on the expected maximum dynamic load the pipes may encounter.

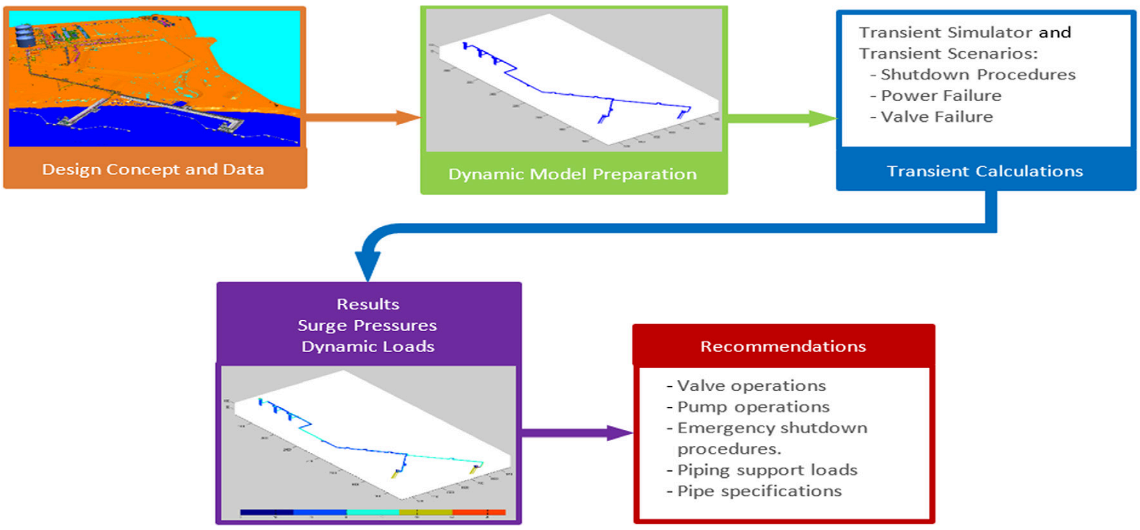

Figure 1 | Typical work process of a hydraulic transient analysis.

If a system is subject to hydraulic transients, or water hammer, the design pressures and forces acting on the pipes are mostly governed by these events. For more information on hydraulic transients, readers are referred to the issue number 2/2020 of the Hydrolink Magazine[2]. Hydraulic transient (water hammer) analysis is the primary method for estimation of the surge pressures and dynamic loads in pipeline systems. The primary outcomes of a hydraulic transient analysis are the estimation of maximum surge pressures and dynamic loads acting on the pipe segments as a result of various operation or accident scenarios such as emergency shutdowns, power failures, and valve failures (i.e. closures). Operational or design related recommendations to mitigate excessive surge pressures or dynamic loads are also provided as a result of the transient analysis. A high-level schematic description of the work process in a typical transient analysis is provided in Figure 1.

Transient analysis requires a detailed model of the system including liquid and pipe properties (e.g. liquid density, vapor pressure, modulus of elasticity of the pipe material), pipe sizes (diameters, wall thicknesses and lengths), elevations, hydraulic characteristics of pumps and valves, and operational procedures of the pipeline system (e.g. emergency shutdown procedures). It is not possible to obtain all these required data at the conceptual design phase of the project. Thus, several assumptions are required for the missing data in order to complete the transient model used to estimate surge pressures and dynamic loads in the system. Every assumption adds some uncertainty to the modeling results. Also, transient processes which result from sudden stoppage of the flow due to valve closures or liquid column separation and rejoining have highly nonlinear and counterintuitive dynamics. Therefore, constructing a detailed hydraulic transient model is not justified at the early stages of a project.

One alternative way of making an informed engineering judgement on the transient response of a system at an early design stage can be reviewing the results of past transient analyses performed as part of the detailed design of similar systems. For this purpose, a database of similar systems was prepared. The database includes the list of pipes with relevant parameters such as pipe size, length, elevation, region, and associated transient analysis results (i.e. maximum simulated surge pressure and dynamic load). This type of database is a useful asset for hydraulic engineers by providing them with statistical information on not only the typical parameters of the piping systems, but also with the estimated transient responses. The hydraulic engineers utilizing the database should be aware of critical background information on the hydraulic system design of each of the projects included in the database. For example, outliers with respect to parameters such as fluid properties, valve closure times or pump moment of inertias should be noted.

Machine Learning (ML) methods can be used to analyze the available data and develop a mathematical model to make predictions on the surge pressures and dynamic loads in a similar system. Artificial Neural Networks (ANN) was chosen as the machine learning method and the database was used to train an ANN to make predictions on the surge pressures and dynamic loads that may occur on a pipe with a given set of parameters.

Artificial neural network applications in hydraulics and hydrology

ANNs are powerful tools that can be used to identify relationships from given patterns. Large scale complex problems such as pattern recognition, nonlinear modeling, classification, association, and control can be solved using ANNs [3]. ANNs have many applications in the fields of hydraulics and hydrology. Several examples of hydrological applications of ANNs such as rainfall-runoff modeling, stream flow modeling, water quality modeling and precipitation estimation can be found in the literature [4]. Some hydraulic applications of ANNs in pipeline systems include monitoring and detecting leakage points in pipelines [5] and predicting internal corrosion in the pipelines [6,7]. ANNs ha ve also been suggested as design aids for air vessels in transient protection of pipe networks [8]. Recent research focuses on more advanced machine learning methods for the solutions of partial differential equations such as the Burgers' equation, Darcy Flow and Navier-Stokes Equation [9].

Liquefied Natural Gas (LNG) loading systems

LNG loading systems were selected for the pilot application of ANNs in the prediction of surge pressures and dynamic loads. This choice was made to address the need of the engineers working on these projects who frequently require early stage design evaluations for these pipe systems.

LNG is the liquefied form of natural gas, a mixture of hydrocarbons, which is usually transported and stored at a temperature very close to its boiling point at atmospheric pressure (approximately -160 °C). Since LNG is a cryogenic substance, physical contact or spillage may result in personnel or equipment hazard [10].

Figure 2 | Example LNG loaFigureding system.

Specially designed loading systems are used to transfer LNG from the storage tanks of a terminal to ship vessels that transport the LNG to different destinations (Figure 2). Main components of these systems are the LNG storage tanks, the pumps, the LNG transfer lines and the loading berths, each equipped with loading arms. Loading systems can have single or multiple lines of these components depending on the design loading rate and shoreline conditions. Typical design flowrates are of the order of 12,000 m^3/h. LNG companies are looking for means of increasing the loading rate as much as possible to minimize the time required to fill up the tanks on the ship vessels. In a typical LNG loading system, the flow rate is maintained by the flow control valves located at the tank top on the discharge pipe of each pump. Shoreline, loading arm and Emergency Release System (ERS) valves are used during emergency shutdowns. Major components of a typical LNG loading system are shown in Figure 3.

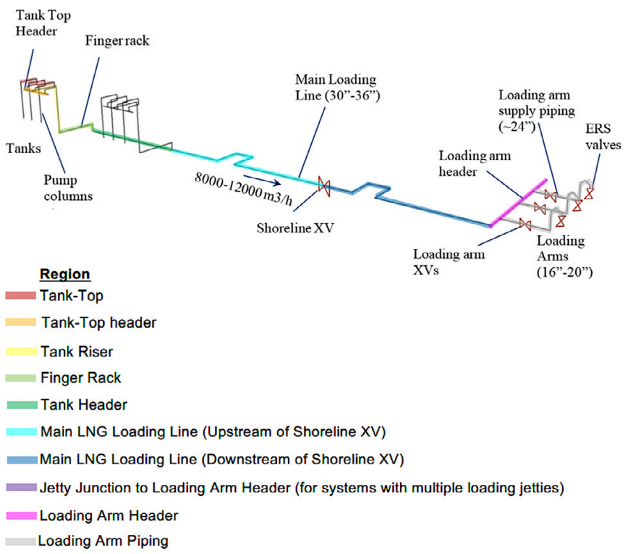

Figure 3 | Piping layout of a typical LNG loading system, showing the ten regions used for the training of separate ANNs.

The transient events which may cause pressure surges in LNG loading systems are planned and unplanned pump shutdowns, valve closures and emergency shutdowns. The system response to these transient events differs from region to region of the system. For example, a pump trip scenario is expected to have the highest impact at the tank-top piping when the pump discharge check valve slams, or when liquid column separation and rejoining occurs. An emergency shutdown scenario is expected to have the highest impact at the loading arms due to the closure of the Emergency Release System (ERS) valves and the Loading Arm emergency shutdown valves. A scenario with an unplanned closure (failure) of a shoreline emergency shutdown valve may impact the piping in the viscinity with a completely different hydraulic transient mechanism at the upstream and downstream sides of the valve (i.e. pressure increase on the upsream side, and pressure decrease with possible liquid column separation and rejoining on the downstream side). These observations are the primary reason for the decision to develop separate ANNs for different regions of the LNG loading system.

Transient analysis of the LNG loading systems involve simulation of a large number of scenarios and determining the maximum estimated surge pressures and dynamic loads on each pipe segment. If the estimated surge pressures or dynamic loads are excessive, various mitigation options are investigated. Since LNG is a hazardous material surge mitigation options which may cause spillage of LNG, such as air inlet valves are not acceptable. Typical mitigation options are slowing down valve closures and adjusting valve closure and pump trip timings. In some cases, surge vessels can be used as a mitigation option. The mitigation options applied in the previous projects are important parameters to be considered in determining the ANN's training database.

Hydraulic transient database for LNG loading systems

A hydraulic transient simulation requires a wide range of detailed system information such as fluid properties, pipe properties (e.g. sizes, length, elevations) pump characteristics, valve characteristics, flowrate, boundary conditions (e.g. tank liquid levels and ship manifold pressure), valve closure times, and pump trip times. All these are input parameters for a single transient scenario. A hydraulic transient analysis involves simulation of multiple scenarios with various valve/pump actions for a variety of initial conditions (e.g. flowrate) and boundary conditions. Therefore, the results of the transient analysis (i.e. estimated maximum surge pressures and dynamic loads) are a combination of multiple simulations. In the current approach, the purpose of developing ANNs is not to predict the results of any specific single transient scenario, but to predict results of an overall transient analysis.

When candidate parameters to be included in the database are considered, fluid properties and typical design flowrate (~12,000 m³/h) are similar among different LNG loading systems. Typical valve and pump characteristics are similar too, and can be decided in the detailed engineering phase of the project (EPC). Typical valve and pump actions (timing and durations) are also similar for most LNG loading systems with possible adustments during EPC. As a result, in the current approach, most of the parameters used in the hydraulic transient simulations may not be needed as input parameters for the ANN development. When selecting the parameters of the hydraulic transient database, the main driver is the data availaibity during early design stage. Therefore, only simple parameters such as pipe segment length, pipe diameter, relative elevation of the pipe with respect to the pump centerline, and relative location with respect to the check valve were selected for the ANN application.

In the current study, a database of pipe segments was prepared from three previously analyzed LNG loading systems including the above mentioned parameters along with the respective transient analysis results (estimated maximum surge pressures and dynamic loads). Two of these systems were selected as the training dataset for ANN development and the third one was spared as the test set. In the future, the author intents to increase the number of systems used for the training of the ANNs, which is expected to improve their predictive performance.

Developing and training ANNs for LNG loading system transients

ANNs are highly flexible tools for identifying relationships from given patterns. Users can define many different ways of training an ANN for a given problem. For the LNG loading system example, Neural Designer[11], a machine learning platform to build, train, and deploy neural network models, was used. Due to the disctinct hydraulic transient responses of different regions (parts) of the LNG loading system, it was decided to train ANNs separately for each region. These regions were selected based on their relative locations with respect to the pumps, tanks and main valves. Ten separate ANNs were trained for ten selected regions across the loading system as indicated in Figure 3. Figure 4 provides general views of tank, loading line and jetty area.from different loading systems As a result, each ANN was developed to have different input parameter requirements. For example, while the ANNs for the tank top header, tank riser, finger rack and loading arm piping have the pipe segment length as the only input parameter, the tank top piping from the individual pump to the tank top header requires input related to the relative location of the pipe segment with respect to the check valve (VC1), and the main LNG loading line requires as input the diameter and relative elevation of the pipe segment with respect to the pump center line in addition to the pipe segment length (Zr). These input parameters were determined by analyzing the sensitivity of the transient outputs (surge pressures and dynamic loads) to the individual input parameters. Three example architectures are provided in Figure 5 for the ANNs developed for the tank top piping, tank riser and main loading line upstream of the shoreline valve. In this figure, the yellow circles represent scaling neurons, the blue circles perceptron neurons, the red circles unscaling neurons, and the purple circles bounding neurons. In the layer of scaling neurons the maximum and minimum scaling method is used, which produces a data

Figure 4 | General view of LNG loading systems. (A) Storage tanks area, (B) Main Loading Lines, (C) Jetty Piping.

set scaled between -1 and 1. In the layer of unscaling, scaled outputs from the neural network are converted back to the original units. The bounding layer limits the outputs of the unscaling layer between the predefined boundary values (in this case, the highest and lowest estimated maximum surge pressure and dynamic load in a given region). More information can be found in the Neural Designer Tutorial[12]. The hydraulic transient data from two previously analyzed loading systems were used as the training set.

Testing ANNs for LNG loading system transients

The transient analysis of a third LNG Loading System was used for testing the performance of the ANNs. Since the transient parameters and transient results of this loading system were not included in the training set, the predictions of the ANNs were deemed to be a good representation of their performance. One example comparison between the ANN predictions and transient analysis re sults for the test case is provided in Figure 6 for the main LNG loading line downstream of the shoreline valve indicated with the blue line in Figure 2. If the ANN performance is defined as how closely the transient analysis results are predicted by the ANN, the results in Figure 6 is one of the best among the ANNs built for different regions. As can be seen in Figure 6, the error in the predicted pressures by the ANN is less than 3 percent, with the exception of one segment where the error is 7.5. The error in the predicted forces is less than 30 percent, with the exception of one segment where it is 80 percent. When overall results are considered, it can be said that the surge pressure predictions made by the ANNs are slightly conservative compared to the transient analysis results. However, this overprediction would not result in a higher-class piping in the early stage design decision. When the dynamic load predictions are analyzed, ANN predictions are significantly higher than the transient analysis results for some segments. This observation warrants further studies and improvements in the ANNs developed for the LNG loading system transients. When evaluating the ANN performance test results, it should be considered that in the proposed approach, the results of a highly complex numerical process is being predicted by the ANN with limited input parameters. The actual physical processes such as liquid column separation and rejoinings, pressure wave reflections at the dead-end pipings, and supepositions estimated in numerical models of the trainin g dataset may not be similar with those in the test data set.

Limitations

The main limitation in training the ANNs was the number of available data due to the limited number of transient analyses included in the data set. This limitation will be overcome by including more and more LNG loading system transient analyses to the training data set. Similarly, the test cases were limited. As the number of training and test data increases, the performance of the ANNs will be assessed more accurately using statistical indicators such as root mean square error.

Recommendations

ANNs can provide valuable information for cost estimation purposes during the very early stages of pipe system projects. In using ANNs, the hydraulic specialist should be aware of all hydraulic components of the systems (e.g. valve closure times and surge mitigations) when preparing the training and test data sets. However, the hydraulic specialist should always keep in mind that the ANN predictions are not confirmed transient analysis results, but they can provide valuable supplemental information for early stage design decisions at a time when no hydraulic transient analysis is performed. ANNs are not intended to and will not replace hydraulic transient analysis for the final design of pipe systems.

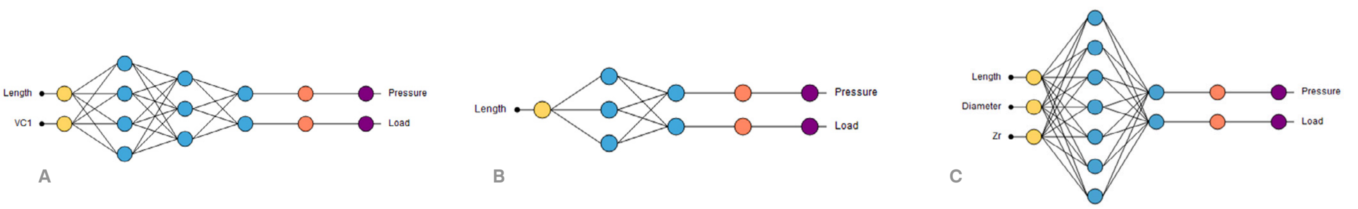

Figure 5 | ANN architectures for (A) tank-top-piping, (B) tank riser, (C) main loading line upstream of the shoreline valve.

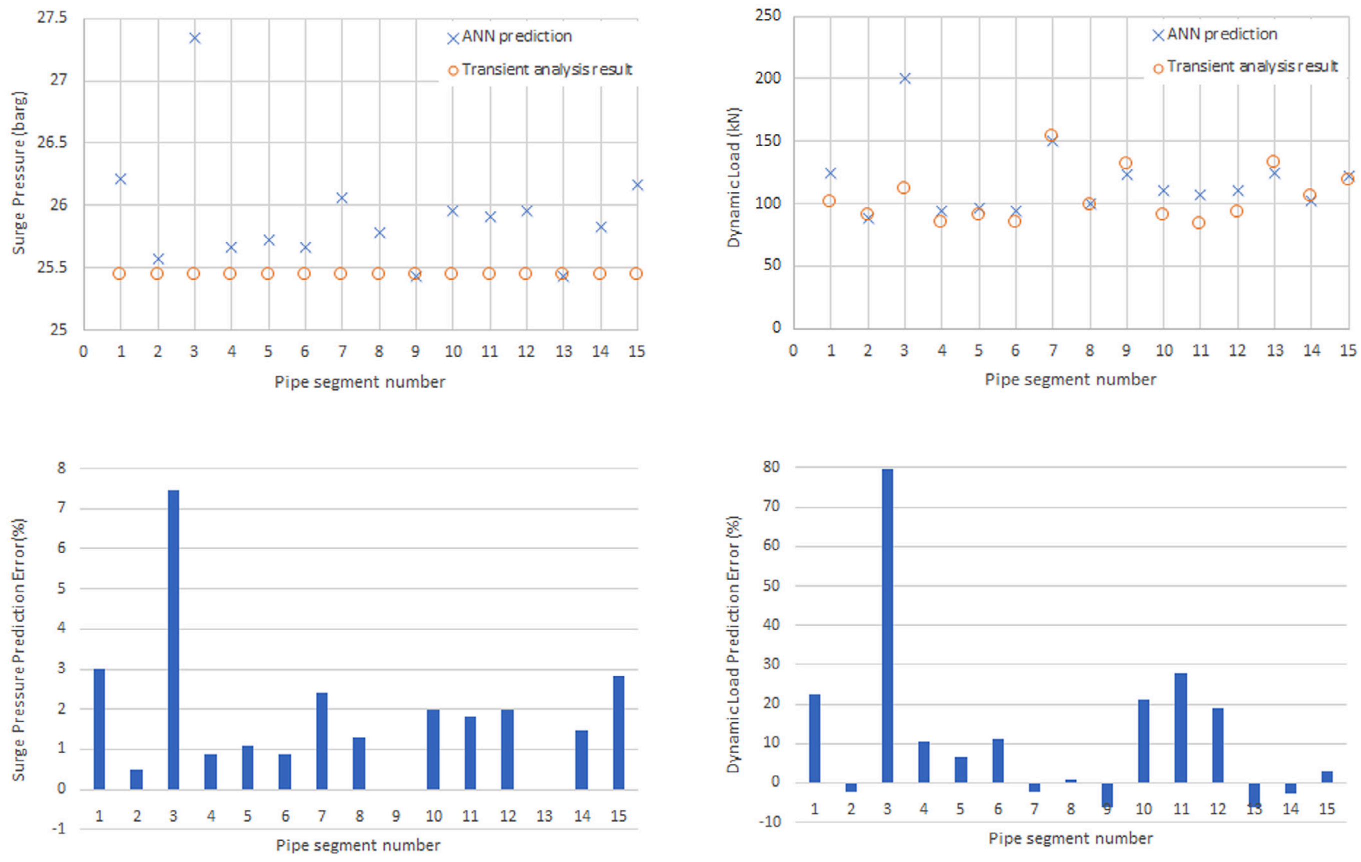

Figure 6 | Comparison of ANN predictions with the transient analysis result for the pipe segments in the main loading line downstream of the shoreline valve.

Ilker T. Telci

Ilker T. Telci holds a M.S. degree in Civil Engineering (2002) from the Middle East Technical University in Ankara, Turkey, and a M.S. and a PhD. degree in Environmental Engineering (2012) from the Georgia Institute of Technology, Atlanta, Georgia, USA. He worked as a postdoctoral fellow at the Centers for Disease Control and Prevention (CDC) performing air quality modeling and uncertainty analyses on a contaminant level reconstruction model. He joined Bechtel Corporation in 2013. He is currently a hydraulics and hydrology engineering group supervisor conducting hydraulic transient analyses in pressurized pipe networks in Liquefied Natural Gas (LNG) plants and chemical refineries. His current research interests are hydraulic transient (water-hammer) simulation, optimization, and machine learning.

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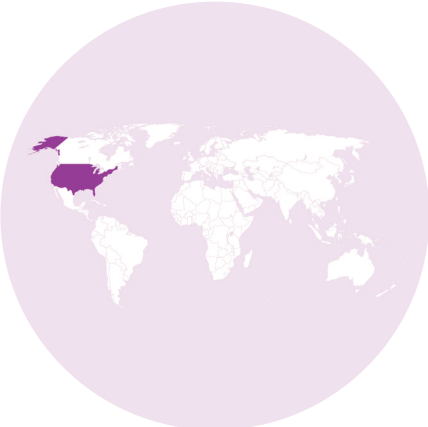
FAMOUS WOMEN IN HYDRAULICS

The IAHR task force on Strengthening Gender Equity intends to raise the profile and visibility of women who made major contributions to hydraulics.



$$\mathrm{Mo} = \frac{g\mu_c^4\,\Delta\rho}{\rho_c^2\sigma^3},$$

Rose Katherine Morton

1925 – 1999, USA

Rose Katherine Morton graduated in 1945 from the University of North Carolina, Greensboro NC, as a mathematician. She then moved as a mathematician to the David W. Taylor Model Basin, Navy Dept., Washington DC, where she was involved in model tests and computations of hydrodynamic problems. In a Report on the Hydrodynamics of slamming of ships, the author acknowledges her help in checking the manuscript and the computations. She then was in the research group of William L. Haberman (1922-1996), becoming known for her research on bubble flow in liquids. Morton married in 1953 and thus left the academic career in favour of her family.

The 1956 ASCE paper deals with a basic study of bubble motion. Experiments were conducted to determine the drag and shape of single air bubbles rising freely in various liquids. The results indicate that a complete description using dimensionless parameters containing viscous, surface tension, and density effects is impossible. In addition, three types of bubbles were observed, namely spherical, ellipsoidal, and spherical cap, in rising order of bubble diameters. For tiny spherical bubbles the drag coefficient is identical with that of the corresponding rigid sphere. As the bubble size increases, the drag reduction as compared with that of the rigid sphere occurs in some liquids so that the drag curves of spherical bubbles fall between these of the rigid and the fluid spheres. The particular finding of this study is the so-called Morton number Mo by which the separate effects of fluid viscosity, surface tension, and density are included, forming a dimensionless number which has turned out important in relation with two-phase air-water flows. It defines the shape of bubbles or drops moving in a surrounding fluid. It may be expressed in terms of the Weber, the Froude and the Reynolds numbers.

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Biography extracted from the IAHR book *Hydraulicians in the USA 1800-2000* by CRC Press ISBN 9780367575601 p. 2367.
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