Offshore renewable energies

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REVIEW

Offshore renewable energies: exploring floating modular energy islands—materials, construction technologies, and life cycle assessment

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Abstract
Floating modular energy islands (FMEIs) are modular, interconnected floating structures designed to collectively produce, store, convert, and transport renewable energy. This review aims to establish a foundation for developing innovative approaches to sustainably harness multi-energy sources in offshore environments. It leverages existing technological expertise while exploring new solutions to address specific challenges associated with FMEIs. The review initially presents existing technologies for floating energy structures and assesses their applicability to FMEI. The structural materials that could be utilised for the construction of a floating energy island are subsequently reviewed. Next, the offshore construction technologies suitable for FMEI are reviewed. Finally, studies on the life cycle assessment of hybrid energy systems are examined, highlighting the environmental advantages of integrating multiple renewable energy sources, thereby underscoring the potential of FMEIs.

Keywords Offshore · Renewable energy · Floating energy islands · Materials · Construction techniques · LCA

1 Introduction

To achieve the European Union's climate neutrality target by 2050 and address the growing global energy demand, offshore renewable energy is expected to play a vital role in the energy mix. This sector encompasses various sources, including wind, wave, solar, and other technologies, each at different stages of maturity. Offshore wind energy, for instance, had a total installed capacity of 14 GW within the EU in 2021, with projections indicating a 25-fold increase by 2030 (European Commission 2021). Meanwhile, emerging ocean energy technologies, such as wave energy converters, are currently less commercially utilised (Aderinto and Li 2018), but they hold the potential to achieve a competitive cost of approximately €0.15 per kWh by 2030 (EU 2022).

Despite the significant investments and developments in offshore renewable energy technologies, there is still a need to plan, design, and develop novel, efficient and innovative future sustainable energy infrastructure (European Commission 2022). The concept of floating modular energy islands (FMEIs) involves modular, interconnected floating structures. These structures work together to achieve multiple objectives, including renewable energy generation, storage, and eventual conversion and transport. Leveraging their modular characteristics, namely enabling to be expanded according to the needs, such islands are expected to be cost-effective and could serve the function of supporting different renewable energy generation alternatives including wind, waves, and solar. FMEIs could potentially offer co-located uses similar to multipurpose offshore platforms. As a recent study by Aryai et al. (2021) has demonstrated, their design must adopt a holistic system-level reliability approach that takes into consideration specific requirements for all the ocean resources (food, energy, etc.) while adopting particular construction materials, structural characteristics and anticipating failure modes, health monitoring needs and reliability targets. A schematic example of a FMEI in intermediate water depths (50–100 m) as well as in deep waters (>100 m)

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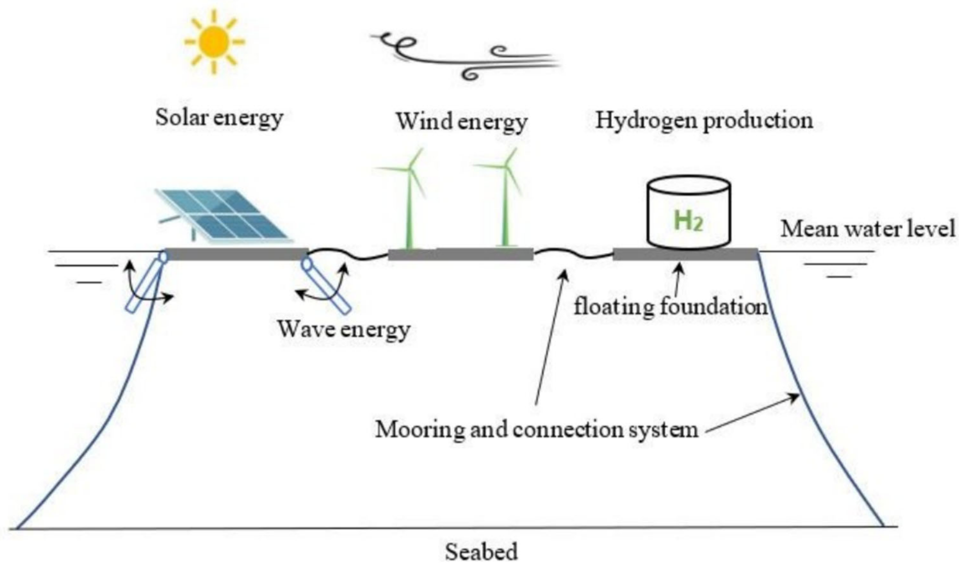

Fig. 1 Schematic of a FMEI with synergies of multiple renewable energy conversion and production devices

is shown in Fig. 1. Figure 1 illustrates a sketch (not to scale) of an energy island, integrating various types of renewable energy sources, including solar, wind, wave, and hydrogen. The energy island will be a floating structure, supported by mooring lines, and designed to collectively generate renewable energy. The basic components include modular floating foundations, mooring systems and inter-module connections, and energy conversion devices.

The present article provides a comprehensive review of topics relevant to the concept of the FMEIs. In particular, we present a perspective on existing technologies for floating islands, the identification of materials suitable for FMEIs, relevant construction techniques and life cycle assessments. As there is a lack of previous experience in such developments, the focus is on discussion of possible methods and solutions. The structure of this paper is as follows. In Sect. 2, state of the art of technologies on energy islands are presented. Section 3 provides an overview of materials and their applications in energy islands. Manufacturing and construction aspects are presented in Sect. 4. Finally, Sect. 5 discusses life cycle assessment (LCA) relevant to FMEIs.

2 Existing technologies for floating energy systems

The potential deployment areas of future FMEIs can be the North, Baltic, Mediterranean and Black Sea and the Atlantic Ocean. The areas that could benefit from FMEIs are for example offshore islands that today have high electricity costs. The exact number of modules, combination of renewable energy devices, geometry, and construction material of the FMEI should be site-specific and must be determined based on a techno-economic analysis. The modularization would enable the possibility to adjust over time the overall capacity of the island by adding new modules. FMEIs present some specific features that make them unique from several points of view. Therefore, the existing know-how borrowed from other marine renewable energy technologies cannot entirely cover all the challenges associated with the design of FMEIs. For example, from the structural mechanics standpoint, the most unexplored field is the interconnection of modules and the coupled nonlinear dynamic response of the multi-platform system. The question on how vibrations and loads are transmitted between modules, or if these connections can possibly be equipped with damping devices are critical aspects to be addressed. Although the concept of FMEI is relatively new, much literature can be found on other types of floating structures which FMEI shares similar features with and differs from. For this reason, existing concepts and recent research developments of very large floating structures (VLFSs), floating offshore wind turbines (FOWTs), wave energy converters (WECs) and floating solar and photovoltaic (FPV) energy devices are briefly reviewed in the following. These concepts have been recently reviewed in a connected work (Marino et al. 2024), and they are also briefly summarised hereafter for completeness.

2.1 Very large floating structures (VLFSs)

VLFSs are megastructures mainly designed for floating airports and ports in calm waters or open seas (Lamas-Pardo et al. 2015). Their development has been driven by the growing demand for exploitable areas, for multiple applications, e.g. agriculture, aquaculture and living, allowing for the development of self-sufficient communities. In the initial phase of conceptual design, the VLFS system was

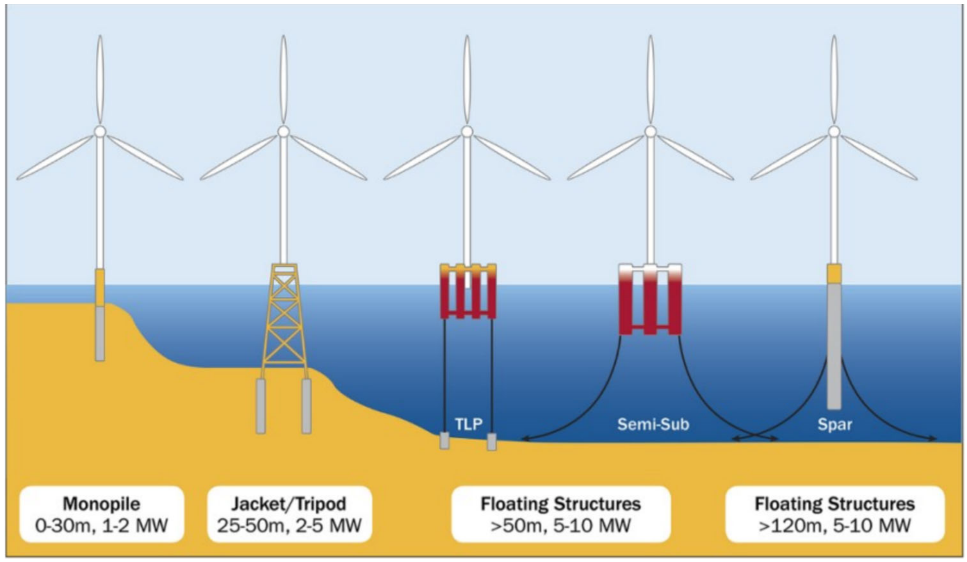

Fig. 2 Offshore wind turbines: Foundation types for offshore wind turbines (Bailey et al. 2014)

considered a single continuous structure, subject to substantial bending moments and shear forces within the floating structure. Japan has been at the forefront of research and development in VLFSs, since the early 1990s, making significant contributions to the field (Miyajima 1995; Pernice 2009). The Mega-Float was a 1-km long floating test runway in Tokyo Bay, which was established in 1995 and served as a prototype for floating airports, providing valuable data on the behaviour of large floating structures (Wang and Tay 2011). Focussing on large-scale floating structures, Suzuki et al. (1996) explored structural design considerations, whilst later Wang et al. (2006) provided comprehensive insights into VLFS, including aspects of hydroelastic analysis.

Later, the modular concept was developed with the benefits of easy fabrication, transportation, installation and expansion. One of the first concepts was the mobile offshore base. The platform was meant to support military operations, providing a modular floating base that can be deployed in any areas. It was made of rectangular, self-propelled semi-submersible modules. This particular geometrical choice has better seakeeping capabilities than pontoon-type platforms and allows for tuning the ballast during transit operations. For modular VLFS systems, the design of connectors is an important consideration, and Jiang (2021) presented the working principles and the effects of different connector technologies for VLFSs. Hydroelastic analysis is also necessary for safe design of systems because of the impact of structural deformations (Ren et al. 2019). Recent advances in VLFS technology have focused on developing multipurpose platforms, where different levels of the structure serve varied functions. For example, in the EU Space at Sea project (Flikkema and Waals 2019), the concept of modular triangular floaters are used to achieve the applications of energy generation, living and urban extension, aquaculture, transport, and logistics. In this sense, the FMEI can be regarded as an unmanned multipurpose platform with a focus on energy conversion, storage and transport.

2.2 Floating offshore wind turbines (FOWTs)

Wind energy, along with solar energy, represents the most dominant way to produce renewable electricity globally. Wind turbines convert the kinetic energy of wind into electrical energy and vary in design and installation location, particularly between onshore and offshore sites. So far, the vast majority of wind power is generated through onshore wind farms. The first offshore wind farm is the Vindeby wind farm, which was commissioned in 1991 in the shallow waters near the Lolland Island in Denmark. Since then, many offshore wind farms have been commissioned worldwide. Most offshore wind turbines today are applied in shallow waters only, as they have gravity-based foundation structure, which must be connected to seabed, usually pile or jacket foundation type, as shown in Fig. 2. The floating technology represents the current challenge in harnessing wind energy through very large turbines. A floating offshore wind farm can be divided into several main components: offshore wind turbine (OWT), floating offshore wind platform (FOWP), mooring (M), anchoring (A), and electrical system (ES) (Grivas et al. 2020). The main components of OWT are the tower (also called the mast), the rotor which houses the blades and a nacelle which comprises the generator and serves as a protective cover (Chandrasekaran et al. 2022).

FOWTs are necessary for deep-water open seas sites where the wind resource is more abundant and there is a reduced environmental impact compared to nearshore or onshore areas. Although the concept of FOWT was proposed

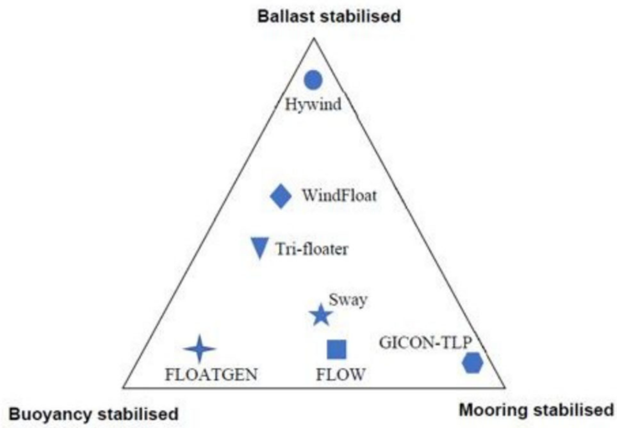

Fig. 3 Categorisation of selected FOWT concepts based on their restoring mechanisms (Jiang 2021)

earlier, substantial academic and commercial interests did not emerge until the early 2000s Jiang (2021). Generally, based on the restoration mechanism used to achieve hydrostatic equilibrium, FOWTs can be classified as ballast-stabilised, buoyancy-stabilised or mooring-stabilised during operation (Jonkman 2007). Figure 3 illustrates the relative position of different commercial concepts in this restoring triangle. As shown, most FOWTs depend on a combination of these mechanisms.

For ballast-stabilised solutions, the hydrostatic stability in rotation is achieved by lowering the centre of gravity of the entire system. To achieve this, the spar platforms may have a deep draft that can exceed 100 m. Spar FOWTs like Hywind (Skaare et al. 2015) belong to this category. Advanced spars with additional damping mechanisms have also been proposed; see (Tao and Dray 2008; Pham and Shin 2019). Semi-submersible FOWTs achieve stability both by the water plane area and by its gravitational position. The semi-submersible type consists of a buoyant steel structure partially filled with water or other suitable materials to provide the ballast, while the SPAR type uses a weight positioned deep under water, usually a long steel cylinder, to provide counterbalance (Henderson et al. 2010). A semi-submersible hull is characterised by moderately drafted columns connected together by slender braces or by pontoons. The construction and installation of a semi-submersible platform is complex due to the large mass of steel used and the large amount of required welded connections (Chandrasekaran et al. 2022). References of semi-submersible designs are found in (Roddier et al. 2009; Robertson et al. 2014; Ferri et al. 2022). Novel designs of semi-submersible FOWTs have also been proposed like the braceless concept (Luan et al. 2016), the V-shape concept (Zhang et al. 2020a, b), and the annular hull concept (Allen et al. 2020). Unlike spars or semi-submersibles, tension leg platform (TLP) FOWTs achieve their stability primarily by mooring tendons with high pretensions and are deemed suitable for deepwater. On the other hand, such designs become complicated due to sensitivity of the system resonance phenomena and to the difficulties arising in anchor installations. As commercial offshore floating wind farms, e.g. Hywind Scotland, consist of individual FOWTs and only have the functionality of wind energy generation, whereas FMEIs should fulfil multiple functionalities, existing floating wind farms are dissimilar to FMEIs. Still, common features can be found between a FMEI and a floating wind farm. First, certain floating platforms of FOWTs, e.g. semi-submersibles, can be of interest for floating modules with similar restoring mechanisms. Second, a reliable and cost-effective station-keeping system must be designed for a floating wind farm and a FMEI. Especially, recent developments of floating wind farms with shared mooring (Connolly and Hall 2019; Liang et al. 2021) provide references for rope connection systems of FMEIs. Ivanov et al. (2023) presented TaidaFloat demo project, a semi-submersible FOWT floater, in Taiwan and Asia-Pacific area, discussing motion constraints the mooring system. Recently, Wan et al. (2024) examined the safety, stability, and lightweight design of a large FOWT in an ongoing project in Wanning City, China, focussing on its aero-hydro-elastic behaviour through numerical simulations.

2.3 Wave energy converters (WECs)

A WEC is made of a floating structure anchored through mooring lines to the seabed. WECs can be classified by criteria like operational principle, absorbing wave direction, location and power take-off (Qiao et al. 2020). In a floating offshore context, the most commonly adopted operational principle is the floating body type, although this may be less efficient than the oscillating water column type (Babarit 2015). The wave direction plays an important role if a WEC is integrated to a large FMEI. The attenuator and terminator are two WEC types strongly influenced by the direction of the waves, while a point absorber can produce power independently of the wave direction (Xu et al. 2019). Although the commercialization of WECs has been slower compared to offshore wind, cost-effective integration is possible when the appropriate type of WEC is incorporated into an FMEI, leveraging positive synergies. See Fig. 1 for an example of a flap-type WEC integration (Wilkinson et al. 2017). As the power capacity of a WEC is relatively small compared to that of an FOWT, WECs often work in a farm. Recent studies demonstrate the economic potential of WECs when built in farms (Castro-Santos et al. 2018), as well as their reliability (Rinaldi et al. 2018) and feasibility (Lavidas and Blok 2021). Still, the additional benefits and challenges of adding WECs to a FMEI require detailed assessment of site-specific environmental conditions, dynamics and synergies of the WECs with the floating platform, economic feasibility and many other considerations; see Choupin et al. (2021).

2.4 Floating solar and photovoltaics (FPVs)

Floating solar, also known as floating photovoltaics (FPVs), or “floatovoltaics”, refers to solar panels installed on a platform that floats on water. The system is considered an environmentally friendly way of producing electricity. It combines marine and renewable energy technologies. The electricity produced by the panels is commonly transported to a transmission tower onshore through underwater cables. Floating solar installations mounted on hydropower plant reservoirs are particularly cost-effective as they can be connected to existing power grids. Installing floating solar panels on water has many advantages over more traditional projects, such as (1) no loss of valuable land space, (2) high solar panel performance, (3) environmental benefits and (4) can be installed at existing power plants. However, they also come with some limitations that can make them difficult to install in certain areas. The limitations refer to (1) cost, (2) applications, (3) disruption of aquatic life, and (4) site selection complications (Mehra 2022). An FPV system typically consists of floating structures, connection systems, mooring and anchoring, solar panels and electrical systems. Although FPV technologies have primarily advanced over the past decade, their use is largely confined to freshwater bodies or nearshore sheltered areas. Due to the significant concerns around manufacturing, installation, and maintenance costs, the FPV industry tends to favour standardised floating modules made from lightweight materials such as high-density polyethylene to support PV panels, along with semi-rigid or flexible connectors to link the floating modules. Examples of such FPV systems can be found in the 1-MW FPV test bed at Tengeh Reservoir in Singapore (Liu et al. 2018). Kim et al. (2016) discussed the adoption of floating photovoltaic systems in Korea, highlighting their advantages, installation trends from 2009 to 2014, and the increasing government support for large-scale FPVs to meet renewable energy targets. For open-sea applications, a few concepts have reached a high technology readiness level and have been demonstrated at a large scale. Figure 4 illustrates four commercial concepts among which the Oceans of Energy concept was successfully tested in the Dutch North Sea in 2019. In addition, there are also research and development of FPV towards harsh offshore conditions. Among the concepts, Seavolt (2023) is designed with a floating platform with an elevated deck above sea level (see Fig. 5a) and hence is prone to large wind loads. In contrast, another concept (Jiang et al. 2023) proposes semi-submersible floats with low drafts and adopts soft connection to make a compliant system in waves (Fig. 5b). Golroodbari and van Sark (2020) have examined the energy yields of solar panels in the North Sea. They created a computer model to simulate how floating solar panels respond to wind, waves, and temperature. Their results indicated that, on average, floating solar panels at sea produce about 13% more energy than those installed on land, with potential increases of up to 18% in certain months. Recently, Dellosa et al. (2024) assessed the risks of floating solar photovoltaic systems in Philippine lakes and explored policies from China, Japan, and South Korea, aimed to mitigate risks and ensure that FSPV systems are deployed in a safe, sustainable, and cost-effective manner.

The FPV is constructed from one or several unit structures. A unit structure consists of solar modules, support frames, a floating system, and connecting devices (see Fig. 6). The solar module must be dustproof, lead free and well protected from the high humidity and effects of water. The buoyancy is achieved using polyethylene floating structures. As a typical FPV system is modularised, it uses lightweight floating support structures and has mooring and connection system, thus the design considerations of FPV plants in marine environments are similar to those of FMEIs. Regarding the support frame structure (Claus and López 2022), most floating photovoltaic designs are made using metallic structures, i.e., stainless steel, galvanized steel (Sharma et al. 2015), low corrosion steel, Kim et al. (2020), or aluminium (Perera 2020). In marine applications, the support frame structure may play an important role in keeping the panels at a safe height from sea level (López et al. 2021). An improved solution could be thin-walled aluminium tubes filled with polystyrene foam. The strengthening effect of foam filling in thin-walled aluminium tubes was investigated by Toksoy and Güden (2005). The research showed that the load bearing capacity of such members was higher than the combined load bearing capacity of the aluminium tubes and foam, due to the interaction effect. The major issue regarding steel or aluminium in marine structures is corrosion. As an alternative, composite materials such as fibre-reinforced polymers (FRPs) are incorporated due to their high resistance to corrosion against seawater (Rubino et al. 2020) but also due to their lower density (Selvaraju and Ilaiyavel 2011; Kim et al. 2017). In Kim et al. (2017), the results of the design, fabrication, and installation of the floating type of photovoltaic energy generation system of 1 MW using pultruded FRP (PFRP) were presented. The structural design was carried out using PFRP members to prevent corrosion of the structure and the results showed potential benefits in construction and cost effectiveness in a floating PV generation system, with PFRPs as an alternative to metallic based solutions.

Unit structures are fabricated on the ground and then connected on the water. To reduce the transfer of bending moments caused by water surface movement, the unit structures are interconnected with stainless steel bolts or bars (Kim et al. 2017). The floating platforms are held in place

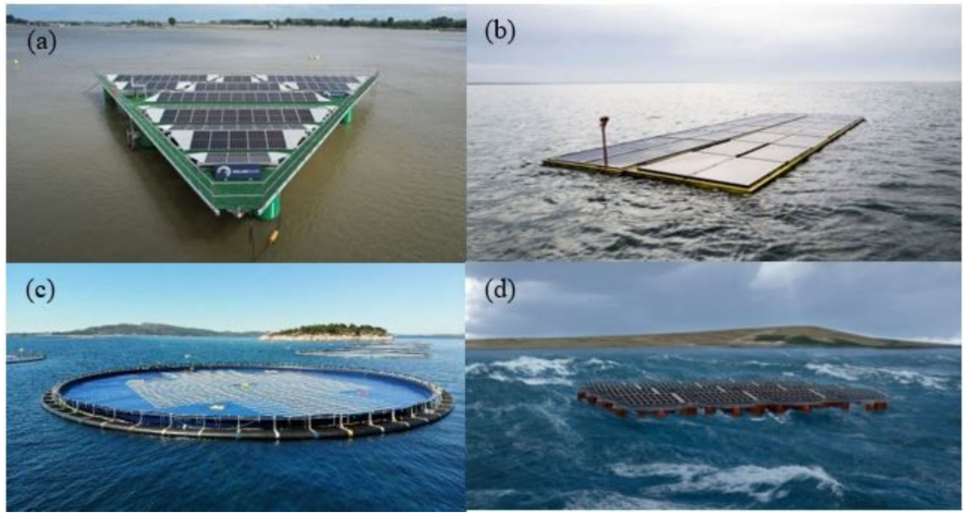

Fig. 4 Illustration of four existing FPV concepts **a** SolarDuck (2022), **b** Oceans of Energy (2022), **c** Vagle and Bjar (2018), **d** Moss Maritime (2021)

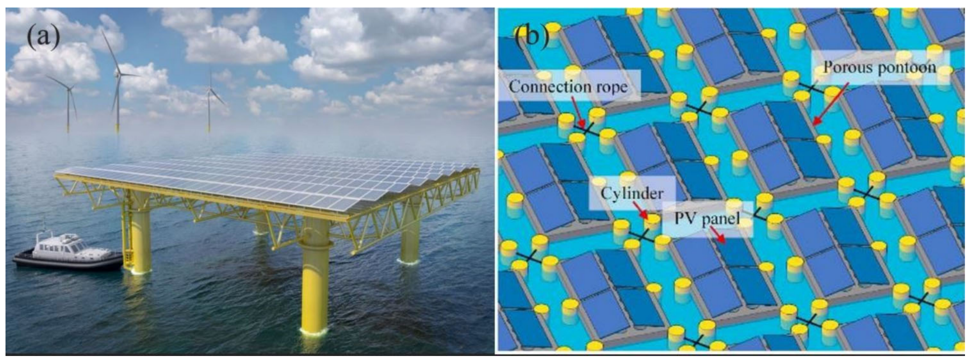

Fig. 5 Illustration of two FPV concepts for offshore applications **a** Seavolt (2023), **b** soft-connected semi-submersible (Jiang et al. 2023)

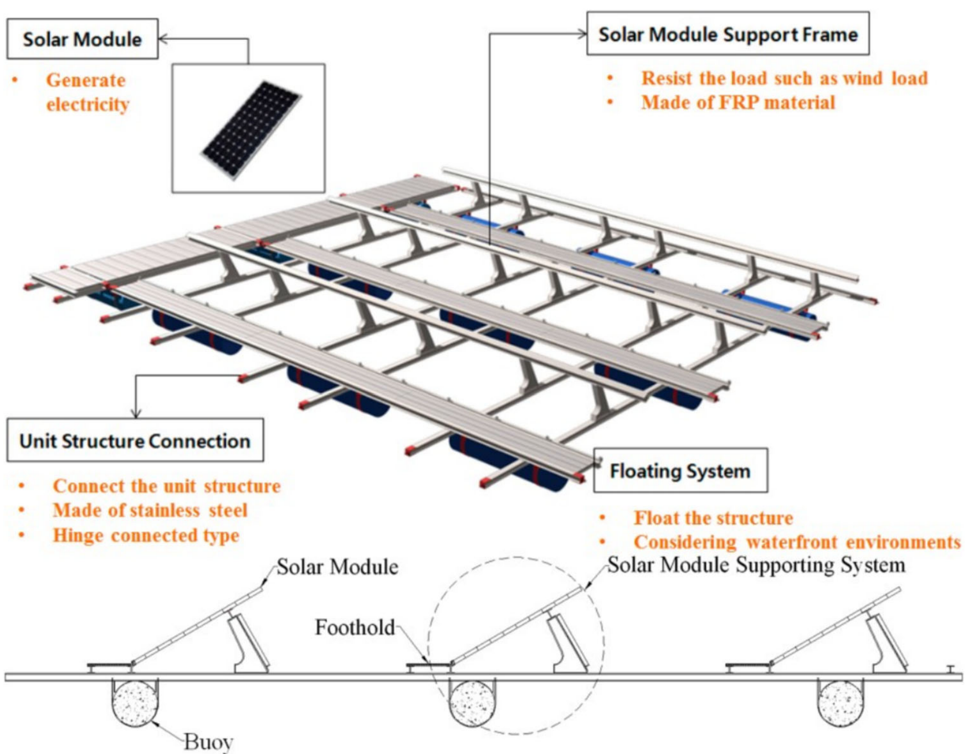

Fig. 6 Composition of unit structure (Kim et al. 2017)

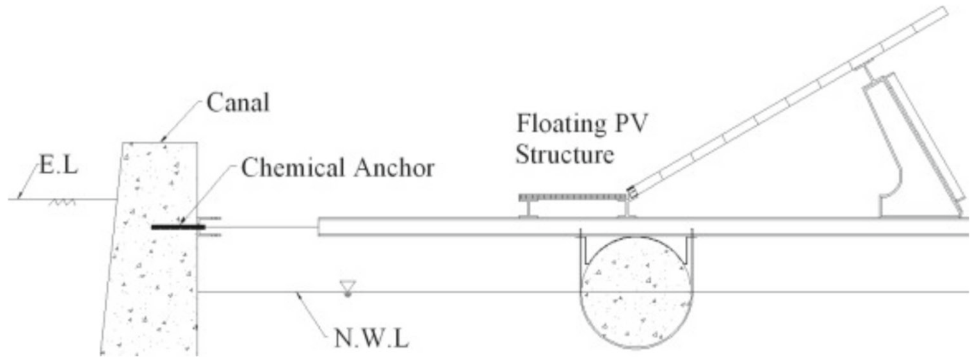

Fig. 7 FPV anchored to the shore (Kim et al. 2017)

by an anchoring and mooring system. This prevents floating platforms from drifting with the wind and water currents and potentially damaging the equipment. Most FPV systems are anchored to the waterbed, while some FPV systems are anchored to the shore (see Fig. 7). The common types of anchors when anchoring to the waterbed are dead weights, such as concrete blocks. The mooring lines that go from the anchor to the floating structure are usually made of galvanized steel wires, chains, wire rope, synthetic fiber rope or a combination of these materials. They often have a spring to allow for variations in water level (Kim et al. 2017).

Oliveira-Pinto and Stokkermans (2020) assessed different FPV technologies and listed the requirements for marine FPV systems. The requirements include survivability, reliability and maintainability, power performance, scalability, and a positive environmental footprint. As recommended practice of FMEIs is not developed, some of the above requirements can be addressed at the design stage. As FMEIs should integrate several renewable energy devices, e.g. wind turbines and WECs, the corresponding environmental loads must be greater than those on FPV systems. Considering this, the development challenges for FMEIs abound.

2.5 Challenges in integrating renewable energy resources into FMEIs

The successful deployment of FMEIs faces several technical and environmental challenges. The structural mechanics issues, such as the complex interconnection of floating modules, the nonlinear dynamic responses and the transmission of vibrations and loads among modules require advanced engineering solutions, including the potential use of damping devices to improve stability. The complexity of mooring systems, particularly with shared mooring lines and varying geometries requires advanced computational models. VLFSs introduce additional challenges related to hydroelastic performance and the feasibility and structural integrity of the modular expansion. The integration of WECs should account for site-specific environmental conditions, platform dynamics, and cost-efficiency of energy harvesting. FPVs face further obstacles, including high installation costs, corrosion of support materials and stability concerns. Addressing these challenges is essential for ensuring the long-term viability, adaptability, and environmental sustainability of modular FMEIs.

3 Materials for floating energy islands

This section presents a review of materials applicable to FMEIs. The materials used in such structures are identified, along with their relevant properties. A recent review article has identified the integration of innovative and improved materials in the manufacture of increasingly larger components, while maintaining quality and keeping costs down, as a significant research challenge for today's large wind turbines, especially offshore (Veers et al. 2023). Materials for FMEIs will need at least as much careful consideration. It should be noted that the FMEIs-specific challenges mentioned above, see Sect. 2, are reflected also on the choice of materials to be used for the construction of modules, connections, mooring system and so on.

3.1 Steels: recent developments and potential applications in FMEI

Although very susceptible to corrosion, steels have a long tradition of use in an aggressive marine environment. The reasons for the wide use of steel in wind turbines lie in its favourable properties, namely strength, flexibility and ability to work at high and low temperatures (Topham et al. 2019). Also, steel is a 100% recyclable material, which can therefore adapt to future requirements from the aspect of sustainable development. In addition, the use of steels in construction presents a series of additional benefits, such as aesthetic appeal and speed of construction. Steels for structural uses can be classified into different categories, based on their chemical composition, tensile properties and manufacturing method. The advancements in material science have led to the development of a variety of high performance construction steels, such as high strength steels and stainless steels. High strength steels (yield strength > 500 MPa) are increasingly used in offshore structural applications and can offer significant benefits when structural weight is a governing design factor. Stainless steels have a high chromium content which makes them resistant to corrosion and hence favourable for marine and offshore applications.

Nowadays, steels find various applications in the renewable energy sector, due to their inherit advantages. The examples include: solar panels, wind turbines, wave power systems, transmission lines, transformation stations, bars for hydraulic pistons and gears. Given that steel is a major component in the construction of energy structures, it is expected to be widely applied in FMEI.

Currently, a variety of steels is used in wind turbine towers, not only for the structural tower itself, but also for the nacelle and the rotor blades. According to Topham et al. (2019), steel accounts for approximately 83% of the total mass of offshore wind turbines. In particular, the wind turbine tower is usually made of a tapered circular steel hollow section. The tower is constructed of fan-shaped segments cut from steel plates, which are then shaped by a rolling process and welded into conical pieces (World Steel Association 2012). In the case of tubular towers, the steel section thickness depends on the steel grade used and on the load conditions and can vary from 8 mm at the top of the tower to 65 mm at the bottom (World Steel Association 2012). In case of lattice towers, different steel sections are used in truss configurations. At the top of the wind turbine tower, the rotor and a nacelle are placed. To hold the composite blades together, a rotor hub is used, which is typically made of cast iron or forged steel (World Steel Association 2012). The nacelle, which protects the most valuable components of the wind turbine, not only the generator, but also the shafts and the gearbox, is also made out of steel, whilst it can also contain composite materials and PVC foam (Catapult 2023). The generator is made of steel (65%) and copper (35%), while the gearbox is mostly made of specially hardened steel components (World Steel Association 2012), along with a small amount of copper, cast iron and aluminium (Catapult 2023). A wind turbine usually has two shafts, the main shaft and the generator shaft, which can be made from different materials, typically steel or aluminium alloys but synthetic composites as well.

In case of floating offshore energy structures, the supporting structures are mostly made of steel and can broadly be categorised into three main types. Platforms are made mainly of steel. To connect the floating platforms to the seabed, mooring lines are used and can be fabricated from a choice of various materials, including steel chains, steel wire ropes and steel pipes, but also synthetic fiber lines (Henderson et al. 2010). Anchors for floating wind turbines can be gravity based (made of concrete), but various types of steel anchors can also be used, such as suction pile anchors (Henderson et al. 2010). In addition to the foundations of the platforms, steels are used in offshore platforms in applications such as fasteners, safety cables, davit cranes and fittings.

In solar energy, supporting structures of solar power plant technologies (e.g. solar photovoltaic, concentrated solar power, concentrator photovoltaics) are mostly made of steel (Mexisteel 2023). Either fixed or moving steel structures are used to orient the technology towards the sun (Fig. 8a). These structures are often made from cold-formed steel profiles with anti-corrosion zinc coating, whereas they can be preassembled at the factory, to shorten the construction period. Similarly, in wave energy systems, steel structures support the main part of the converter system. For example, a jacket steel structure with an oscillating water column (OWC) is shown in Fig. 8b. In addition, the world's largest wave energy converter, which involves a series of air-inflated cells, will be mounted on a steel foundation structure secured beneath the ocean's surface (Bomborawave 2023).

3.2 Aluminium alloys: recent developments and potential applications in FMEI

In the last decades, aluminium alloys are considered a popular material in marine and offshore applications as they can provide significant benefits regarding minimization of costs, manufacturability, flexibility, and performance reliability within aggressive environments. Material mechanical and physical properties, along with the technological and normative evolution, play an important role for the deployment of this material. Aluminium is light ($\rho = 2700$ kg/m^3), reducing weight up to 70% over steel and reaching weight savings to 50% for both mechanical and electrical applications (Mazzolani et al. 2020). In offshore oil and gas industry, lightweight aluminium components and systems, which provide up to 12% cost saving and allow for modularity, prefabrication, and assembling through bolting, contribute to minimizing transportation expenses and speeding up installation processes, while facilitating decommissioning activities (Mazzolani 2006). Moreover, due to the development of an aluminium oxide layer when material is exposed to air, aluminium is highly resistant to corrosion in the atmospheric zone, making it thus a suitable material choice for marine applications, such gangways and floating docks (Kissell and Ferry 2002). Consequently, protecting surface coating, expensive inspections and repairs are not required, leading to less maintenance costs. Moreover, the extrusion process that is strongly connected to aluminium production technology and its flexibility in design, leads to high functionally of relevant structural profiles and shapes and provides tailored cross-sectional solutions according to the specific application (Mazzolani 1994). As Kim et al. (2021) highlighted in a recent research on the design of an offshore aluminium tertiary component, although the primary material cost for

Fig. 8 Examples of steel applications in energy structures: **a** a substructure for photovoltaic panels made of thin-walled cross-sections with typical bolt connectors (Mrówczyński et al. 2022); **b** a jacket-type structure installed with OWC converter (Zhang et al. 2020a, b)

aluminium exceeds that of carbon steel, the non-requirement for hot-dip galvanization and welding in assembly due to extrusion in case of aluminium resulted in similar or even lower cost. Moreover, considering the maintenance period, aluminium is more cost-effective than carbon steel after an average of 5.7 years.

Owing to the performance reliability within aggressive environments, aluminium is widely employed in structures situated in corrosive or humid environments such as swimming pool roofs, river bridges, hydraulic structures and offshore super-structures (Mazzolani 2003), see Fig. 9a. With respect to the latter, frequently aluminium is used for items in the topside structure of offshore platform such as handrails (Fig. 9b), stair towers, mezzanine flooring, access platforms (Mazzolani 2003). Aluminium's suitability for construction of decks, bulkheads and superstructures as well as ships, is further enhanced by the utilization of friction stir welding (FSW), a solid-state joining method characterised by limiting MIG welding costs, eliminating the necessity of filler material to create flat surfaces and collaborating with the extrusion feature, to merge thin-walled lightweight designs into large and flat panels that are so important in the marine and offshore industries (Hydro 2023).

Aluminium alloys are typically classified based on the primary alloying element added to aluminium, which influences the thermal and mechanical processes involved. The basic classification distinguishes between wrought and cast aluminium alloys. With respect to which of the aluminium alloys are more suitable for marine and offshore applications, there is the EN 13195-1 (2013) standard which refers to the alloys that are qualified for naval architecture, sea and offshore technology. Towards improved performance in wet aggressive environment, special alloys are added, developing marine-grade aluminium. Marine grade wrought aluminium alloys usually comprise of EN AW 5xxx (Al–Mg/aluminium-magnesium) and EN AW 6xxx (Al–Mg–Si/aluminium–magnesium–silicon) alloys family (Thyssenkrupp (2022). They are generally used in shipbuilding industry, docks, and several other offshore structural applications. Additionally, cast aluminium alloys are employed in a variety of marine applications due to the ability of casting processes to produce relatively intricate shapes, such as ship superstructures, structural components, interior fixtures, and various supports. They are usually 4000 series (Al–Si alloys) or 5000 series (Al–Mg alloys).

Regarding the deployment of aluminium in offshore wind energy sector, Jupp (2011) summarised the potential of providing the advantages that material technology can confer to the applications and the respective components of offshore wind structures. Recently, Grivas et al. (2020) investigated numerically the feasibility of cables with aluminium conductor and high- lighted the advantages for floating offshore wind projects for low weight, low cost and deep water applications. Aluminium cores for static power cables applications were examined in relation to respective ones made of copper which is the conventional choice of material due to its lower resistive losses and a comparative analysis of these two options in terms of costs and performance was presented.

Further to the usage of aluminium as structural material, aluminium-based coatings can be efficiently used in marine environments. Recently, the use of thermally sprayed aluminium (TSA) coating with the thickness of 350 µm in combination with organic coatings was announced for a wind farm in the Baltic Sea as an alternative technique to avoid the use of anodes, thus reducing the metal emissions (Syrek-Gerstenkorn et al. 2020). Furthermore, the KOKON II project, examined a new zinc-aluminium coating with copper for its suitability as corrosion protection for flange connections (Strom-Forschung 2021). In Fig. 10, the corrosion effects on uncoated specimen are depicted. Within the renewable energy field, one of the latest developments is the synergy of aluminium in a support structure of a new offshore floating solar solution. SolarDuck and Hydro introduced recently a floating solar solution, Fig. 11, where a photovoltaic-covered three-sided structure contains aluminium profiles and the weight reduction was the primary reason for selecting aluminium (Hydro 2021).

A very recent development regards the partnership of two companies World Wide Wind AS and Hydro and their plans to use aluminium in floating offshore wind (FOW) through developing vertical axis floating wind turbines with a design specifically meant for offshore conditions (World Wide Wind 2023). The concept behind is to enhance sustainability and recyclability in construction and to enable the deployment of aluminium in several parts of the wind turbine structure, see Fig. 12.

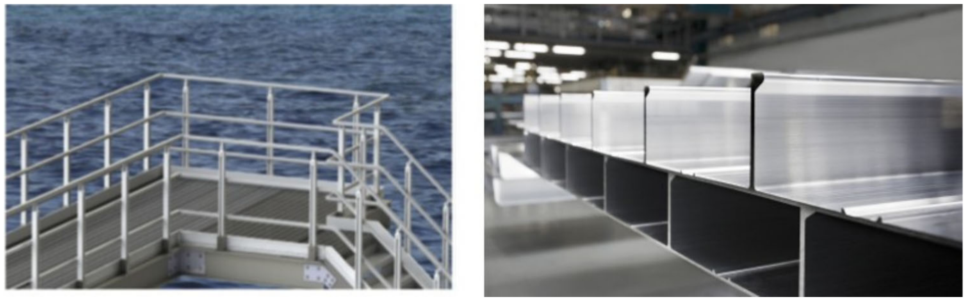

Fig. 9 Aluminium applications in marine and offshore field: **a** handrails; **b** ship building-deck panels (Mazzolani 2003)

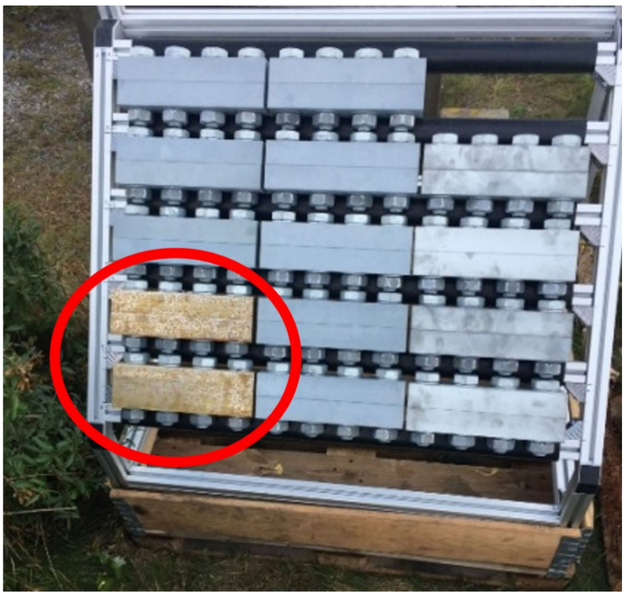

Fig. 10 KOKON II project-corrosion effects on uncoated demonstrators (Strom-Forschung 2021)

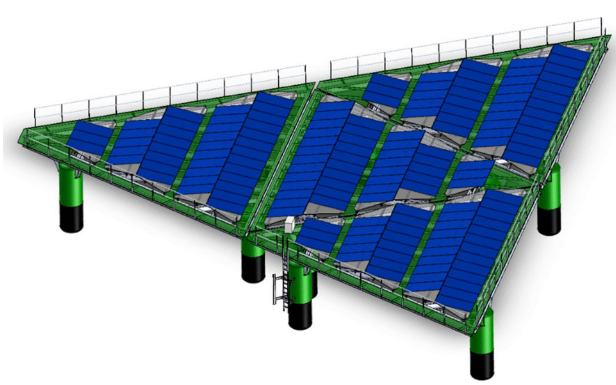

Fig. 11 Integrated aluminium offshore floating solar solution (Hydro 2021)

3.3 Metal additive manufacturing: recent developments and potential applications in FMEI

Commonly referred to as 3D printing nowadays and rapid prototyping in the past, additive manufacturing (AM) is an upcoming technology based on the addition of material layer by layer. Early applications of this process centred on the rapid production of concept designs and initial prototypes. However, as the technology surrounding AM improves, more final and mass-produced applications become popular in almost all industries, from medicine to engineering (Post et al. 2017). AM has already been used in the energy production industry by producing moulds for turbine blades (Gibson et al. 2015). Likewise, larger applications of concrete AM started to raise in popularity in the early months of 2022 in the United States aiming to solve transportation difficulties and promote on-site construction (Office of Energy Efficiency & Renewable Energy 2022; GE Renewable Energy 2022).

Metal AM can be achieved by several techniques, the two most widespread are powder bed fusion (PBF) and direct energy deposition (DED). PBF uses a thermal energy source—laser or electron beam—to fuse powdered metal. The finishing of the pieces is of high accuracy but the production time is lengthy, making it suitable for small and complicated volumes. Likewise, the production requires a controlled and inert atmosphere to prevent the material from oxidising, limiting its application to small components that can fit into this closed environment (Buchanan and Gardner 2019).

On the other hand, DED does not require an enclosed space since the technique consists of melting the source material to accumulate layers, i.e. the source material that is being melted, has not been pre-laid in a working bed but is rather melted as being deposited. This source material can be either a metallic powder flow or a metallic wire, melted through laser or electron beams (Gibson et al. 2015).

Wire arc additive manufacturing (WAAM) has become a widely used technique for producing large steel components, such as those needed in construction engineering, due to its time and cost efficiency (Tankova and da Silva 2020). WAAM belongs to the DED family, in which the layers of metal are

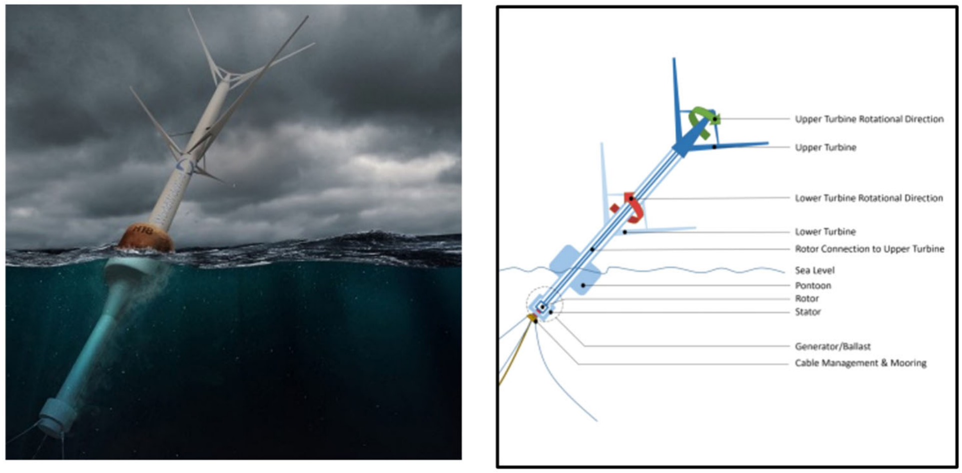

Fig. 12 Aluminium based design of vertical axis floating offshore wind turbine (World Wide Wind 2023)

deposited through robotic gas metal arc welding (GMAW). WAAM is essentially the same method of production used nowadays for the robotic welding of wind towers and jacket structure's nodes but depositing the material in layers instead of a single weld. Nevertheless, WAAM technology is not fully developed yet and—to this date—it is challenging to obtain a final printed piece of high quality. Like the welding process that inspired it, WAAM is subjected to fast cooling, resulting in high residual stresses and distorted geometry, as well as variable material properties and internal voids that is amplified when layers are accumulate during production (Tankova and da Silva 2020).

Wire feed rate, arc current, inter-pass temperature and torch speed have proven to considerably affect the mechanical properties of the obtained material. Hence, a lot of the scientific effort is focussed on solving these issues, both in terms of calibration of the process accordingly to the desired result (Cheng et al. 2019; Hu et al. 2019) or searching for statistical models that will help predict the material properties (Dodwell et al. 2021).

AM has rapidly evolved since its first application in the structural engineering sector and could be employed for the development of structural nodes. These could be efficiently applied in for FMEIs, where custom made solutions might be essential. Initially, AM was being used to create only architectural components to hide the real joints. In Galjaard et al. (2014) a structural node was presented with a 15% weight reduction. This investigation demonstrated that optimised AM joints can help reduce peak stress values, improve fatigue (a feature of significant relevance in offshore structures) and make a more efficient material use. Likewise, Strauss et al. (2015) used AM with polymers to print the nodes of a facade system of high structural complexity (see Fig. 13a).

WAAM was used by Erven et al. (2021) to print a traditional T-stub connection. Nevertheless, despite trying to print with a rotated welding torch to improve the final shape, the results were not particularly better and led to further difficulties while printing, leading to an uneven surface that made the tightening of the bolts almost impossible. This study concluded that the printing technique has a great influence on the behaviour of the connection and that special care needs to be taken regarding the roughness of the surface (see Fig. 13b). Space frames using tubular sections often require the production of devices to accommodate the geometrical needs of a node. An effort to solve this through AM can be found in Lange et al. (2021) where the node for a connection involving four members with symmetric loading was fabricated (see Fig. 13c).

For the AM technology to be employed in FMEIs, understanding of the fatigue performance of AM structures is critical. Indeed, many of the advantages of this innovative technology have been shadowed due to lack of research about its fatigue performance, a pressing issue on the offshore field. The AM process may include in the fabricated pieces many initial defects that can be the root of crack initiation. Some researchers have already started a discussion on the topic. Zhang et al. (2016) compared the fatigue crack propagation behaviour between WAAM and wrought alloys, finding that the crack growth rate was, in fact, lower in WAAM due to the tortuous path the crack had to overcome and the lamellar structure. Later, Zhang et al. (2017) completed a study to investigate the fracture toughness in WAAM concluding that this new technique appears to be a good option for damage tolerance-driven designs because of its fracture toughness performance, but that its behaviour is dependent on the propagation direction (i.e. across or aligned with the additive layers). In Xin et al. (2021), the fatigue life of WAAM stainless steel was compared to that of structural steel S355 and S690. It was found that both structural steels have a better fatigue performance than the stainless steel WAAM and confirmed what other researchers stated in

Fig. 13 AM connection examples: **a** Nematox facade (Strauss et al. 2015), **b** T-stub (Erven et al. 2021) and **c** space frame (Lange et al. 2021)

the past about having a different fatigue performance depending on the printing direction. Recent studies have also tried to characterise the fatigue behaviour for AM materials using probabilistic approaches and successfully predict the fatigue curves to ensure the reliability and safety of the parts (Niu et al. 2022).

The suitability of metal AM for offshore applications is highly dependent on the research performed in terms of its fatigue behaviour. Therefore, further investigation needs to take place to ensure that this new fabrication technique is able to provide materials and shapes that can withstand the cyclic loading actions present in a structure such as a floating platform.

3.4 Concrete: recent developments and potential applications in FMEI

The construction industry is responsible for the consumption of a significant number of resources including energy use in the production of construction products. The degradation of structures exposed to aggressive environments results in high maintenance requirements and also the need to replace damaged structures and infrastructure. This leads to a significant environmental impact, as a result of durability issues, therefore, encouraging the use of more durable construction materials. Hence, the need to produce highly durable materials requiring minimal maintenance, which are resilient with a long service life, has recently emerged. In parallel, the degradation of reinforced concrete structures remains a key concern in the construction industry with increasing efforts in ensuring more durable structures and infrastructure particularly in coastal regions. Extending the service life of existing strategic coastal infrastructure made of reinforced concrete remains a main priority. Improving the mechanical and durability properties of cementitious materials has been the subject of continuous research. Improvements have been made possible through the use of admixtures, fibres, and other constituents, creating an enhanced material.

Two of the major causes of deterioration in concrete are the exposure to aggressive substances as well as cracking. These cracks allow for the penetration of fluids, hence negatively affecting the concrete durability. It has been proven through an abundance of literature that small cracks in concrete will experience self-healing. This means that the material has the potential to close the cracks and restore itself to its original state. When this occurs naturally, without any additives in the concrete, it is said to have undergone autogenous healing. This mainly occurs under moist conditions due to hydration, but as the concrete ages, carbonation becomes the main stimulator towards healing. In basic terms, healing occurs when the cracks are filled due to chemical reactions occurring in the presence of moisture. To further enhance this naturally occurring phenomenon other constituents are added to the mix leading to autonomous healing. Crystalline admixtures added to the mix react and reduce concrete porosity with the penetration of aggressive substances being limited, enhancing durability. They react when in contact with water meaning that crystals form in the cracks in concrete, filling the pores, and in turn reducing the penetration of fluids. Each time a crack is formed in the concrete, the same process is repeated and healing re-occurs.

Suitable for aggressive marine environments, like offshore energy structures, ultra-high durability concrete (UHDC) is based on a higher percentage of cement or binder, fly ash or silica fume, aggregates smaller than 6mm, steel fibres, superplasticiser, and a small amount of water, with a high water-cement ratio. The mix design for UHDC eliminates coarse aggregate to achieve a better packing density, hence increasing its strength. The large amount of cement, compared to that of water causes some of the cement grains to remain dehydrated initially. These grains remain inert, however when cracks eventually start forming in the concrete, this material can be hydrated and a reaction begins. This gives UHDC the ability to self-heal any cracks forming within. The addition of steel fibres increases the tensile strength and ductility of concrete. These properties are advantageous over normal concrete mixes since they prevent cracking and limit the penetration of substances. Hence UHDC is adequate in aggressive environments. Since UHDC can achieve very high strengths, it can be applied in reduced volumes in optimised design, hence decreasing the self-weight of a structure and increasing its efficiency. High performance textile reinforced concrete with self-healing properties can also be exploited to achieve improved performance in aggressive environments. The material is based on a Carbon fibre textile, embedded in resin and cast as reinforcement in a high-performance mortar.

Reinforced concrete structures degrade over time and a key factor accelerating degradation in reinforced concrete is exposure to chlorides, especially in marine environments. Chloride penetration in concrete causes corrosion of the steel inside which in turn causes internal expansion in the concrete. To mitigate this scenario, the porosity and permeability of the concrete should be reduced. Ultra-high-performance fibre reinforced concrete (UHPFRC) has been assessed under such conditions. Negrini et al. (2019) achieved positive results in reducing permeability and water penetration in UHPFRC. The samples that underwent chloride penetration displayed better performance in autogenous healing. This was also confirmed by Borg et al. (2018) who found that self-healing in concrete is accelerated when the material is exposed to a chloride-rich environment. Hence, UHDC and UHPFRC are materials appropriate for application in marine environments, like those of a FMEI.

As part of the ReSHEALience Horizon 2020 project, which dealt with the development of self-healing ultra-high performance concrete (UHPC) and textile reinforced concrete (TRC), these materials were developed and also applied in real scenarios including coastal and floating structures. Several pilot projects were carried out bringing the concept to life in realistic scenarios. The pilot projects included floating structures such as a floating raft, a floating wind turbine and a floating pontoon/breakwater construction using ultra high durability concrete. A concrete raft constructed using UHPC was floating in Valencia. The strain of the beams was continuously monitored, with some beams intentionally designed to experience micro-cracking during service to assess the effectiveness of self-healing in various concrete mixtures. The beams themselves are of different widths to measure the evolution of corrosion. A floating wind turbine structure was designed and constructed using UHPC. It was designed by taking a floating steel off- shore platform as a reference to reproduce a similar structure using UHDC concrete. The structure constructed did not reproduce the complete platform but a part that included one of the floaters and a part of the connecting arm between floaters. A floating pontoon was constructed in Ireland, with different technologies including different textile reinforced self- healing concrete. A degraded coastal structure in the Grand Harbour in Malta was retrofitted using UHPC and Textile reinforced concrete with crystalline admixtures for self-healing and nano-additives, following an extensive repair and restoration intervention. Textile-reinforced concrete was used in the Tank and UHPC was applied to the columns. The UHDC used in the concrete columns also included different nano-additives to improve strength and durability performance in aggressive coastal environments. The structural health and durability of the structure are monitored using an advanced sensor network system, with embedded sensors.

These projects display the performance of UHPC when exploited in chloride-rich and marine environments. They further demonstrate the potential of concrete for coastal marine and floating structures for aggressive environments.

3.5 Composites: recent developments and potential applications in FMEI

Non-metal composite materials have attracted the interest of engineers for decades especially due to their durable performances and reduced weight. Early applications are designed to overcome corrosion problems experienced with steel and aluminium. If a composite structure is properly designed, it may allow for reduced maintenance costs, reduced self-weight, increased reliability, reduced environmental impact and improved durability (Huang et al. 2020). There are three commonly accepted types of composites, i.e. fibre composites, particle composites, and laminated composites. Fibre-reinforced polymer (FRP) composites are one of the most used non-metal composites. FRP composites have been utilised in aerospace engineering, wind power generation, road and bridge retaining walls, and marine engineering due to their desirable material properties, including a high strength-to-weight ratio, exceptional durability and corrosion resistance, and ease of construction. (Han et al. 2020) There is an enormous opportunity for the adoption of composites in energy structures and in FMEI. In recent times, composites have grown in popularity and are mostly used for full thermoplastic composite pipes or hybrid composite structures (Amaechi et al. 2022). A potential application of composites in energy structures and in FMEI can be found in the literature (Razavi Setvati et al. 2014).

Although they are usually made from steel, mooring lines connecting floating structures to seabed can also be fabricated from synthetic fibre lines such as nylon, polypropylene, polyester and Kevlar. Furthermore, non-metal composite materials are an essential part of wind turbines as they are used to fabricate the blades. Fibreglass has become increasingly popular in recent years due to its high tensile strength and lightweight. Traditionally, glass fibres were used almost exclusively for the production of blades. However, due to the rapid increase in blade size, interest has shifted from glass to carbon fibre, a newer lightweight alternative material with high stiffness, which was adapted a few years ago for use in larger turbines, but its cost is still high (Spyroudi 2021). In addition to the blades, the wind turbine generator shafts can be made of composite materials. Following concerns regarding the environmental impact of composite waste from wind turbines (Majewski, et al. 2022; Rani et al. 2021), a possible solution is to reuse and recycle the material for the construction of solar farms, including floating solar panel structures (Vattenfall 2022).

3.6 Material selection: summary

FMEIs require advanced materials that not only ensure durability in harsh marine environments, but also support modularity, efficient energy integration, and long-term environmental sustainability. Material selection plays a crucial role in the feasibility of the modular construction, since components should be strong, yet lightweight to allow easy transportation and assembly. Steels and aluminium alloys can be used as structural materials in the energy infrastructure, but each presents challenges: steel offers high strength but is prone to corrosion, while aluminium has a very good strength-to-weight ratio and is more adaptable for modular designs, but comes with stability and fire performance considerations. For energy integration, materials should be able to support and combine different renewable technologies, while maintaining structural integrity under dynamic loads. AM presents opportunities for customised modular components, but issues with residual stress, fatigue performance and quality control should be considered to ensure long-term reliability. For the concrete applications in FMEIs, exposure to chlorides and cracking can reduce lifespan. Innovations, such as self-healing concrete and UHPC, can potentially enhance durability. From an environmental sustainability perspective, material selection affects the life cycle impact of FMEIs. Lightweight materials, such as FRPs, can improve the energy efficiency, by reducing transport and installation costs. In addition, sustainable alternatives, such as bio-based composites and corrosion-resistant alloys, could offer low environmental impact, whilst ensuring modular scalability. Ultimately, balancing durability, modular adaptability, and sustainability is key to the successful material selection and deployment of FMEIs.

4 Offshore construction techniques for energy islands

In general terms, offshore construction can be divided into two stages. First, the onshore manufacturing of components and their transportation to the site—usually towed by a vessel of substantial capacity—and second, the offshore lifting, placing and alignment of the parts. Thus, the logical trade sequence, the simplicity of the on-site works and the practicality of the erection order are critical to a successful construction process and determine a project's buildability level (Cheetham and Lewis 2001). Floating offshore relies more heavily on onshore manufacturing than their bottom-fixed counterparts, adding an additional space constraint to the works due to the availability of port facilities, the limited resources required for such endeavour and the considerable size of the structures. Nowadays, only a few shipyards and ports can host these massive projects (Crowle and Thies 2022). Moreover, only limited number of vessels are up to the task of transporting and erecting such structures (O.E. Magazine 2022; Calma 2022; Offshore Construction Associates 2022). Even though the energy island may later supply the necessary surface to install other components, a significant construction effort will inevitably need to be undertaken to accomplish this concept.

4.1 Traditional offshore erection techniques

Generally, offshore structures are built in a large workshop close to a port or in the port itself and later transported to the site. Once they are towed out to sea or other bodies of water, the lifting and assembling procedures occur. Some typical offshore erection techniques are explained below and illustrated in Fig. 14.

- Transportation by crane vessels: large crane vessels can lift and position heavy structures into place. Currently, they are often used for installing offshore wind turbines and assembling oil rigs.
- Foundations by pile driving: Pile driving inserts large steel or concrete piles into the seabed to provide a foundation for offshore structures.
- Foundations by suction pile technology: suction pile technology uses a large vacuum to create suction and secure the foundation piles into the seabed, which can effectively and efficiently install structures in soft soil.
- Erection by jack-up rigs: often used for installing offshore wind turbines, these offshore mobile platforms are built up of a buoyant hull with movable legs that can self-lift the hull above the sea's surface to create a stable platform to mount other structures. The buoyant hull allows the unit and all attached machinery to be transported to the desired location. Once on-site, the hull is "jacked up" to the required elevation above the sea surface. They are not self-propelled and must be transported by tugs or heavy lift ships.
- Floatover construction: this method involves a heavy-lift vessel to transport and in- stall a prefabricated deck or platform onto a pre-installed jacket or foundation piles. The prefabricated platform floats over the prebuilt structure.
- Installation by skidding: Skidding is the process of placing heavy structures along a prepared track or skidway using specialised equipment. Oversized jackets, modules, and other offshore structures are frequently installed using this technique.

Fig. 14 Traditional offshore erection techniques: **a** crane vessel transportation also used for pile driving (van de Burg 2006), **b** suction pile technology (BoH 2006), **c** common offshore jack-up rig (Mirafiori 2010), **d** skidding equipment mounted on a vessel (Mammoet nd), and **e** characteristic vessel for FLO-FLO (Seaway 7 nd)

- Float-off and float-on practice (FLO-FLO): This technique involves using a barge to transport and install large structures. The barge is floated into position, and the structure is then floated off onto the pre-installed jacket or foundation piles.

These are but a few of the several construction methods used in the offshore sector. The approach chosen will rely on numerous variables, including the structure's size and nature, the water's depth, the seabed's state, the available resources, and others. Detailed information about these methods can be found in (El-Reedy 2019; Gerwick 2007; Jiang 2021; Sadeghi 2007)

4.2 Critical resources for floating offshore construction

As with traditional offshore construction, floating offshore construction concentrates heavily on ports and shipyards, since most of the structures need to be completely finished before towing. This makes port infrastructures a critical resource. Another critical resource in offshore construction is the crane time demand. Cranes are usually expensive equipment that can even draw the boundaries of a project. The productivity of a crane can vary in the rapidity of its movements (i.e., hook travel time, slewing or jibbing out), lifting capacity, ability to move and the characteristics of the construction site. Specifically for offshore applications, there are a reduced number of cranes around the world mounted on vessels (Offshore Construction Associates 2023). Offshore installation operations rely on only a few cranes available worldwide, whose demand is growing faster than the supply. In addition, it has been seen how unforeseen accidents in vessels have cost severe disruptions in projects. The latter confirms the significant impact Operation and Maintenance has on new developments and the paramount importance of rethinking the way offshore structures are built. One more critical aspect of offshore construction is weather scheduling. On top of the limited and expensive resources available for construction operations, weather conditions can significantly delay an offshore project. Therefore, a thorough simulation of the construction activities must include models to simulate the site's wave height and wind speed. A methodology to accomplish this can be found in Kerkhove and Vanhoucke (2017).

Early decisions during the design can highly impact the construction and erection processes and related costs. Hence the relevance in planning the construction sequence and improving site practice. Two design factors that significantly influence construction costs are repetition and standardisation, and successfully achieving the desired tolerances (Steel Construction Institute 1995, 1997). An appropriate example of this is the fabrication of joints. Offshore bolted joints are sometimes undesirable because they require regular maintenance and are prone to start corrosion. However, site welding is significantly more expensive because of the high level of expertise needed from the workers. Finally, deciding which type of joint is more suitable for a project must take into consideration the available resources and infrastructure. As a result of this, method statement development has gained traction in recent decades. With this methodology, the design process is established by assuming a specific method of construction beforehand. Another popular option is "partnering", which involves the collaboration of organisations with different expertise (Barlow 2000).

The success of a project might be intrinsically related to its buildability and good site coordination that understands the capabilities of the resources available and the site weather conditions. Hence, industrialised production of standard modular parts that can be easily transported from the port to the open sea is necessary to reduce port facilities' time and space requirements. In recent years, some offshore wind farms have migrated from high-capacity wind energy generators that require massive logistical efforts to smaller ones that are still easier to handle with the existing infrastructure due to the scarcity of construction resources. This situation might be interpreted as a call for attention to what could happen in the development of other types of offshore projects, such as FMEI. Rethinking how offshore projects are conceived and constructed must be a priority, in which modular systems that are simple to manufacture, transport and erect can play an important role. Modularisation could also increase the number of suppliers and diversify the supply chain, waiving many of the risks associated with the supply of large critical components that require particular infrastructure to be built. Furthermore, offshore construction is often carried out in challenging and remote locations, posing significant risks to workers and the environment. As a result, strict safety and environmental regulations should be in place to ensure that construction activities of a FMEI are conducted safely and sustainably.

4.3 Challenges related to construction of FMEIs

Constructing modular offshore energy islands requires specialised techniques to ensure stability, durability, and cost-efficiency. Timely execution of large-scale projects, such as a FMEI, is highly dependent on the availability of specialised vessels and cranes. Offshore construction is also highly weather-dependent, necessitating advanced simulation models to optimise scheduling. In addition, fabricating and maintaining modular joints is complex and requires skilled personnel. To overcome these obstacles, there is a critical need for standardised designs that streamline the manufacturing, transport, and assembly procedures, ensuring the efficient and cost-effective construction of FMEIs.

5 Life cycle assessment of energy islands

In order to evaluate the environmental impact of a product or service over its entire life cycle, from raw material extraction, through production and use, to disposal/recycling, life cycle assessment (LCA) can be performed. LCA is a systematic approach defined by ISO 14040 (2006a) and ISO 14044 (2006b) that takes into account various environmental problems, such as greenhouse gas emissions, resource depletion, and pollution, and can help identify opportunities for improvement in terms of sustainability. LCA can provide useful information in evaluating the environmental impact of different types of energy systems, and identifying areas where improvements can be made and can therefore be applied for floating offshore structures and FMEIs. There are many commercial or open-access software available that can be applied to LCA of energy systems, including GEMIS (2023), SimaPro (2023), Gabi (2023). Although the application of LCA to energy modular islands is still not popular, some studies are already available in the literature focussing on LCA and energy systems. Hence, this section of the paper provides a review of LCA studies in the field of hybrid energies and other sources of renewable energy, such as wind and photovoltaic.

5.1 LCA of hybrid energy systems

Hybrid energy generation refers to the simultaneous use of multiple energy sources to generate electricity or other forms of energy (Manwell 2004; Palatel 2017) as presented in Fig. 15. This approach combines two or more renewable or non-renewable energy sources to create a hybrid power plant, increasing the energy production process's efficiency, reliability, and cost-effectiveness.

Hybrid energy systems can combine traditional fossil fuels like coal or natural gas and renewable sources like solar, wind, hydroelectric power and biomass (Manwell 2004). In FMEI context, practical combinations could be wind and solar power, wind and hydropower, and solar and hydropower. The combination of wind and sea/ocean waves as hydropower to make a hybrid system which offers several advantages when compared with standalone offshore wind farms, has been investigated in Rasool et al. (2023). Offshore wind energy is expanding steadily, while offshore wave energy, despite its considerable global potential, remains largely underutilised. The main challenges to the commercial development of wave energy conversion systems are their high cost and complexity. However, these challenges can be offset if they are integrated into the well-developed offshore structure of wind turbines. These are the reasons why Gao et al. (2022) and Zou et al. (2021) and explored the idea of introducing wave energy converters into the offshore wind system as a hybrid system.

When it comes to assessing the environmental impact of hybrid energy systems, a life cycle assessment can be a useful tool. Hence, there are many investigations related to LCA of onshore and offshore wind energy systems (Gkantou and Baniotopoulos 2018; Liu et al. 2021; Yildiz et al. 2021) and

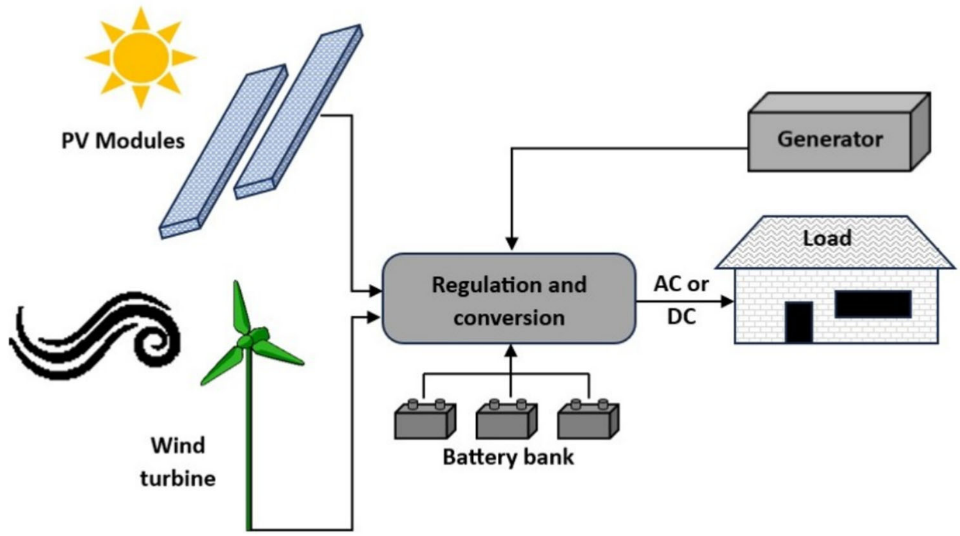

Fig. 15 Hybrid energy system

of hybrid onshore energy systems (Abubakar Jumare et al. 2019; Petrillo et al. 2016; Yildiz et al. 2022a, b; Yuan et al. 2023). Hydrogen from ocean wind was studied in McDonagh et al. (2020) while electro fuel offshore was presented in Thommessen et al. (2021). Ababneh and Hameed (2022) presented a review on the recent advances in the field of electro fuels and discusses the Electro fuels life cycle assessment, and their economic and technical evaluation.

Another study by McKenna et al. (2021) synthesised the state of the art in offshore energy system integration. A review of hybrid offshore wind and wave energy systems was carried out in McTiernan and Sharman (2020). Hybrid technologies for marine energy harvesting were discussed in Taveira-Pinto et al. (2021) and a roadmap to hybrid offshore system with hydrogen and power co-generation was provided by Yan et al. (2021). Turconi et al. (2013) conducted a critical review of 167 LCA of electricity generation based on hard coal, lignite, natural gas, oil, nuclear, biomass, hydroelectric, solar photovoltaic and wind power. The emission data were assessed across three life cycle phases: fuel supply, plant operation, and infrastructure. It was determined that greenhouse gas (GHG) emissions alone are insufficient as a sole measure of a system's or technology's environmental performance. The variability in LCA results for electricity generation can result in conflicting conclusions about the environmental impact of adopting new technologies. Bonou et al. (2016) investigated the environmental impacts of integrating 1 kWh of wind power into the European grid, and recommendations were made on how LCA can aid in technology development and system planning. The study focussed on four representative power plants: two onshore with 2.3 and 3.2 MW turbines, and two offshore with 4 and 6 MW turbines. It was found that the energy payback time for all technologies is less than 1 year. The overall higher impact of offshore turbines compared to onshore turbines is mainly due to the higher material requirements for the capital infrastructure.

5.2 LCA of floating offshore wind energy

The floating offshore wind energy (FOWE) has shown a promising potential to unlock the plentiful and reliable wind source in deep-waters, avoiding the visual impact near coasts and competition for land use. Besides the technical innovation, the techno-economy and environment impact play even more crucial roles in the development of FOWEs. FOWEs are preferable to fixed-bottom systems at deep-waters due to their better techno-economy and environment performance, rather than technical feasibility. Thus, it calls the first-class priority of research efforts on the life-time economy and ecological performance of FOWEs through the execution of LCAs (Davidsson et al. 2012).

The traditional onshore wind energy has been well developed since the installation of the world-first commercial wind farm Delabole in the UK in 1991 (Edwards and Milborrow 1992). Accordingly, a large number of LCA studies can be found on onshore wind, in terms of both the economy (Garrett and Rønde 2013) and environment (Guezuraga et al. 2012). Currently, novel onshore wind structures are of particular concerns, including the lattice tower (Stavridou et al. 2020) and lattice-tubular hybrid tower (Gkantou et al. 2020), which enables the installation of large-size turbines at improved heights. With the sufficient data from the literature, regression-based LCA works have been carried out at national level (Xu et al. 2022) or general level (Bhandari et al. 2020), with regard to the turbine size and capacity factor.

However, limited studies can be found on offshore wind energy, particularly on the emerging FOWE. For instance, Mendecka and Lombardi (2019) conducted a comprehensive review and regression analysis on a total of 148 publications respecting LCA of wind energy in Europe. Out of these studies, only 32 are specified to offshore wind, among which 6 works are dealing with floating wind. The findings suggest a negative correlation between the environment impact per kWh and the nominal power for both the onshore and offshore wind energy. Nevertheless, the actual trend in the FOWE still remains unclear due to the limited data. A pioneering work on LCA of FOWEs was carried out by Weinzettel et al. (2020), who investigated the environmental impact of a floating farm comprising 40 turbines of 5MW and a transition station. The study indicated that the FOWE has an environment impact similar to the classical offshore wind due its better capacity factor. In addition, the result highlighted the importance of the end-of-life (EOL) recycling in mitigating the total impact. Myhr et al. (2014) employed LCA to investigate the levelised cost of energy (LCOE) of FOWEs, considering various type of floating foundations. The LCOE of FOWEs was found comparable to fixed-bottom ones in the water depths ranging from 50 m to 150 m, and superior beyond 150 m. The work also identified the optimal type of foundations for different water depths, such as tension leg platform (TLP) for depths from 40 m to 75 m, tension leg buoy (TLB) for depths from 75 m to 300 m, and tension leg spar (TLS) for depths greater than 300 m. The finding also suggested a sizable reduction in LCOE by minimizing the usage of steel. Castro-Santos et al. (2018) studied the economy performance of different FOWE in Portugal, and claimed an urgent demand to reduce the LCOE to enhance the economic viability of FOWEs. It was found that, only Spar and Semi-submersible FOWEs exhibited positive economy performance after raising the electrical tariff from 200 €/MWh to 300 €/MWh. Several featured studies can be also found specified to different regions, including Italy (Maienza et al. 2020; Pulselli et al. 2022), France (Poujol et al. 2020), China (Yuan et al. 2023) and Brazil (Ferraz de Paula and Carmo 2022).

Li et al. (2022) introduced a prospective LCA model to predict the worldwide environment impact of the offshore wind from 2020 to 2040. The study elucidated a notable drop of 20% in the GHG emission via the standard routine, with a potential reduction of 14–25% by implementing novel technologies such as FOWE. As commonly adopted in LCA of FOWEs, the system boundary (Li et al. 2014) covers cradle-to-grave phases of manufacturing, installation, operation & maintenance (O&M), and decommissioning & disposal (also called as EOL). In most of the reviewed works, the manufacturing has been regarded as the primary contributor to both the environment impact and LCOE, while the share of O&M is often underestimated, ranging from 1 to 6% (Myhr et al. 2014; Li et al. 2022) Poujol et al. (2020) investigated the lifetime GHG emission by the 6 MW floating wind turbine installed on either a spar or a semi-submersible foundation. Manufacturing was found to account for 70% and 75% GHG emission in the spar and semi-submersible foundations, respectively. On the other hand, a minor contribution by O&M was reported, i.e., 7.8% and 9.7% attributed to Spar and semi-submersible, respectively. Yuan et al. (2023) also claimed the crucial role of manufacturing in determining the GHG emission, and suggested a reduction in GHG by 71% due to switching of steel production method from blast furnace and basic oxygen furnace to electric arc furnace. However, the O&M of FOWEs is complicated due to the factor such as long distance to shore, large-scale structure and turbine, and harsh environment. It is hence deemed essential to scrutinise the influence of O&M with refined assumptions and modelling. Garcia-Teruel et al. (2022) investigated the environment impact of two pilot wind parks (Hywind Scotland Jacobsen and Godvik (2021) and Principal Power (2022)) in the UK via a detailed O&M model to quantify the effect of vessels choices. The study confirmed a total contribution of 26%–49% to the total GHG emission of FOWEs by O&M, and highlighted a prominent variation of up to 34.8% induced by the choice of O&M vessels. A further effort by Rinaldi et al. (2021) was conducted on the economic performance of the above two wind farms in terms of LCOE. The O&M was identified as a major contributor the total LCOE, i.e. a share of 13.9–19.6%, with sparse parts and vessel hiring account for the major cost. The study also indicated that a positive techno-economy performance could be expected by raising the current electric tariff in the UK from 57.5 to 100 £/MWh.

With the growing investment in FOWEs, an extension in the service life is assumed as a viable strategy to maximise economic performance and to minimise environment impact, due to the additional energy production. At the global scale, a notable reduction of 11% in the GHG emission was predicted to stem from extending the normal service life from 20 to 25 years (Li et al. 2022). According to the regression analysis by Bhandari et al. (2020), a similar reduction of 8% in GHG emission of wind energies is expected by extending the service life of both the onshore and offshore wind from 20 to 25 years. More specifically, Poujol et al. (2020) indicated that an increase in the service life by 20% could result in a reduction of 15%–20% in the environment impact of FOWEs. Nevertheless, it is crucial to strike a delicate balance as the longer life leads to increased O&M costs and environment impact (Poujol et al. 2020), and more crucial, the structural risks due to the long-term deterioration (Heng et al. 2022a, b). In facing the challenge, Yildiz et al. (2022b) developed the refined O&M and EOL models for LCA of a barge-type floating wind turbine. The findings suggested that GHG are lowered by extending the service life from 25 years to 30 years via frequent major maintenance actions. The study also considered four different paths for the EOL scenario, including landfilling, mechanical recycling, incineration and mechanical recycling-to-incineration. The outcome indicated that the mechanical recycling is the most feasible option according to most recent environmental policies.

5.3 LCA of photovoltaic energy systems

Photovoltaic (PV) systems have been claimed to be zero-emissions systems. However, an in-depth assessment of all possible environmental issues is warranted. During operation, PV energy is a clean energy source; nevertheless, its influence on air quality and climate change may be observed during the manufacturing phase (Tawalbeh et al. 2021). The majority of environmental issues originate from the manufacturing process, particularly heavy elements such as steel, iron, copper, silicon, and aluminium, which demand a lot of energy (Hemeida et al. 2022). In addition, in comparison with other types of renewable energies, PV systems demands a large area for operation and maintenance (Tawalbeh et al. 2021; Hamed and Alshare 2022).

The environmental consequences of PV systems might be significantly reduced by optimised design, development of innovative materials, reduction of hazardous components, recycling, and better site selection. Such mitigation activities would minimise GHG emissions to the environment, limit solid waste accumulation, and conserve vital water resources (Tawalbeh et al. 2021).

According to Ling-Chin et al. (2016), the existing onshore PV panels, for example thin film, amorphous, mono- and poly-crystalline, can also be used for offshore applications. Naturally, the adaptation for installing this system in a marine environmental needs to take into consideration some additional design peculiarities, like high humidity and salt, installation conditions and shading issue (Kobougias et al. 2013). From a LCA perspective, offshore PV systems differ from onshore only on the requirement of coated or galvanised metallic parts (Ling-Chin et al. 2016).

For the selection of the offshore PV system components, some key factors should be taken into consideration to build a proper life Cycle Inventory (LCI). For example, the life span of different types PV systems ranges from 20 to 30 years and their greenhouse gas (GHG) emission rates from 9.4 to 280.0 gCO 2 e/kWh (Sherwani and Usmani 2010). In addition, according to Peng et al. (2013), 1 m2 of thin-film, mono-crystalline, and poly-crystalline PV modules require respectively 811–3150, 2860–11,673, and 2699–5150 MJ of energy to be produced.

5.4 LCA: observations for FMEIs

This section provided a brief overview of studies focussing on LCA of hybrid energy systems, floating offshore wind energy and photovoltaic systems. Although renewable energy systems, as those that will be installed in a FMEI, are much more environmentally beneficial than fossil fuel sources, particularly in term of GHG emissions, the production and decommission of such systems are not burden free. The manufacturing processes for the energy infrastructure are material-intensive, contributing to greenhouse gas emissions and resource depletion. The operation and maintenance of a FMEI can face logistical difficulties, related to the long distances to shore, harsh environmental conditions and the complexity of the floating modular structures, and can thus lead to increased costs and environmental impact. The end-of-life management of a FMEI can present additional environmental challenges, especially regarding the disposal and recycling of wind turbines and solar panels. Therefore, developing recycling strategies and improving the sustainability throughout the FMEI's life cycle is essential for long-term viability and for minimisation of the environmental impact.

6 Conclusions

The concept of FMEIs refers to modular, interconnected, floating structures that function together to provide renewable energy generation, storage, and eventually conversion and transport. The implementation of such a concept requires the effective synergy of multiple engineering disciplines and industries in the construction, marine and renewable energy sectors. As such, the present paper efficiently collates and reviews past knowledge on a wide range of topics, relevant to the realisation of FMEIs.

The paper starts with a review of existing technologies of floating structures. The developments of very large floating structures, floating offshore wind turbines, wave energy converters and floating solar and photovoltaic energy devices, are reviewed. The discussion includes development challenges owing to the combined integration of energies and technologies in FMEIs. The review then focuses on construction materials and construction techniques relevant to FMEIs. In is concluded that advances in materials and manufacturing processes have enabled the development of high performance materials, comprising excellent mechanical properties, good ductility and corrosion resistance. It is also emphasised that the latter will be of particular importance in the marine environment of FMEIs. Hence, the corrosion characteristics of high performance steels, aluminium alloys, ultra-high durability concrete could be an efficient choice for such applications. It is also concluded that advancements in automated construction, such as metal additive manufacturing, could be applied for the complex geometries of structural components of the floating islands. The offshore construction techniques that could be employed for FMEIs construction are then reviewed and discussed. Particular emphasis is placed on critical resources that could have a significant impact for offshore structures. We also conclude that the importance of FMEIs can be further comprehended by quantification of environmental savings through the execution of life cycle assessments. To this end, the last section of the paper reviews LCAs in the field, discussing the performance of floating structures and of hybrid energy systems.

The present review paper encompasses a critical basis for the FMEIs concept understanding and subsequent implementation. It will also establish a strong basis for movements towards future studies in this field.

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Declarations

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