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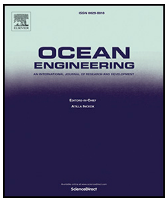

Review

Floating offshore wind farm installation, challenges and opportunities: A comprehensive survey

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ABSTRACT

The deployment of floating offshore wind farms marks a pivotal step in unlocking the vast potential of offshore wind energy and propelling the world towards sustainable energy solutions. Despite the compelling prospects of floating wind technology, its implementation is challenging. Complex installation procedures, associated high costs, and evolving regulations can hinder widespread adoption. However, these challenges present opportunities for innovation and cost reduction. This paper delves into the technical, operational, and economic aspects of floating offshore wind farm installation, providing a comprehensive overview of the current state-of-the-art. The analysis goes beyond simply describing the current landscape by critically examining the complexities involved in floating offshore wind farm installation. It identifies critical research areas for advancing floating wind technology towards broader adoption and greater efficiency. The findings underscore the critical need for standardised foundation designs, advanced installation methods, and robust collaboration between academia and industry. By fostering such collaboration, for example, by creating research consortiums or knowledge-sharing platforms, the floating wind industry can accelerate advancements and unlock its full potential as a clean and sustainable energy source.

1. Introduction

The determined pursuit of sustainable and clean energy sources has driven the offshore wind energy sector to the forefront of the global energy landscape. As areas suitable for onshore wind farms development become limited, installation offshore wind farms presents untapped potential for harvesting wind energy. Amidst this scenario, floating offshore wind (FOW) energy is emerging as a feasible solution, offering many advantages over fixed offshore wind power, such as access to deeper waters, greater flexibility and scalability, increased energy yield and capacity factor, and reduced social disturbance and environmental impact compared to onshore installations.

By installing offshore wind turbines on floating foundations with moorings anchored to the seabed, FOW enables deployment in deep-water environments over 50 metres. This innovative technology opens up new avenues for offshore wind energy development, unlocking vast reservoirs of clean energy and contributing significantly to the global transition towards low-carbon energy. As such, FOW will be a driving force in exploiting the full potential of the future offshore wind market.

However, despite its promising prospects, FOW technology faces a number of challenges that need to be addressed before it can be widely commercialised. These challenges cover various aspects of the floating offshore wind farm (FOWF) lifecycle, from installation and operation to maintenance and decommissioning. One of the main challenges is the cost and complexity of installation, especially given the goal of increasing the global capacity of FOWFs to 270 GW by 2050, see Fig. 1 (DNV, 2023a). This is equivalent to installing more than 700 units of 15 MW wind turbines annually. In order to achieve this ambitious target, several key areas require focus: strategic planning for FOWF siting, thorough assessment of physical and human resources for construction and installation, and ongoing research and development (R&D) to optimise installation methods.

One example of R&D activities towards these goals is the SFI MOVE project, a global research and innovation centre committed to improving offshore operations (NTNU, 2015). The project aims to strengthen the competitiveness of the Norwegian offshore industry by developing

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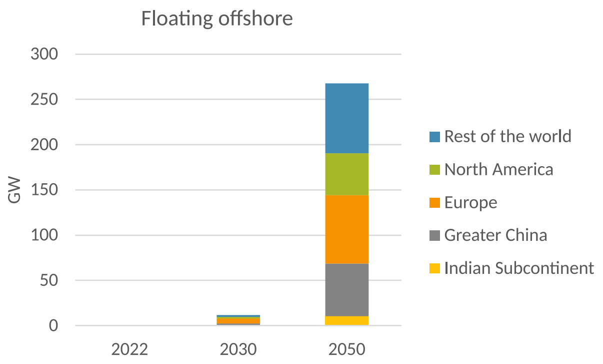


Fig. 1. World installed and expected FOW capacity by region (GlobalData, 2023; DNV, 2023a).

knowledge, methods and tools to install and maintain offshore structures and equipment more safely, efficiently and robustly. One of the main focus areas is the development of methods for installing floating wind tower generators (WTGs), and the project has published numerous research results over the past eight years.

Despite ongoing R&D activities, the FOW industry is still in its infancy, which limits the scope and amount of research that has been conducted and is currently available. In addition, detailed data is insufficient due to the small number of completed projects and limitations in sharing intellectual properties. This lack of data makes it challenging to conduct an extensive review of specific factors that affect the efficiency and safety of FOWF installation.

This paper addresses this gap by conducting a systematic review of recent FOWF installation R&D. By following the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) method (Moher et al., 2009), we aim to gain a broad overview of the nascent FOW energy industry and promote ongoing development and commercialisation. Our systematic review will shed light on the current state-of-the-art, identify emerging trends, highlight critical challenges and limitations, and propose noteworthy future research areas.

It is important to note that this review focuses on the broader picture, not delving into specifics such as FOW towers, blades, or foundation designs, nor offering detailed analyses of particular installation methods.

This study is organised as follows:

- Section 2: Details the systematic review methodology, including the search strategy and the number of papers identified at each stage.
- Section 3: Provides a general overview of the FOW industry. This covers floating foundation types, existing projects, installation process, and inherent challenges.
- Section 4: Presents the latest trends in research contributors, wind turbine capacities, floating foundation technologies, project sites, and installation resources for offshore wind turbine installation.
- Section 5: Explores state-of-the-art research related to FOWF installation, specifically focusing on planning, cost assessment, and installation design methodologies.
- Section 6: Discusses the study with a concise summary of the main findings from this systematic literature review and provides valuable suggestions for future research.
- Section 7: Concludes the study.

2. Literature survey methodology

This section outlines the comprehensive literature search strategy employed in this study, the literature review methodology, the screening process for retrieved literature, and the categorisation of selected articles.

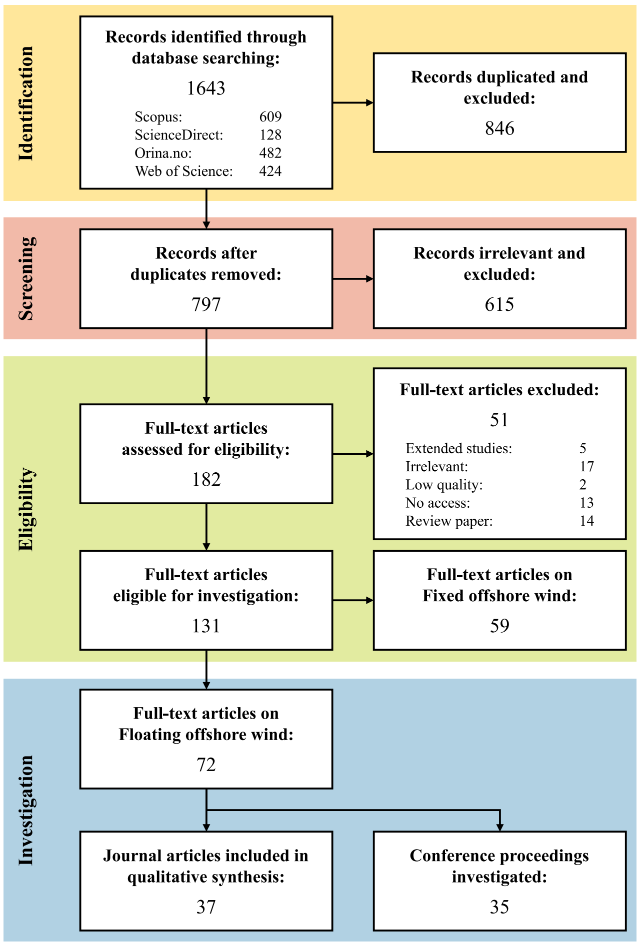


Fig. 2. Flowchart of the number of publications retrieved and categorised through the different stages of a systematic review.

2.1. Systematic literature search

This study followed the PRISMA methodology (Moher et al., 2009) to comprehensively review and analyse the literature on FOWF installation. Publications were identified through a systematic search of titles, keywords, and abstracts using the search term "floating wind installation”. Fig. 2 illustrates the article selection process, highlighting the number of articles retrieved, reviewed, and excluded at each stage.

The initial search yielded journal articles and conference proceedings published in English between 2010 and January 2024. During the screening phase, duplicates from various databases and irrelevant articles were excluded. We then focused on studies specifically related to FOWF installation. The eligibility phase involved a full-text review of each publication to identify those suitable for further investigation. Finally, in the investigation phase, the content of the journals and conference proceedings were categorised, with a particular focus on an in-depth analysis of the journal articles.

2.2. Classifications

Floating offshore wind installation research encompasses not only the wind turbines and their floating foundations but also the installation of other crucial components such as cables, mooring systems, and substations. To achieve optimal installation, researchers consider various aspects, including site layout, thorough transport and installation planning, cost analysis, and the resources required for the entire process. Recognising that reader interest and utility can vary depending on the specific focus of each paper, the selected studies were classified into the following categories to facilitate analysis and understanding of research trends in FOWF installation:

- **Publication year:** Identifies the year of publication, highlighting recent shifts in research focus.
- **Author country:** Showcases key global contributors to FOWF installation R&D by indicating the author's country.
- **Target site:** Illustrates the geographical locations considered for the FOW projects.
- **Rated wind turbine capacity:** Presents the rated capacity of the wind turbines considered in the studies.
- **Foundation type:** Describes the types of foundations employed for the floating wind turbines.
- **Floating foundation technology:** Represents the specific technologies of floating foundations addressed in the studies.
- **Installation components:** Lists the installation components of FOWF considered in the studies.
- **Vessel resources:** Identifies the types of installation resources and specific vessels used to install FOWF components.
- **Research approach:** Categorises the research approaches applied in the studies, including analytical solution and numerical analysis.
- **Installation process:** Describes the specific installation procedures covered in the studies, such as towing operations and offshore lifting techniques.
- **Research and simulation scope:** Categorises the scope of the studies and performed simulations.
- **Software and tools:** Lists the software and tools utilised in the studies.
- **Environmental condition:** Presents the environmental conditions considered in the studies.

The research scope of the publications was further categorised based on following taxonomies:

- **Planning (P):** Identifies publications that discuss planning activities involved in various phases of a FOW project.
- **Cost assessment (C):** Classifies publications that address the economic aspects of the project, including capital expenditures (CAPEX), operating expenditures (OPEX), decommissioning expenditures (DECEX), annual energy production (AEP), and levelized cost of electricity (LCOE).
- **Fabrication (F):** Specifies publications that consider the fabrication of components for FOWFs.
- **Logistics (G):** Denotes publications that discuss the logistics involved in the fabrication and installation processes.
- **Maintenance (M):** Represents publications that address the maintenance of FOWFs.
- **Design/Method (D):** Identifies publications that introduce or analyse new designs of systems and/or methodologies related to FOWF installation.

For simulation-specific studies, an additional categorisation was employed, encompassing Regional planning (R), Weather forecasting (W), Stability analysis (S) and Hydrodynamic analysis (H).

3. State of floating offshore wind industry

This section provides a general overview of the FOW industry, including existing projects, types of floating foundations, installation processes, and limitations.

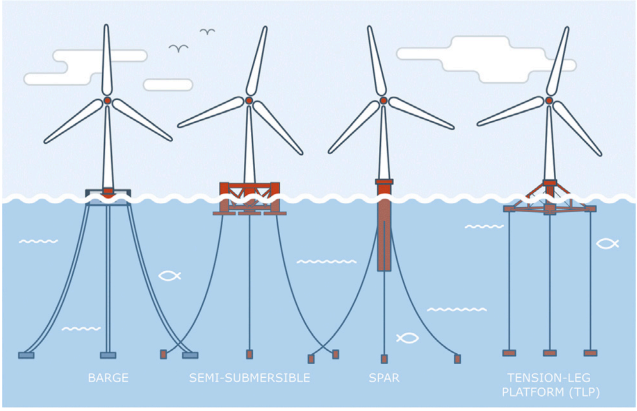


Fig. 3. Illustration of FOW foundation examples, from left to right: barge, semi-submersible, spar, and TLP (COWI, 2021).

Table 1
Floating offshore wind turbine floater types and characteristics (Empire Engineering, 2023; Aegir Insights, 2022; Aaron Du, 2021).

	Barge	Semi-sub	Spar	TLP
Stability	Hydrostatic	Hydrostatic	Ballast	Mooring-tension
Fabrication	Simple	Complex	Simple	Complex
Installation	Simple	Simple	Simple-restricted	Complex
Water depth	> ~30 m	> ~30–60 m	> ~50–100 m	> ~40–60 m

3.1. Floating foundations

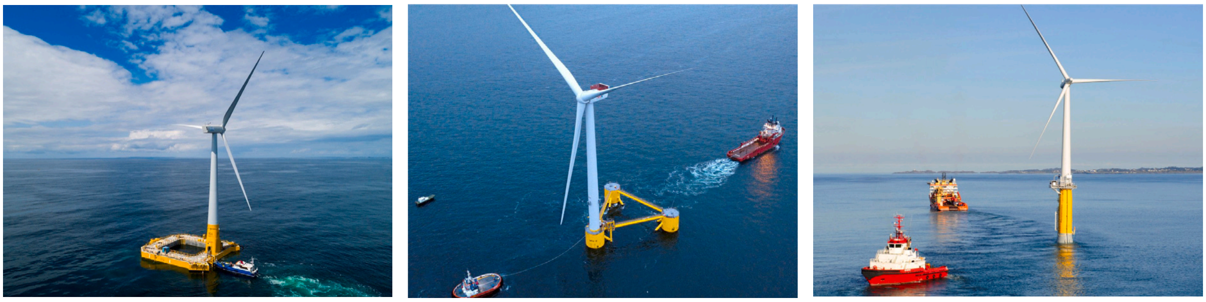
Fig. 3 depicts different types of typical FOW foundations. Barge, semi-submersible, spar and tension-leg platform (TLP) are the most frequently considered foundations in the recent studies and projects. Table 1 summarises the characteristics of floating foundations in terms of stability, fabrication, installation, and feasible water depth. Detailed comparisons of floater types can be found in Aegir Insights (2022).

Barge foundation is a large and flat structure similar to a barge ship that floats on the surface of the water to support a wind turbine and its associated equipment. A catenary mooring system stabilises the foundation. Due to its simple design, the fabrication and installation are relatively simple, and the required water depth is shallow.

Semi-submersible foundation usually consists of three or more pontoons that are connected by a structure above the waterline. The wind turbine is mounted on top of the centre or one of the side columns, and the foundation is anchored to the seabed normally using catenary mooring lines. The pontoons are fitted with plates in the lower part to reduce heave motions and provides structural stability in rough seas due to the distributed buoyancy of the partially submerged pontoon.

Spar is a long and cylindrical floating structure anchored to the seabed using catenary mooring lines. Spar stabilises the structure in rough seas by lowering its centre of gravity with ballast loads inside the structure. Compared to the other foundations with complex shapes, the spar has a simpler shape, which is more favourable for manufacturing. On the other hand, the long cylindrical design of spar requires a deeper water depth, regional restrictions exist for near-shore or quay side installation and maintenance, and towing operations.

TLP is a floating platform connected to the seabed using taut mooring lines. The wind turbine is mounted on top of a platform designed to remain stable in rough seas, and the tensioned legs hold the platform in place and prevent it from drifting. However, the TLP foundation is not stable in itself and only remains stable when the mooring line is under tension; thus, a loss of even one line could result in the loss of the entire unit. TLPs must be securely anchored to the ground to withstand wave, wind and seismic loads. This may require specialised foundations, anchors, and installation methods. Due to more



(a) BW Ideol Floatgen (b) WindFloat Atlantic (c) Hywind Scotland

Fig. 4. Examples of barge, semi-submersible and spar foundation specific designs and project towing operations: (a) BW Ideol Floatgen, (b) WindFloat Atlantic and (c) Hywind Scotland projects.
Source: BW Ideol; Dock90; Equinor.

complex requirements than the installation of other foundations, the applicable water depth may be limited by seabed conditions and/or project requirements.

The minimum water depth needed for FOWFs depends on several factors, including the chosen foundation type, its design characteristics, the size of the wind turbine it supports, and the stability required for safe operation. Each type of floating foundation has advantages and disadvantages related to installation, particularly regarding the minimum water depth they can accommodate. As shown in Fig. 3, barge and semi-submersible types have relatively low draft, making it easy to wet tow from the quay to the operational location. On the other hand, spar can also be wet towed, but its length presents geographic difficulties where the water depth is not sufficient for vertical wet towing. In this case, the spar can be towed horizontally and upended at the mating location with the wind tower. The TLP is beneficial with relatively smaller footprints and better stability in operation but is unstable without mooring lines, requiring a temporary buoyancy device during wet towing. In addition, the installation process is more complicated and more expensive than that of other foundations because TLP needs additional work to satisfy the required tension of the mooring lines after installing the anchor and connecting the mooring line. Ultimately, foundation selection will depend on factors such as water depth, environmental loads, seabed conditions, and project requirements.

3.2. Existing projects

A significant portion of the potential offshore wind resources is in deep water, where fixed offshore turbines are not practical (The Carbon Trust, 2021). Due to the complexity of the floating wind environment, a universal solution does not currently exist and different countries are approaching it with various designs. So far, Europe is leading the way in FOW technology, while research is also being initiated in regions with deep water coastlines and future potential for FOW technology, such as the United States and Asia.

Floating offshore wind is a nascent industry, so many challenges have yet to be identified. However, despite these challenges, several successful projects have emerged utilising a variety of design concepts. A few selected existing FOW projects are listed in Table 2, and additional project lists can be found in FWE (2024) and Neddermann et al. (2023). Table 2 provides a comprehensive overview of existing FOW projects, including completed ventures, ongoing development, and future plans, and provides valuable insights for continued evolution.

The project list reveals a clear preference for semi-submersible platforms, with 17 out of 33 projects utilising this design. The most mature and widely adopted designs are WindFloat and EOLINK (Roddier et al., 2010; Eolink, 2020b). Spar buoys follow closely with 8 projects. The leading spar designs are Hywind and Hybrid Spar (Jonkman, 2010; Utsunomiya et al., 2015). Notably, recent projects and future developments show growing interest in barge and TLP designs.

Another key trend is the increasing scale of wind turbines and FOW project capacities in newer ventures. For instance, the 1,300 MW capacity Korea Floating Wind (2028), with greater than 10 MW of wind turbines, is much larger than the WindFloat Atlantic (2019), which totals 25 MW with 8.4 MW of wind turbines (Principle Power, 2023). This shift highlights the move towards establishing larger wind farms. Furthermore, comparing the maximum planned capacities for different floating foundation types provides clues about their development stage. Semi-submersibles lead the pack with wind farm capacities reaching 1,300 MW, followed by spars at 88 MW, barges at 30 MW, and TLPs at 25 MW.

The majority of projects operate in waters exceeding 50 meters in depth. This showcases the potential FOW technology to unlock wind energy in previously inaccessible areas. Project locations also exhibit significant variation in distance from the shore. Some projects, such as SeaTwirl S2x (CACOR, 2023), are located close to the coast, while others, e.g. Hywind Tampen (Equinor, 2024), venture further out. This adaptability underscores the suitability of the technology for a wide range of geographical environments.

3.3. Installation process

The installation process of offshore wind farms is critical to the success of offshore renewable energy projects. This plays a pivotal role in determining the feasibility, efficiency and long-term viability of these projects. Efficient and effective installations are essential to maximising energy production, minimising operating costs, mitigating environmental impacts, and promoting sustainable expansion of offshore wind, which significantly contributes to global clean energy goals.

Compared to fixed offshore turbines, floating WTGs experience harsher environmental loads due to their floating foundations, resulting in more complex dynamic responses. Because of this complexity, the complex relative motions between the floating foundation, installation vessel, and wind turbine components must be carefully considered during installation and maintenance.

To minimise the difficulties caused by complex multibody relative motions and to perform safe installations, all floating offshore wind turbines installed to date have undergone the same installation process, regardless of the type of foundation they employ. The wind turbine components and floating foundations were combined in nearshore or protected waters, where environmental conditions are less harsh than in the far ocean and the mating operation can be performed in a more controlled environment. The completed wind turbine units were then wet towed to the final operating location and connected to the mooring lines.

The main installation procedures can be briefly summarised below, and one can find detailed procedures for mooring system installation, cable laying, floating substation installation and commissioning in Torres et al. (2023).

Table 2
List of existing floating offshore wind project examples.

Type	Technology (Reference)	Project name (Reference)	Wind farm site	Country	Water depth	Distance to shore	Project capacity	Turbine capacity	Num of turbines	Comm -ission
Barge	Damping Pool (BW Ideol, 2024)	Floatgen (WEAMEC, 2022)	SEM-REV site, Le Croisic	France	33 m	22 km	2 MW	2 MW	1	2018
		Hibiki (NEDO, 2019)	Kitakyushu	Japan	55 m	15 km	3 MW	3 MW	1	2018
		Eolmed (Qair, 2024)	Occitanie	France	55 m	16 km	30 MW	10 MW	3	2024
	SATH (Saitec, 2022)	DemoSATH (RWE, 2023)	BiMEP site, Armintza	Spain	85 m	3 km	2 MW	2 MW	1	2023
Semi	WindFloat (Roddier et al., 2010)	WindFloat 1 (Principle Power, 2023)	Aguądoura	Portugal	45 m	5 km	2 MW	2 MW	1	2011
		WindFloat Atlantic (Windplus, 2024)	Viana do Castelo	Portugal	85–100 m	20 km	25 MW	8.4 MW	3	2019
		Kincardine OWF (Principle Power, 2023)	Aberdeen Coast, Scotland	UK	60–80 m	15 km	50 MW	9.5 MW	5	2021
		Les Éoliennes Flottantes du Golfe du Lion (Principle Power, 2023)	Leucate/Le Barcares Coast, French Mediterranean Sea	France	70–100 m	16 km	30 MW	10 MW	3	2024
		Erebus (Principle Power, 2023)	Celtic Sea, Wales	UK	70 m	44 km	96 MW	>9 MW (TBC)	7–10 (TBC)	2027
		Korea Floating Wind (Principle Power, 2023)	East Sea, Ulsan Coast	S Korea	250 m	80 km	1,300 MW	>10 MW (TBC)	60–100 (TBC)	2028
	EOLINK (Eolink, 2020b)	EOLINK demonstrator (Eolink, 2020a)	SEM-REV site, Le Croisic	France	–	–	5 MW	5 MW	1	2023
		BLOW project (European Commission, 2022)	Black Sea	Bulgaria	–	–	5 MW	5 MW	1	2025
	Compact Semi-Sub (Yamaguchi and Imakita, 2018)	Fukushima Mirai (Fukushima OWC, 2013)	Fukushima Coast	Japan	120 m	23 km	2 MW	2 MW	1	2013
	V-Shape Semi-Sub (Ohta et al., 2015)	Fukushima Shimpuu (Fukushima OWC, 2015)	Fukushima Coast	Japan	32 m	23 km	7 MW	7 MW	1	2015
	Semi-Sub (Wison, 2021)	Yangxi Shapa III Demo (offshoreWind.biz, 2021)	Yangjiang Coast, Guangdong	China	30 m	28 km	5.5 MW	5.5 MW	1	2021
	FuYao, Semi-Sub (CSSC HZ Windpower, 2022)	FuYao prototype (offshoreWind.biz, 2022)	Xuwen County	China	50–70 m	13 km	6.2 MW	6.2 MW	1	2022
	Semi-Sub (unknown)	Haiyou Guanlan (NorthWind, 2023)	Hainan province	China	100+ m	136 km	7.25 MW	7.25 MW	1	2023
	OO-Star Wind Floater (Pegalajar-Jurado et al., 2018)	FLAGSHIP (Andersen et al., 2021)	METCentre, Karmøy Coast	Norway	220 m	10 km	>10 MW	>10 MW	1	2024
	VolturnUS (University of Maine, 2023)	New England Aqua Ventus I (Dagher and Viselli, 2023)	Maine coast	US	60–110 m	3 km	12 MW	6 MW	2	2024
	TetraSub (Stiesdal, 2023)	Pentland FOWF (Marshall and Watt, 2022)	Dounreay Coast, Scotland	UK	60–102 m	7.5 km	100 MW (TBC)	15 MW (TBC)	7	2026
	TwinWind (Hexicon, 2022)	TwinHub demo (TwinHub, 2022)	Celtic Sea, Cornwall	UK	50–60 m	16 km	32 MW	8 MW	2 × 2	2026
Spar	Hywind (Jonkman, 2010)	Unitech Zefyros (Hywind Demo) (EMETCENTRE, 2024)	West coast of Karmøy	Norway	220 m	12 km	2.3 MW	2.3 MW	1	2009
		Hywind Scotland (Equinor, 2017)	Peterhead Coast, Scotland	UK	95–120 m	25 km	30 MW	6 MW	5	2017
		Hywind Tampen (Equinor, 2024)	Snorre/Gullfaks Field, North Sea	Norway	260–300 m	140 km	88 MW	8 MW	11	2022
	Hybrid Spar (Utsunomiya et al., 2015)	Haenkaze/Sakiyama (Toda Corporation, 2013)	Sakiyama Coast, Nagasaki	Japan	100 m	5 km	2 MW	2 MW	1	2013
		Goto floating wind farm (INPEX, 2023)	Goto City, Nagasaki	Japan	–	–	16.8 MW	2.1 MW	8	2026
	Advanced Spar (Matsuoka and Yoshimoto, 2015)	Fukushima Hamakaze (Fukushima OWC, 2015)	Fukushima Coast	Japan	48 m	23 km	5 MW	5 MW	1	2016
	TetraSpar (Wiley et al., 2023)	TetraSpar demonstrator (Stiesdal, 2021)	METCentre, Karmøy Coast	Norway	200 m	10 km	3.6 MW	3.6 MW	1	2021
	S2x (s2x, 2024)	SeaTwirl S2x 1MW pilot (CACOR, 2023)	Boknafjorden	Norway	130 m	0.7 km	1 MW	1 MW	1	TBC
TLP	Tensioned line floats (Heavy Lift News, 2023)	Provence Grand Large (Prysmian Group, 2023)	Marseille Coast	France	100 m	17 km	25 MW	8.4 MW	3	2023
	Tension leg platform (Pek, 2022)	Bluewater TLP demonstrator (Bluewater, 2022)	METCentre, Karmøy Coast	Norway	200 m	–	6 MW	–	1	2024
	X30 platform/PivotBuoy (X1 Wind, 2024)	PivotBuoy Project (X1 Wind, 2023)	PLOCAN, Canary Islands	Spain	50 m	1 km	225 kW	225 kW	1	2023
	X90 platform/PivotBuoy (X1 Wind, 2024)	NextFloat Project (European Commission, 2023)	French Mediterranean Sea	France	–	–	6 MW	6 MW	1	2025

1. Floating foundations and wind turbine components are fabricated and transported to the mating location.
2. Wind turbine components are installed and mounted on the foundations.
3. The combined units are towed to the operation site.
4. Moorings and cables are installed and connected to the floating wind combined units.

Fig. 4 shows examples of the towing operations of the BW Ideol Floatgen, WindFloat Atlantic and Hywind Scotland projects (BW Ideol, 2024; Windplus, 2024; Equinor, 2017). Equinor's Hywind Tampen project also followed the conventional installation method relying on towing operations, and the marine operation plans for the Hywind Tampen (Equinor, 2024) project are presented in Fig. 5. The initial sections of the spar foundation were built at Stord in Norway and

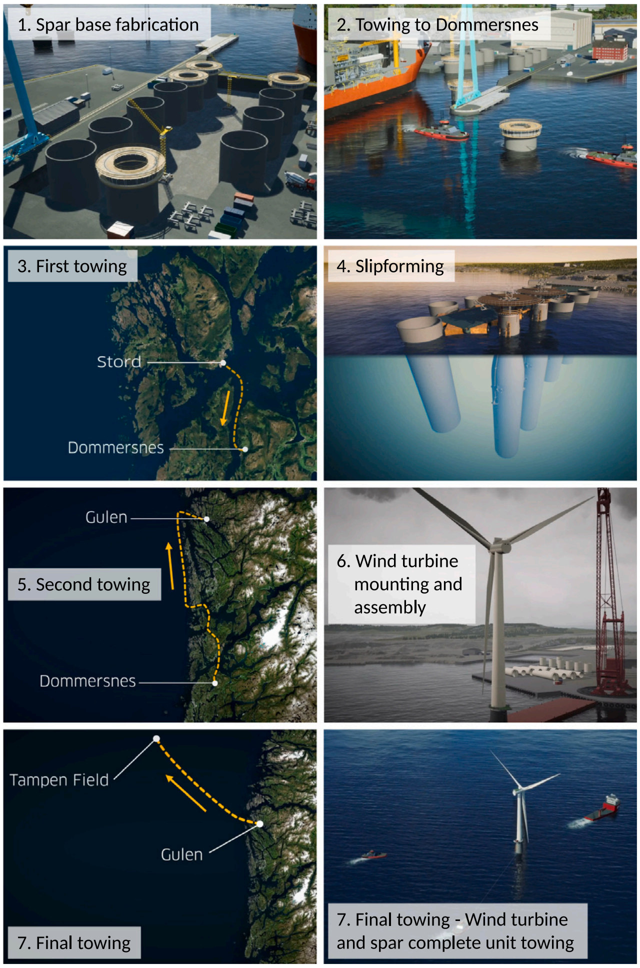


Fig. 5. Fabrication and marine operation plans for the Hywind Tampen project (Kvaerner, 2019).

towed about 25 km to Dommersnes for further fabrication. After the slipforming and extending the length, the foundations were towed about 200 km to Gulen for wind turbine unit assembly. Wind turbine components were mounted and assembled on top of foundations with several lifting operations using onshore cranes, and the assembled units of wind turbines and foundations were towed to the Tampen field, about 200 km.

3.4. Challenges in conventional installation practices

Floating offshore wind farm installation is a complex and challenging task that requires significant expertise and planning. While several successful projects have been completed worldwide, there are still a number of challenges that need to be addressed to make FOW a more cost-effective and widely adopted technology. One of the main limitations of existing installation practices is the towing operation of the assembled wind turbine and foundation. This process is highly weather-dependent and can be significantly impacted by complex environmental factors such as wind, waves, and currents. Unpredictable weather conditions and towing speed limitations can pose significant challenges for the widespread deployment of floating wind farms worldwide.

The floating WTGs are exposed to harsh offshore environments, and currently, no reliable method exists for safely performing complex installation and maintenance tasks directly at offshore sites. Therefore, during installation and heavy maintenance activities, the entire wind turbine foundation assembly must be towed between the quay and the operating site, incurring significant transportation and installation (T&I) and operation and maintenance (O&M) costs. A recent example is the Hywind Scotland project, where turbines will reportedly be towed back to a Norwegian port for maintenance (reNEWS.BIZ, 2024). Not only does this increase O&M expenses, but it can also create resource and logistical challenges, such as installation vessels for the large amount of wind turbines planned, especially as wind turbines continue to increase in size and future wind farms are located further out to sea.

Spar-type floating wind turbines present additional unique challenges for installation due to its geographical constraints of deep water. The considerable length of the spar limits the assembly space for wind turbine mating and towing paths, which significantly limits suitable locations for installation and maintenance operations.

Despite these limitations, it is essential to recognise the need for innovation and research into alternative installation and maintenance methods for FOW industry. As the industry continues to grow, the urgency to lower cost barriers and overcome challenges posed by current practices will increase. Developing cost-effective and reliable installation and maintenance methods holds the key to unlocking the future of FOW energy. With a firm commitment to ongoing R&D, the industry can effectively address the challenges posed by current practices, embrace breakthrough innovations, and realise the full potential of FOW energy technology. Furthermore, analysing and responding to the limitations of the FOWF installation resources that we will face in the future, along with realistic planning and investment, will contribute significantly to increasing sustainability and helping the world transition to a low-carbon economy.

4. Trends of offshore wind installation research

This section delves into the current trends of offshore wind installation studies, highlighting ongoing challenges and promising opportunities for future development. We specifically examined the global upsurge in research interest, focusing on major R&D contributors worldwide to understand regional trends. Additionally, we reviewed the wind turbine capacities addressed in these studies to identify potential gaps between industry strategies and current advancements in academia and technology. This section further explores broad research surges and trends, especially in floating wind installation studies, focusing on floating foundation technologies, project sites, and resources and discussing challenges and opportunities for FOWF development.

While Table 3, Figs. 6 and 7 incorporate both fixed and floating offshore installation studies under the umbrella of "offshore wind installation studies”, it is crucial to note that the number of studies on fixed offshore wind installation research was derived from searches using "floating wind installation" as the primary search keyword. Therefore, these figures serve as an indicator of overall trends, not a definitive comparison. Further investigation is required for a complete picture of fixed offshore wind research.

For a more precise analysis of FOWF installation, Table 4, Figs. 8 and 9 are based on a thorough review of 72 peer-reviewed journal publications and conference papers specifically focused on FOWF installation research.

4.1. Key contributors

The geographical location of a research institute is an essential indicator for considering current offshore wind research trends and potential wind farm areas for future development, as most research institutes conduct offshore wind research for the region in which they are located. Consequently, identifying the location of a research institute can provide valuable insights into the environmental conditions, challenges, and direction of development in each region. For example, offshore wind conditions and water depth can vary significantly from region to region. Thus, the regional specification can affect the design and installation of offshore wind turbines and foundations as well as

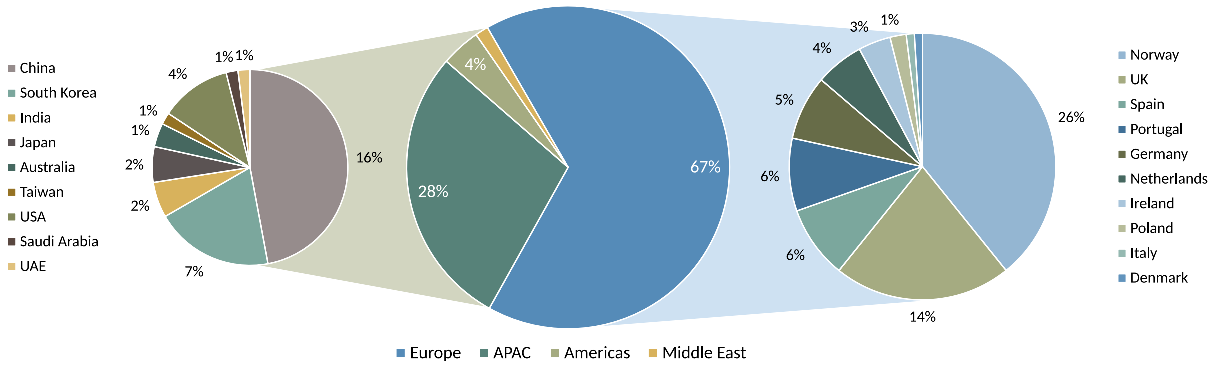


Fig. 6. Countries of the key publication contributors for offshore wind installation studies (131 screened records in total, Eligibility stage of the flowchart in Fig. 2).

Table 3
Number of publications of each author country for offshore wind installation studies (131 screened records in total, Eligibility stage of the flowchart in Fig. 2).

Region	Country	Floating	Fixed	Subtotal
Europe	Norway	20	20	40
	UK	21	1	22
	Spain	9	0	9
	Portugal	6	3	9
	Germany	5	3	8
	Netherlands	3	3	6
	Ireland	3	1	4
	Poland	2	0	2
	Italy	1	0	1
	Denmark	1	0	1
APAC	China	7	17	24
	South Korea	1	9	10
	India	2	1	3
	Japan	2	1	3
	Australia	1	1	2
	Taiwan	0	1	1
Americas	USA	3	3	6
Middle East	Saudi Arabia	0	1	1
	UAE	0	1	1
Total		86	66	152

their performances and environmental impacts. Hence, it is important to consider the geographical context in which the research organisation is located in order to assess the relevance and applicability of the research findings.

Fig. 6 summarises the distribution of countries that have contributed to the study of the offshore wind installation process, while Table 3 shows the number of publications in each country that have studied floating and fixed offshore wind installation specifically. Currently, most of the R&D related to FOWF installation has taken place in Europe, with Norway having the most research output, followed by the UK and Spain. When comparing academic R&D with the track record of existing floating offshore wind projects, it is clear that despite several projects being installed in French and Japanese waters, there are few or no academic papers published on FOWF installation in these countries.

Due to recent developments with the UK and the outcome of the recent Scottish Wind leasing round, the UK is expected to have over 20 GW of floating wind turbines installed by 2032 (BEIS, 2019), making it a major area of interest for UK-based developers. At present, the UK, Norway, Portugal, China, and Japan are the leading nations in terms of total net floating wind installations. However, by the end of 2030, South Korea is expected to overtake Japan and enter the top five (Williams and Zhao, 2023).

The Asia-Pacific region boasts significant potential for offshore wind energy, and research activity is keeping pace with growing awareness. Several countries stand to benefit significantly due to their unique geographic features, environmental conditions, and established industrial base. China, with its extensive coastline, exemplifies this. Similarly, South Korea and island nations like Taiwan and Japan are surrounded by water, offering vast offshore wind resources. These countries share a common thread – well-developed heavy industries, including shipyards, and robust infrastructure – critical assets for construction, transportation, and installation of offshore wind farms. While current research focuses on fixed offshore wind, FOW holds promise for the region. Ambitious government plans for FOW industry (offshoreWind.biz, 2020; China Dialogue, 2020; POWER, 2022), supported by dedicated research institutions, suggest significant future development in this area.

Compared to Europe and Asia-Pacific countries, the offshore wind market in the United States is still in its nascent stages. Research outputs are often closely linked to the level of market activity and government support for renewable energy projects. However, the US government has recently set ambitious targets for offshore wind development to generate 30 GW of offshore wind energy by 2030 (The White House, 2021), which is likely to lead to increased R&D activity in the coming years.

The pace and direction of R&D for FOW varies depending on the advantages and disadvantages of each country's geographical characteristics. Therefore, when utilising various studies on FOW, it is necessary to evaluate their applicability and suitability by considering the region where each study was conducted and the project characteristics of the relevant wind farm.

4.2. Wind turbine capacity

The size of wind turbines has significantly increased due to ongoing R&D, with the largest turbines now capable of generating 15 MW (Offshore Engineer Magazine, 2023). While much R&D has been done to develop larger and more efficient wind turbines, much of this research has been focused on design aspects such as blade design, materials science, and control systems, with only a few studies focusing on installation.

Fig. 7 shows the range of turbine capacities considered in studies of FOWF installation since 2010. It can be seen that around 65% of the studies have considered 5 MW and 10 MW turbines, and while interest in larger turbines has increased in recent years around 2017, the period of the Hywind Scotland project.

The size of bubbles in Fig. 7 indicate the number of publications for each turbine capacity. The figure also presents the capacity-weighted average offshore wind turbine capacity in operating and announced projects (black dashed line). While new offshore wind farm projects are planning to utilise 15 MW wind turbines, academic R&D have not yet fully caught up with these industry aspirations. Examples of upcoming projects with 15 MW wind turbines include the Inch Cape (1.1 GW) project in Scotland (Inch Cape, 2023), the Empire Wind 1 and 2 (2.1 GW) projects in New York (Equinor and BP, 2023),

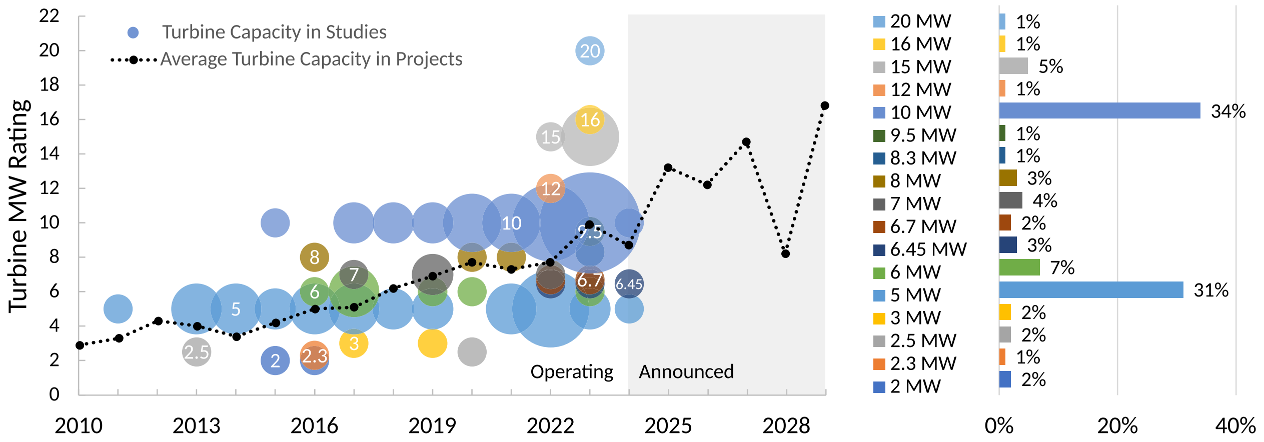


Fig. 7. Offshore wind turbine capacity considered in offshore wind installation studies (bubbles and bar chart) and capacity-weighted average offshore wind turbine capacity in operating and announced projects (dashed line, Musial et al. (2023)). The bubble and bar chart are based on 131 screened records from the Eligibility stage of the flowchart in Fig. 2.

the Moonmubaram (1.3 GW) FOW project in South Korea (Shell and Hexicon AB, 2023), the Atlantic Shores (1.5 GW) offshore wind project in New Jersey (Shell New Energies US LLC and EDF-RE Offshore Development, 2023), and the He Dreiht (900 MW) offshore wind project in Germany (EnBW, 2023).

In the context of offshore wind energy development, the introduction of 15 MW turbines represents a notable paradigm shift due to their much larger size and higher power output compared to existing offshore wind turbines. This transition involves a number of complex technical challenges, including the development of new materials and manufacturing processes, as well as transportation and installation methods. In addition, the development and deployment of 15 MW turbines is likely to be costly, requiring more in-depth R&D in order for the offshore wind industry to compete with other conventional forms of energy generation, such as fossil fuels and nuclear power. Notably, the installation of 15 MW turbines must be verified by comprehensive simulations and prototype tests to understand technical complexities and potential risks that could lead to project delays and cost overruns.

On the other hand, beyond these initial challenges, the long-term outlook for 15 MW turbines is more optimistic. These turbines have significant cost reduction potential due to their ability to generate more energy (and therefore revenue) without a proportional increase in cost. In addition, the development of 15 MW turbines opens up promising avenues for the offshore wind industry, allowing it to expand into new markets, particularly in deeper waters where traditional smaller turbines were not suitable. Finally, the development and deployment of 15 MW turbines has the added benefit of stimulating job creation in the offshore wind sector. This strengthens the industry and contributes to the economic prosperity of countries that have invested in offshore wind energy, helping to bolster their economies.

4.3. Surge in FOWF installation studies

Interest in FOW has experienced a substantial surge in recent years, evidenced by a notable increase in journal and conference paper publications dedicated to the subject. A visual representation of the surge in research interest is presented in Fig. 8, which shows the number of journal and conference papers published for FOWF installation studies from 2013 to 2023. As the graph shows, there were no studies related to floating offshore wind installation until 2013, and papers began to be published in 2014 in preparation for the Hywind Scotland construction campaign, which began in 2016. Since 2018, following the successful installation of Hywind Scotland, interest in FOWF installations has steadily increased, with a sharp rise in the number of published papers.

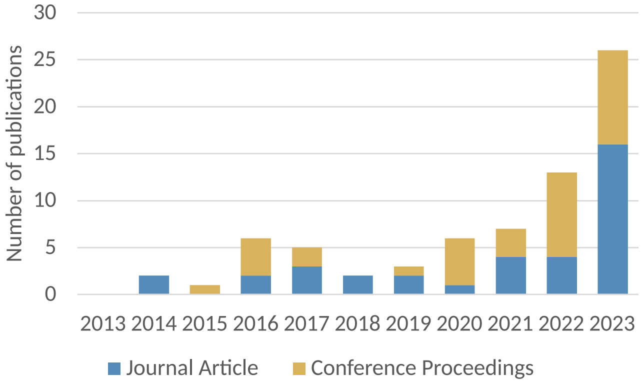


Fig. 8. Number of publications per year for FOWF installation studies, (72 screened records in total, Investigation stage of the flowchart in Fig. 2).

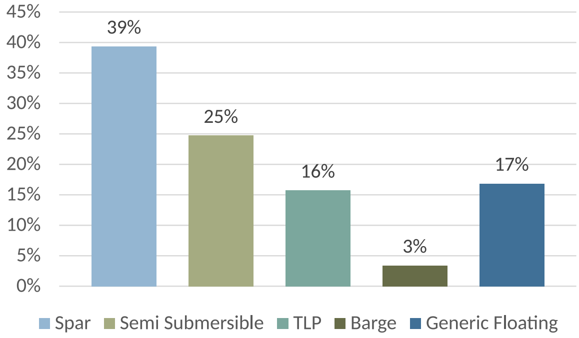


Fig. 9. Floating wind foundation types considered in the 72 publications for FOWF installation studies (Investigation stage of the flowchart in Fig. 2).

4.4. Floating foundation technology

Determining the most appropriate offshore wind foundation type and design is essential to the success of offshore wind projects. The selection of foundation type depends on several factors at the project site, including water depth, seabed characteristics, and environmental conditions. Additionally, factors such as wind turbine size, fabrication capabilities, and logistics also play a crucial role. Recognising this complexity, researchers have dedicated significant effort in recent years to address these critical aspects.

Fig. 9 provides an overview of the various FOW foundation types examined in the 72 publications and their proportions. Of the literature on the installation of floating wind systems, the majority of papers focused on spar foundation designs. This may be due to the fact that Hywind spar technology is new to floating wind, and significant R&D investment has been made in recent operational projects. After spars, the largest number of studies considered semi-submersible types, represented by WindFloat designs, followed by studies that considered TLP-type foundations. Only a small number of studies examined barge-based floating wind installations.

Table 4 summarises the literature examining various floating foundation technologies. It presents key findings from recent studies on the preferred deployment sites and water depths for these foundations, along with the wind turbine capacities they can support. See Table 6 for the detailed scope of research and considerations in the FOWF installation studies.

As discussed earlier, the Hywind design stands out prominently in the category of spar-type foundations. While there is consideration of other spar-type foundations, the number of studies focusing on them is comparatively limited. Within the studies on semi-submersible foundations, research does not exhibit a strong bias towards any single foundation type. Nevertheless, WindFloat and Tri-Floater have been studied more than other designs. For TLP-type foundations, GICON-TLP has attracted the most attention, and MIT/NREL TLP has also been studied more than other TLP technologies.

Floating offshore wind is a nascent industry, and a gap exists between academic research and industrial needs. This can be attributed to intellectual property concerns surrounding floating foundation designs. Additionally, published research often delves deeply into specific technical aspects of individual foundation types, neglecting broader comparisons. In order to bridge this gap and propel FOW development, several areas require focus:

- **Deeper investigation:** More comprehensive research is needed to fully understand the benefits and limitations of each technology.
- **Comparative analysis:** Direct comparisons between foundation types are critical for project planning and decision making.
- **Multi-disciplinary design:** Optimising foundation design requires collaboration across multiple engineering disciplines (Ojo et al., 2022).
- **Practical considerations:** Research should encompass the entire project lifecycle, including production, installation, maintenance, and decommissioning.

4.5. Floating wind project site

Site selection for FOWFs is crucial for project success, viability, and sustainability. A comprehensive assessment of critical criteria is essential, including potential wind resources, social and environmental impacts, and infrastructure and supply chain availability. As shown in Table 4, current research focuses on deploying FOWFs in regions such as the North Sea, Baltic Sea, and Galician Coast.

The choice of foundation type heavily influences deployment suitability. Spar foundations excel in challenging environments with deep water depth and harsh conditions (e.g., North Sea) and are also being explored off the west coast of the US, Baltic Sea, and Japan. Semi-submersible foundations are better suited for shallower waters, and they are popular in coastal areas near Spain, Portugal, and South Korea. TLPs have been considered across varying water depths, with prominent applications in the Baltic Sea, offshore Spain and Portugal, and the Aberdeen coast.

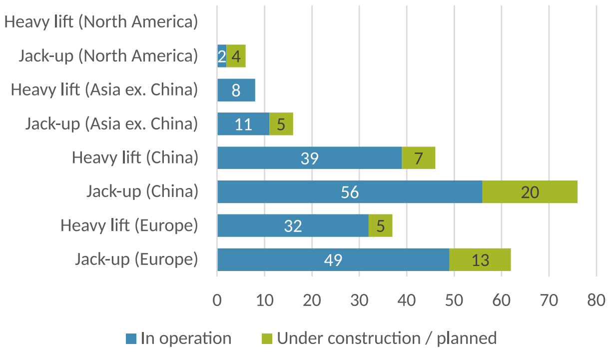


Fig. 10. Number of wind turbine installation vessels in 2023 (Source: GWEC market intelligence global offshore wind turbine installation vessel database, July 2023 (Williams and Zhao, 2023)).

Each offshore site has unique environmental and geographical characteristics and infrastructure. Additionally, floating foundation types differ in stability, deployment depth, fabrication methods, and installation procedures, as summarised in Table 1. Therefore, selecting the most appropriate foundation for each site is critical. While initial studies often prioritise wind resource assessment in the early stages of FOW development, comparative studies focusing on optimal foundation selection are limited. Two key areas require focus to bridge this gap and accelerate FOW development:

- **Foundation design optimisation:** Each foundation type needs further development and optimisation to enhance its capabilities.
- **Site-specific foundation selection:** Determining the best type of foundation based on site-specific characteristics requires comprehensive research and comparative analysis.

By addressing these areas, one can significantly improve the efficiency and effectiveness of future FOWF development.

4.6. Installation resources

The global FOW industry aims for a massive leap, targeting 270 GW capacity by 2050. This translates to installing around 20,000 massive floating wind turbines (10–15 MW class) in the coming years. In order to achieve this ambitious goal, it is essential to assess material availability, manufacturing and logistics infrastructure, human resources, and especially installation means and the available installation vessels.

The rapid growth of the floating wind industry is placing increasing pressure on the availability of specialised installation vessels. The deployment of FOWFs necessitates specialised vessels equipped with robust heavy-lifting capabilities to transport and install the massive floating platforms and wind turbine components. Unlike traditional bottom-fixed wind farms, FOWF installations involves unique challenges and require a diverse fleet, including tug boat, barge, heavy-lift vessel (HLV), anchor-handling vessel (AHV), and cable laying vessel (CLV). The daily rates for the various installation vessels are shown in Table 5.

As of 2023, the existing fleet of 194 specialised installation vessels faces the risk of being overwhelmed by the projected surge in installations due to the limited number of new vessels being built. While 54 additional vessels are under construction or planned (see Fig. 10), this number may not be sufficient to meet the projected surge in FOWF installation. Furthermore, the current capacity for installing large turbines is particularly limited. There are only 17 vessels capable of handling 10 MW turbines, and a mere 3 vessels can install the newest 14 MW models (Robinson, 2023). This shortage of vessels specifically equipped for larger turbines could significantly hinder project timelines and inflate costs.

Despite the limitations of specialised vessels, tug boats emerge as the most commonly utilised vessel for FOWF installation due to several advantages. They are cost-effective, manoeuvrable, and adaptable to various platform configurations. This adaptability offers a solution to

Table 4

Specific floating foundation technologies and details considered by 44 of the 72 publications on FOWF installation studies (Investigation stage of the flowchart in Fig. 2).

Type	Technology	Design	Year	Author country	Target site	Water depth	Capacity	Reference
Spar	OC3-Hywind	Jonkman (2010)	2016	Spain	Galician coast	–	5 MW	Castro-Santos (2016), Castro-Santos et al. (2016)
			2018	Norway	North Sea	110 m	10 MW	Jiang et al. (2018)
			2020	Norway	North Sea	–	6 MW	Lande-Sudall et al. (2020)
					North Sea	110 m	10 MW	Vågnes et al. (2020)
					–	200 m	10 MW	Jiang et al. (2020)
					–	130 m	10 MW	Gran et al. (2020), Xu et al. (2020)
			2021	Norway, Netherlands	–	–	10 MW	Ren et al. (2021)
				Norway	–	130 m	10 MW	Hong et al. (2021)
			2022	UK	–	–	5, 10, 15 MW	Crowle and Thies (2022b)
				Norway	–	130 m	10 MW	Hong et al. (2022), Yuan et al. (2022)
			2023	Norway	–	120–130 m	10 MW	Ataei et al. (2023), Hong et al. (2023a), Hong et al. (2023b), Liu et al. (2023a), Liu et al. (2023b)
				Norway, China	Atlantic Ocean, North Sea	–	10 MW	Gao et al. (2023)
	Hybrid Spar	Utsunomiya et al. (2015)	2015	Japan	Kabashima Island	100 m	2 MW	Utsunomiya et al. (2015)
	DSI-Wind Float	Srinivasan (2017)	2017	US	U. S. West Coast	20–91 m	6 MW	Srinivasan (2017)
	CELL Spar	Dymarski et al. (2019)	2019	Poland	Baltic Sea Polish EEZ	> 66 m	6 MW	Dymarski et al. (2019)
	DTI-F	Serret et al. (2019)	2019	UK	Buchan Deep	90–120 m	7 MW	Serret et al. (2019)
	Bluewind	Heiberg-Andersen et al. (2021)	2021	Norway	–	30 m	5 MW	Heiberg-Andersen et al. (2021)
	Triple-column Spar	Gao et al. (2022)	2022	China, USA, UK	–	–	5 MW	Gao et al. (2022)
	WindCrete	Vigara et al. (2019)	2023	Spain	Gran Canaria Coast, Morro Bay Coast	200 m, 870 m	15 MW	Ferreira et al. (2023)
Semi	WindFloat	Roddier et al. (2010)	2016	Portugal	Galician coast	> 50 m	8 MW	Díaz et al. (2016)
			2022	UK	–	–	5, 10, 15 MW	Crowle and Thies (2022b)
			2023	UK	Scotland, England, Wales Coast	95–115 m	10 MW	Torres et al. (2023)
	Tri-Floater	Bulder et al. (2002)	2016	Spain	Galician Coast	–	5 MW	Castro-Santos et al. (2016), Castro-Santos (2016)
	NOVA Platform	Collu et al. (2014)	2014	UK, Italy	Dogger Bank	18–80 m	–	Collu et al. (2014)
	Hybrid platform	Kim and Kim (2017)	2017	South Korea	Jeju Island coast	80 m	10 MW	Kim and Kim (2017)
	RM3	Correia da Fonseca et al. (2021)	2021	Portugal	The Ports Normands Associés	–	–	Correia da Fonseca et al. (2021)
	TELWIND	Altuzarra et al. (2022)	2022	Spain, Portugal	Lannion	75 m	10 MW	Altuzarra et al. (2022)
	CENER	Sandner et al. (2014)	2023	Netherlands, Ireland	–	–	5 MW	Ramachandran et al. (2023)
TLP	GICON-TLP	Adam et al. (2013)	2016	Germany	Baltic Sea German	> 30 m	2 MW	Dahlhaus and Großmann (2016)
						–	2.3 MW	Adam et al. (2016)
			2017	Germany	Baltic Sea	–	6 MW	Hartmann et al. (2017)
	MIT/NREL TLP	Matha (2009)	2016	Spain	Galician Coast	–	5 MW	Castro-Santos et al. (2016), Castro-Santos (2016)
	TLPWIND	Amate et al. (2016)	2016	Spain, UK	Aberdeen coast	–	5 MW	Amate et al. (2016)
	STLPWT	Ding et al. (2017)	2017	China	–	70–150 m	5 MW	Ding et al. (2017)
	CENTEC TLP	Díaz and Guedes Soares (2023a)	2023	Portugal	Ribadeo (Galicia), F15 (Clare)	150–210 m	10 MW	Díaz and Guedes Soares (2023a)

Table 5
Day rates of vessels for FOWF installation.

Vessel type	Vessel day rate	Reference
Tug boat	22,502 €/day	Castro-Santos and Diaz-Casas (2014)
	22,672 €/day	Kim and Kim (2017)
	34,352 €/day	Kim and Kim (2017)
	14,704 €/day	Correia da Fonseca et al. (2021)
Barge	7,500 €/day	Castro-Santos et al. (2018)
HLV without storage	116,000 €/day	Castro-Santos and Diaz-Casas (2014)
HLV with storage	811,886 €/day	Castro-Santos et al. (2018)
AHV	48,860 €/day	Castro-Santos et al. (2016)
	36,466 €/day	Correia da Fonseca et al. (2021)
	40,000 €/day	Altuzarra et al. (2022)
CLV	90,436 €/day	Correia da Fonseca et al. (2021)
	60,000 €/day	Lerch et al. (2021)

the limited supply of specialised vessels, which are expensive and take longer to build. A study by Lieng et al. (2022) highlights the significant financial benefits of using tugs for anchor installation, traditionally handled by larger, more expensive vessels. Castro-Santos et al. (2019) further emphasise the importance of vessel draft and port depth in optimising fabrication and installation planning. Utilising versatile tugs throughout construction, from installation to transport, can significantly reduce overall project costs.

Responding to the growing demand for specialised FOWF installation vessels requires a multi-pronged approach:

- **Fleet expansion:** Increasing the number of specialised vessels through new builds is crucial.
- **Vessel upgrades:** Upgrading existing vessels to handle larger turbines and harsher environments can extend their utility.
- **Innovation:** Exploring innovative vessel designs and operational practices can improve efficiency and capability.

However, even with these efforts, a vessel availability gap might persist in the near future. Project developers can mitigate this by:

- **Proactive scheduling:** Early planning and securing vessels well in advance are essential.
- **Flexible timelines:** Building flexibility into project timelines can accommodate potential scheduling delays.
- **Strategic partnerships:** Collaborating with vessel operators can secure access to the required resources.

Long-term investments in vessel fleet expansion, innovation, and operational efficiency are crucial to ensure that the availability of specialised vessels matches the rapid growth in demand for FOWF installation.

5. State-of-the-art of floating wind installation research

This section delves into the state of the art of R&D on FOWF installation, providing valuable insight into the scope and depth of ongoing research in this area. A thorough review of 37 journal articles explored research approaches, installation processes, specific research topics, and simulation details (see Fig. 2, Investigation stage in the flowchart).

The literature was categorised into three research approaches: analytical solution, numerical analysis, or not specified, and the installation process was categorised into towing operations or offshore lifting. Following the literature classifications introduced in Section 2.2, the specific research topics were categorised as planning, cost assessment, fabrication, logistics, maintenance, and design/method. Depending on the simulation scope, the studies were further classified into regional planning, weather forecasting, stability analysis, and hydrodynamic analysis. Table 6 summarises the categorisation results.

As can be seen from the classification of research scope in Table 6, most publications that have studied planning also address cost assessment, highlighting the intrinsic link between them. Several studies on planning and cost also include aspects such as fabrication, logistics, and maintenance, as these elements contribute to the CAPEX and OPEX of a project. While there are similarities between installation and maintenance in terms of the installation or replacement of key components, there are limitations to applying findings from installation studies to maintenance; therefore, further research on maintenance is considered essential in the future. Research classified with design and method presenting novel installation methods and systems for various components considered in FOW projects, including tower-rotor-nacelle (TRN) components and their complete assemblies, foundations, cables, anchors, moorings and substations.

5.1. Research approach and installation process

Regarding the overall research approaches applied in the FOWF installation studies, analytical solutions have mainly been used for installations involving towing operations to address essential considerations related to planning, cost assessment, logistics, installation procedures, regional planning, layout optimisation and scheduling. Interestingly, most of these investigations have mainly focused on semi-submersible foundations, with only a limited number of studies considering spar and TLP foundations for towing operations. However, there are no studies on installation planning and cost assessment that specifically consider only barge foundations. Detailed discussions for the planning and cost assessment can be found in Sections 5.2 and 5.3.

On the other hand, numerical analyses have become increasingly popular in recent years, with a surge of research in offshore wind turbine installation methods. Much of this research has focused on the introduction of new installation methods and systems, with different perspectives and analyses. Papers that have studied installation designs and systems involving offshore lifting operations have mainly considered spar floating foundations and have utilised hydrodynamic analysis of coupled multibody systems to assess the feasibility of innovative installation technologies employing catamaran, SWATH, and floating dock. Detailed descriptions of the design and method considered for the FOWF installation studies can be found in Section 5.4.

Given the R&D trends for specific floating foundation types, there are few studies on new installation methods for semi-submersible and TLP foundations. Additionally, there is a significant lack of studies addressing the planning and cost assessment of FOW projects considering spar foundations, highlighting research topics that should be addressed in the future.

5.2. Planning

The integration of FOWFs into the global energy landscape offers a promising path towards a cleaner and sustainable energy future. However, the successful deployment of these innovative structures requires careful planning, encompassing diverse aspects from site selection to installation logistics.

5.2.1. Regional and layout planning

Effective regional planning involves identifying areas with optimal wind resources, minimal environmental impact, and compatibility with existing maritime activities. GIS-based regional planning analyses developed by Castro-Santos et al. (2016, 2019) can be utilised to evaluate various factors and identify suitable areas for developing offshore wind and wave energy projects, enabling comprehensive economic evaluation of FOW projects. Factors to consider in determining suitable locations for FOWFs include extreme environmental loads, water depth, seabed conditions, electrical infrastructure, and port facilities (Crowle and Thies, 2022a; Díaz and Guedes Soares, 2023a).

Table 6

Summary table of research topic, simulation scopes, simulation tools, and considered environmental conditions for each FOWF installation study.

Approach	Installation process[a], Research/Simulation scope[b]												Capacity	Foundation	Installation components	Vessel resources	Tools	Environment	Reference
Analytical Solution	T	L		C	F	G			R				5 MW	Spar, Semi, TLP	TRN-F assem, TRN compon, Found, Anchor, Mooring, Cable, Substation	Tug, AHV, HLV, Cargo barge	GIS	Wind	Castro-Santos et al. (2016)
	T		P	C		G							10 MW	Semi	TRN-F assembly, Mooring	Tug	DEVS, OSCAR, WAVEWATCH III	Wave, Wind, Current	Kim and Kim (2017)
	T	L	P	C		G		D					5 MW	Spar, Semi, TLP	TRN-F assem, TRN compon, Found, Anchor, Mooring, Cable, Substation	Tug, AHV, HLV, Cargo barge	–	–	Castro-Santos et al. (2018)
	T		P		F				R				7 MW	Generic	Generic	Tug, Cargo barge	GIS	Wave, Wind, Water depth	Castro-Santos et al. (2019)
	T		P	C	F		M			W			5 MW	Generic	Foundation, Anchor, Cable	Tug	WRF	Wind	Kumar et al. (2021)
	T		P	C		G	M						–	Semi	TRN-F assem, TRN compon, Found, Anchor, Mooring, Cable, Substation	Tug, AHV, CLV	DTOceanPlus suite	Wave, Wind	Correia da Fonseca et al. (2021)
			P	C				D	R				10 MW	Semi	Cable	CLV	MATLAB, PSO	Wind	Lerch et al. (2021)
	T		P	C		G							10 MW	Semi	TRN-F assembly, Mooring	Tug, AHTS	Mission Planner	Wave	Altuzarra et al. (2022)
			P	C			M	D		W			9.5 MW	Generic	TRN compon, Found, Anchor, Mooring	AHTS, CTV, FSV, HLV	UNEXE O&M	Wave, Wind, Current	Xie and Johanning (2023)
	T		P		F	G	M						–	Generic	TRN-F assem, TRN compon, Found, Cable	Tug, HLV	–	Wave, Wind, Current	Díaz and Guedes Soares (2023b)
	T		P			G							10 MW	Semi	TRN-F assem, TRN compon, Found, Anchor, Mooring, Cable, Substation	Tug, HTV, AHV, CLV, SOV	ForeCoast Marine	Wave, Wind, Current	Torres et al. (2023)
	T		P	C	F	G	M	D					15 MW	Spar	TRN-F assem, TRN compon, Found, Anchor, Mooring, Cable, Substation	Tug, HLV, CLV	FowApp	–	Ferreira et al. (2023)
	T		P	C		G							10 MW	TLP	TRN-F assem, TRN compon, Found, Anchor, Mooring, Cable, Substation	Tug, HLV	Logistics Simulation	Wave	Díaz and Guedes Soares (2023a)
	T		P	C			M	D					10 MW	Semi	TRN-F assembly	Tug	–	Wind	Martinez and Iglesias (2024)
Numerical Analysis	T										S		–	Semi	TRN-F assembly	Tug, AHTS	SESAM, HydroD	Wave, Wind, Current	Collu et al. (2014)
	T										S	H	5 MW	TLP	TRN-F assembly	Tug	SIMO, OpenFAST/Aerodyn	Wave, Wind	Ding et al. (2017)
		L						D				H	10 MW	Spar	TRN assembly	Catamaran	SIMO, HydroD, HAWC2	Wave, Wind	Jiang et al. (2018)
	T							D			S		6 MW	Spar	Foundation	Tug	–	Water depth	Dymarski et al. (2019)
		L						D				H	10 MW	Spar	TRN components	Floating dock	HydroD, SIMO, MIMOSA	Wave	Jiang et al. (2020)
		L						D				H	10 MW	Spar	TRN assembly	Catamaran	MATLAB/Simulink, Singular Perturbation	Wave	Ren et al. (2021)
				C				D			S	H	–	Generic	Anchor, Mooring, Winch	AHTS	FLAC3D	Wave, Soil	Lieng et al. (2022)
		L						D				H	10 MW	Spar	TRN assembly	Catamaran	GeniE, HydroD, SIMO	Wave	Hong et al. (2022)
											S		–	Generic	Anchor	AHV	–	Soil	Cerfontaine et al. (2023)
											S		–	Generic	Anchor	AHV	Abaqus/Expricit 2020	Soil	Dao et al. (2023)
	T							D				H	–	Generic	Anchor	AHV	Marine Simulator	Wave, Current	Martinez et al. (2023)
	T					G		D			S	H	–	Generic	Substation	Tug	Model test, SESAM	Wave	Wang et al. (2023)
		L						D				H	10 MW	Spar	TRN assembly	Catamaran, SWATH	SIMO, Riflex	Wave	Liu et al. (2023a)
		L						D				H	10 MW	Spar	TRN assembly	SWATH	SIMO	Wave	Liu et al. (2023b)
		L						D				H	10 MW	Spar	TRN assembly	Catamaran	SIMO, Riflex	Wave	Ataei et al. (2023)
		L						D				H	10 MW	Spar	TRN assembly	Catamaran	GeniE, HydroD, SIMO	Wave	Hong et al. (2023b)
		L						D				H	10 MW	Spar	TRN assembly	SWATH	WADAM, SIMO, Riflex	Wave, Wind	Gao et al. (2023)
Not Specified	T	L		C	F	G	M						5 MW	Spar, Semi, TLP	TRN-F assem, TRN compon, Found, Anchor, Mooring, Cable, Substation	Tug, HLV Cargo barge, AHV	–	–	Castro-Santos and Diaz-Casas (2014)
	T			C		G							–	Spar, Semi, TLP	TRN-F assem, TRN compon, Found, Anchor, Mooring, Cable, Substation	Tug, HLV Cargo barge, AHV	–	–	Castro-Santos (2016)
	T							D					6 MW	TLP	Foundation	Tug	–	Wave, Wind, Water depth	Dymarski et al. (2017)
	T	L	P		F	G							5, 10 MW	Spar, Semi, TLP, Barge	TRN-F assembly, Foundation	Tug, HTV, SSCV	–	Wave, Wind, Current	Crowle and Thies (2022a)
	T	L				G		D			S	H	16 MW	Semi	TRN-F assembly	Twin barge	Digital Twin	Wave, Wind, Current	Liu et al. (2023c)

[a] (T) Towing operation, (L) Offshore lifting

[b] (P) Planning, (C) Cost assessment, (F) Fabrication, (G) Logistics, (M) Maintenance, (D) Design/Method, (R) Regional planning, (W) Weather forecasting, (S) Stability analysis, (H) Hydrodynamic analysis

In particular, port facilities must be compatible with specific turbine types, vessels, road connections, and berthing requirements (Crowle and Thies, 2022a; Díaz and Guedes Soares, 2023b; Martinez and Iglesias, 2024). Despite the UK being a current frontrunner in FOW projects, UK ports can only partially support the fabrication and installation processes required for large-scale commercial FOWF deployments (Torres et al., 2023). Areas with abundant wind resources for potential FOWFs may not be economically attractive due to the additional time and cost involved in developing ports, roads and infrastructure to meet the requirements.

Therefore, a review of available ports and infrastructure is essential to site planning of new wind farms (Martinez and Iglesias, 2024). Ultimately, significant global investment in port infrastructure and supply chain development is required to meet global energy transition goals.

5.2.2. Grid optimisation

An efficient grid layout that optimises the placement of WTGs, cables, and substations is critical for the economics of FOWFs, but most studies still prioritise bottom-fixed offshore wind installations (Kallinger et al., 2023). However, a promising study on FOWF grid layout by Lerch et al. (2021) utilises an optimisation model built with MATLAB and Particle Swarm Optimisation (PSO, (Hou et al., 2016)). This model considers wind speed, wave effects, connectivity, and installation costs.

Continued research on optimisation methods is crucial to develop more cost-effective, energy-efficient, and reliable inter-array layouts for FOWFs. Specific areas for further investigation may include:

- **Diverse foundations and mooring systems:** Understand how different foundation and mooring system choices affect the optimal grid layout.
- **New technologies:** Investigate the integration of high voltage direct current (HVDC) transmission and smart grid management systems to improve grid stability and resilience.
- **Deep water cable laying:** Develop cost-effective and efficient cable-laying methods for deep water environments.

5.2.3. Transportation and installation planning

Logistics and installation significantly impact the cost and feasibility of FOW projects. Transporting and installing FOWF components, especially in deep waters, presents substantial logistical challenges. Factors such as distance from port to site, component size and weight, vessel type, and weather conditions affect overall costs. In particular, logistical distance is a significant variable affecting the total T&I period.

Installation modelling and simulation can aid decision-making during planning and identify potential risks, logistical bottlenecks and supply chain issues that could cause delays and budget overruns (Torres et al., 2023). Installation analysis results should be interpreted with the alpha factor to account for the uncertainty inherent in weather forecasts during installation operations and ensure realistic planning and decision-making for safe operations (DNV GL, 2020; Wu and Gao, 2021).

Several studies have explored FOW project logistics and proposed optimisation methods. Kim and Kim (2017) focused on optimising the T&I process for floating hybrid generator platforms. Their study, using DEVS# (Hwang, 2009) simulation and real-time data from WAVEWATCH III (WW3DG, 2019) and OSCAR models (ESR, 2009), highlighted key logistical factors influencing T&I cost and duration, emphasising the importance of careful consideration for risk mitigation and project success. Torres et al. (2023) simulated and compared T&I durations for three FOWF sites in the UK using ForeCoast Marine software (JBA Consulting, 2024), considering various transport and installation sequences for FOW components. Correia da Fonseca et al. (2021) introduced a tool integrating logistics planning, weather modelling, and cost estimation within DTOceanPlus (European Commission, 2018).

While these studies offer valuable insights, several challenges remain:

- **Limited applicability:** Current simulation and optimisation tools often focus on specific projects or components, limiting their broader use.
- **Validation and scalability:** Future research should prioritise validating simulations against completed real-world projects, scaling tools for larger, more complex projects, and standardising data formats for wider industry adoption.
- **Enhanced simulation fidelity**: Incorporating alpha factors and safety factors specific to FOWF installation operations would improve the reliability and realism of simulation results.
- **Real-time integration**: Existing tools primarily incorporate weather models for planning, lacking real-time data integration for dynamic adjustments during installation. Integrating real-time weather data would enable more effective risk mitigation and cost optimisation.

5.2.4. Mooring installation planning

Mooring system installation involves various stakeholders, including project developers, contractors, manufacturers, and shipping companies. Mooring components are often large, heavy, and manufactured in different locations, requiring transport to the site. Additionally, mooring installation is challenging due to the need for specialised vessels and equipment such as transport vessels, anchor installation vessels, and mooring line tensioning vessels (Altuzarra et al., 2022). Favourable weather conditions are crucial for safe and efficient mooring connections during FOWF installation. High winds and waves significantly complicate this critical task, leading to potential delays, increased costs, and safety hazards (Torres et al., 2023).

Future research in this area can focus on:

- **Cost-effective and modular mooring systems:** Develop systems using standardised components and innovative transportation and installation methods.
- **Advanced weather forecasting and risk management:** Design tools specific to mooring system designs and installation processes to optimise scheduling and minimise weather-related delays and risks.

5.3. Cost assessment

High costs remain a significant barrier to the widespread adoption of FOW projects. While accurate cost estimates are essential for identifying optimisation opportunities, existing models often fall short (Sykes et al., 2023). They lack consistency and neglect crucial installation factors, such as limited weather windows and waiting-on-weather events, which significantly impact FOW projects. This is particularly problematic as the LCOE of FOW projects (250 €/MWh) is estimated to be roughly three times higher than that of fixed offshore wind (74 €/MWh) in 2023 (DNV, 2023a). Bridging this significant cost gap is critical to making FOW a competitive renewable energy source.

This study delves into the cost aspects of FOWF installation, drawing insights from various methodologies. Castro-Santos et al. (2018) offers a framework for calculating installation costs by considering design criteria, including foundation type, mooring systems, layout, and installation vessels. Their work also provide tools for analysing the entire life cycle cost breakdown structure (LCCBS) and assessing the economic feasibility of FOW projects (Castro-Santos and Diaz-Casas, 2014; Castro-Santos et al., 2016; Castro-Santos, 2016). The study highlights the significant cost differences between installation methods. Utilising an onshore crane and towing operation was found to be significantly cheaper at around €20 million than using an HLV, where installation costs can inflate to around €70 million (Castro-Santos et al., 2018).

While a standardised tool for evaluating both environmental and economic impact on FOW projects is still under development, FowApp, introduced by Ferreira et al. (2023), attempts to address this need by estimating the LCOE and environmental performance using the life cycle assessment (LCA) methodology. This tool considers various

Table 7
LCOE comparison of floating wind projects with different floating foundations, installation processes and distances to shore.

Floater	Installation process	Distance to shore	LCOE estimation	Reference
Spar	Onshore crane, floating crane with storage	100 km	88–195 €/MWh	Myhr et al. (2014)
	Onshore crane, cargo barge, floating crane without storage	5 km	81–91 €/MWh	Castro-Santos et al. (2016)
	Offshore crane and tug	10 km	67–72 €/MWh	Ferreira et al. (2023)
	Offshore crane and tug	60 km	115–120 €/MWh	Ferreira et al. (2023)
Semi	Onshore crane, floating crane with storage	100 km	98–237 €/MWh	Myhr et al. (2014)
	Onshore crane and tug	5 km	75–89 €/MWh	Castro-Santos et al. (2016)
TLP	Onshore crane, floating crane with storage	100 km	87–183 €/MWh	Myhr et al. (2014)
	Onshore crane, cargo barge, floating crane without storage	5 km	96–114 €/MWh	Castro-Santos et al. (2016)
Generic	Onshore crane and tug	67 km	80–100 €/MWh	Kumar et al. (2021)

significant factors, including platform technologies, mooring systems, and O&M activities.

The weather research and forecasting (WRF) model offers valuable tools for optimising FOW projects. It allows for assessing the accuracy of weather forecasts, estimating the energy yield of wind resources at potential sites, and calculating the LCOE (Kumar et al., 2021; Thomas et al., 2023). A hierarchical met-ocean data selection model can be used to reduce the computational cost associated with stochastic simulation of O&M activities (Xie and Johanning, 2023; Rinaldi, 2018). Both the WRF model and the hierarchical selection model can also assist in estimating operational weather windows for installation campaigns. Continuously improving the resolution and accuracy of these models and integrating them with optimisation algorithms can further enhance their efficiency.

As shown in Table 7, the LCOE of a FOWF can vary depending on the type of floating foundation, installation process, and distance from shore. In general, the LCOE increases proportionally with the distance between the wind farm and the shore and is sensitive to the cost of the installation vessel. Therefore, the installation method that does not use expensive floating cranes will result in a lower LCOE. However, with so few FOWFs in operation and a short FOW industry lifespan, accurate cost estimates remain challenging, leading to a significant variation in the LCOE assessments, ranging from 67 to 237 €/MWh.

The studies discussed in this section on cost assessment emphasise the importance of considering diverse factors and methodologies for accurate FOWF installation cost evaluation. This knowledge is critical for project planning, economic assessment, and optimising the cost-effectiveness of FOW projects. Proposed methodologies offer structured frameworks for comparing installation approaches and identifying their economic advantages and limitations. By analysing the impact of each method on the overall project cost, developers can select the most cost-effective solution aligned with their specific needs.

While ongoing advancements in FOW technology are promising, further research is essential to ensure the validity of existing project cost estimates. Refining cost estimation methods and identifying innovative cost-reduction solutions are crucial to narrowing the gap between FOW and fixed offshore wind projects. By continuously validating estimations against real-world projects and exploring novel solutions, one can bridge this cost gap and pave the way for the widespread adoption of FOW as a viable and cost-effective renewable energy source.

5.4. Installation design and method

The demand for FOWF installation is growing significantly, while the available resources are relatively limited. Therefore, developing cost-effective and reliable installation methods holds the key to unlocking the future of FOW energy. Several studies have investigated new designs and methods for FOWF installation from different perspectives, including towing operations, anchor installation, and novel installation systems and concepts.

5.4.1. Towing operation stability

Floating offshore wind turbines are exposed to various environmental loads throughout their lifecycle, including wind, waves, and currents. These loads can induce significant motion and instability during towing, assembly, and power generation. A critical design consideration for WTGs is ensuring stability throughout these stages to prevent fatigue damage, performance degradation, and even turbine failure.

Several studies have investigated the stability of FOWF components under various conditions using different numerical methods. For instance, Collu et al. (2014) developed a framework to analyse the stability of a WTG during assembly and temporary stages. This framework was applied to a case study involving a semi-submersible FOW structure and numerical stability analysis was performed using the SESAM software package with HydroD (DNV, 2023d,g).

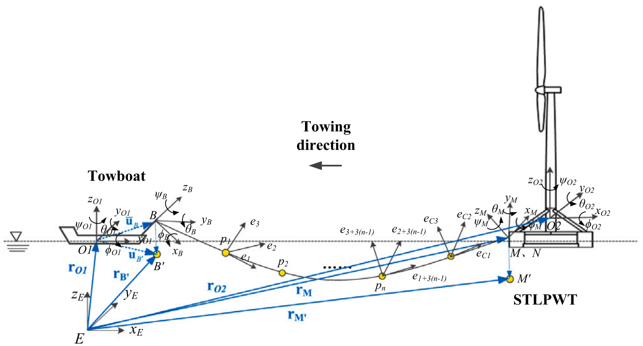
Recent studies investigated the stability of TRN and foundation assembly units and substations during towing operations. The studied considered various foundation types, including semi-submersible (Collu et al., 2014; Liu et al., 2023c), spar (Dymarski et al., 2019), and TLP (Ding et al., 2017; Dymarski et al., 2017). For the substation towing stability analysis, wide-shallow bucket jacket foundation (WSBJF) was considered (Wang et al., 2023).

One crucial aspect of designing WTGs is ensuring their stability during assembly and temporary installation stages. Collu et al. (2014) developed a framework specifically for analysing WTG stability during these critical phases. The framework was applied to a case study involving a semi-submersible foundation and numerical stability analysis was performed using the SESAM software package with HydroD (DNV, 2023d,g).

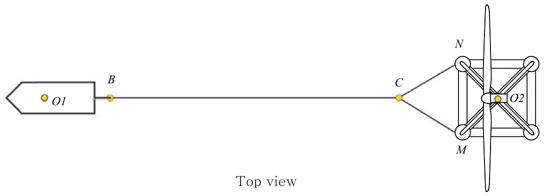
Liu et al. (2023c) introduced a novel float-over installation method utilising a digital twin framework. The framework integrates dry and wet towing operations with machine learning to predict structural responses based on real-time measurements. Digital twin technology has the potential to improve the efficiency, safety, and reliability of marine operations through onboard decision support systems. However, further research is needed to validate the accuracy and reliability of this framework through practical applications.

Upending the foundation becomes a critical step for spar-type WTG installation when geographical constraints necessitate horizontal towing during transportation. Dymarski et al. (2019) investigated the upending process stability of spar foundations for WTGs. Their study revealed that meticulous tank ballasting is critical for successful upending. Ballast water distribution significantly impacts the foundation's centre of gravity and overall stability during this critical phase. To ensure the upending process is conducted safely and efficiently, the study recommends employing additional computational fluid dynamics (CFD) analysis or model testing for even more precise stability verification.

Another crucial stage in WTG installation involves towing the submerged TLP wind turbine (STLPWT). Ding et al. (2017) developed a numerical model using multibody dynamics to simulate wet towing of the STLPWT with SIMO software and OpenFAST/Aerodyn code (DNV, 2023b; NREL, 2023), see Fig. 11. Their study focused on how environmental loads from wind, waves, and current affect both the stability of

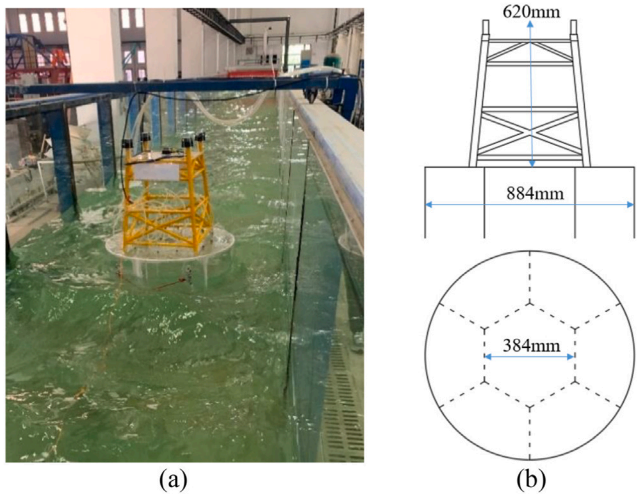


Side view



Top view

Fig. 11. Coordinate system of STLPWT towing operations (Ding et al., 2017).



(a) (b)

Fig. 12. Substation stability experiment: (a) Model experiment of wave flow tank (b) Scale model dimension. Wang et al. (2023).

the WTG and the forces acting on the towline during towing operations. The simulations demonstrated that the WTG remained stable under harsh sea conditions. However, the height of the towing points significantly affected pitch motion and, more importantly, the towline force experienced a substantial increase under these demanding conditions.

Dymarski et al. (2017) addressed design considerations for towing operations. The study discussed the critical design considerations and technical challenges associated with towing and installing a TLP in 60 meters of water. The study emphasised the importance of designing the TLP platform to withstand the forces and post-installation environmental loads. Key considerations include maintaining platform buoyancy and stability, ensuring sufficient structural strength and stiffness, and designing a towing system for transporting the TLP to the installation site. While this study focused on the TLP towing operation, its findings offer valuable insights for designing towing operations for other floating foundation types.

As FOWFs move further offshore, the need for robust floating substations is also growing. Research on floating substations is still in its early stages, but recent studies are starting to address the challenges. Wang et al. (2023) investigated the dynamic response and stability of a fixed offshore substation foundation during wet towing. Their study validated the feasibility of wet towing through model experiments and numerical simulations using the SESAM package, see Fig. 12. The study focused on a bucket-type substation foundation being towed to the installation site. The results showed good agreement between model tests and simulations, highlighting the sensitivity of towing stability to wave height and period. Additionally, the draft of the foundation plays a crucial role in balancing stability with economic benefits. Since the foundation stability is vulnerable to resonant response with waves, future designs may need adjustments to ensure natural periods fall outside the wave period range.

5.4.2. *Anchor installation and stability*

A paramount challenge in FOWF design is guaranteeing the safe, efficient, and cost-effective installation and maintenance of the anchors that moor the turbines. Cerfontaine et al. (2023) emphasise the critical importance of integrating anchor design from the outset, both within the overall FOWF plan and the foundation design, to achieve these crucial goals.

Recent studies have explored various anchor installation methods and their effectiveness. Lieng et al. (2022) investigated the installation and pull-out capabilities of dynamically installed anchors (DIAs) through three-dimensional finite difference analysis using FLAC3D software (ITASCA, 2023). DIA is a type of anchor that can free-fall from a certain height, penetrate the seabed, and rotate to a stable position.

Martinez et al. (2023) proposed a simplified, cost-effective craneless deployment method for variable buoyancy anchors using virtual prototyping tool, Marine Simulator based on AGX Dynamics (Algoryx, 2019). While promising for planning real-world deployments, this method requires further research to consider broader anchor designs, water depths and deployment dynamics.

Dao et al. (2023) introduced a 3D large deformation finite element (LDFE) model for drag-embedded anchors (DEAs) in soil, highlighting significant discrepancies between analytical and numerical results. The study emphasises the importance of understanding anchor-soil interaction and the limitations of unvalidated simulations due to uncertainties in soil response.

Cerfontaine et al. (2023) compared various anchor types, highlighting the trade-offs between performance, scalability, and installation challenges for different seabed conditions. While plate anchors offer the most efficient geotechnical performance, the optimal anchoring solution from a project perspective also depends on the chosen mooring type and the capabilities of the available supply chain.

As the size of WTGs and foundations increases, so will the size of the anchors. Future studies should conduct comparative analyses of various anchor designs, considering:

- Anchor-soil interaction
- Performance and stability
- Fabrication and installation feasibility

Focusing on these considerations will pave the way for the development of next-generation anchoring solutions for WTGs, ensuring robustness, efficiency, and cost-effectiveness.

5.4.3. *Innovative installation system designs*

Conventional FOWF installation processes that rely on towing operations may need to be improved to meet the growing installation demand in the FOW industry. Therefore, numerous studies have explored new FOWF installation designs and systems, and recent research incorporates offshore lifting technologies (see studies in Table 6, labelled D and L in the research scope).

A new installation concept is called an onsite lifting operation, in which the TRN assemblies are transported to the offshore operation site, lifted from the installation vessel, and mated onto pre-installed

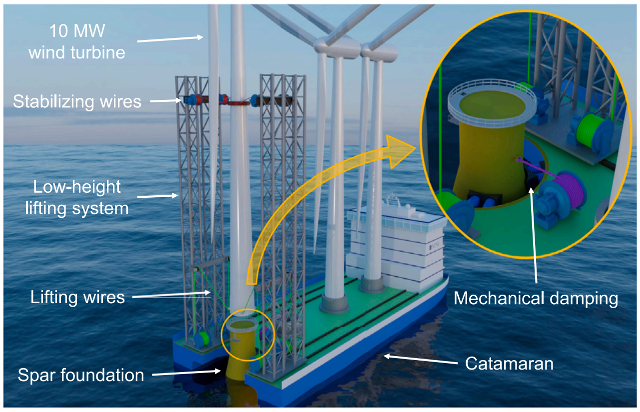


Fig. 13. Onsite installation method using catamaran installation vessel (Hong et al., 2022).

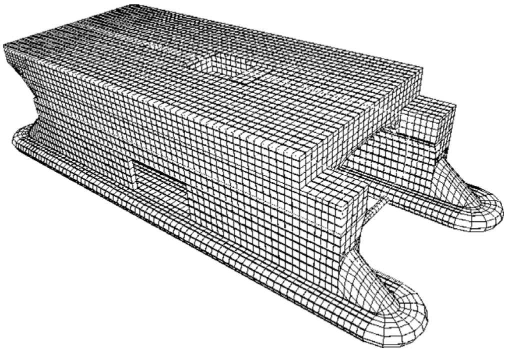


Fig. 14. SWATH installation vessel.

floating foundations. Several studies considered catamaran installation vessel (Jiang et al., 2018; Ren et al., 2021; Hong et al., 2022, 2023b; Liu et al., 2023a; Ataei et al., 2023), while utilisation of SWATH (Small Waterplane Area Twin Hull) installation vessel is also studied (Seacraft, 2000; Liu et al., 2023a,b; Gao et al., 2023). Fig. 13 illustrates the onsite lifting operation using catamaran installation vessel.

The conventional installation process involves a series of steps to combine the wind turbine and foundation, transport it to the operational site, and connect it to the mooring system. In contrast, the new onsite installation concept offers time and space advantages as the various fabrication, assembly and installation steps can take place simultaneously. A detailed installation process and its advantages and disadvantages can be found in Jiang et al. (2018) and Hong et al. (2022).

While this new installation method has several advantages over traditional methods, there are expected to be technical challenges in lifting wind turbine components and entire assemblies that are subjected to harsh offshore environmental loads. Therefore, recent research has focused on validating the feasibility and improving the performance of the new offshore lifting installation method through comprehensive analyses.

The studies have considered the complex multibody system for onsite installation analysis, which consists of catamaran installation vessel with the dynamic positioning system, lifted wind turbine, spar foundation and mooring system. The base system was numerically constructed using the SESAM software package, encompassing GeniE, HydroD, and SIMO (DNV, 2023b,c,d,g). Aeroelastic simulations were performed using HAWC2 (DTU Wind Energy, 2007) and the multibody hydrodynamic analysis were performed in SIMO. Jiang et al. (2018) performed the hydrodynamic analysis to understand the dynamics of the installation concept. The analysis results revealed that the complex multibody installation system is sensitive to environmental conditions and mooring configurations.

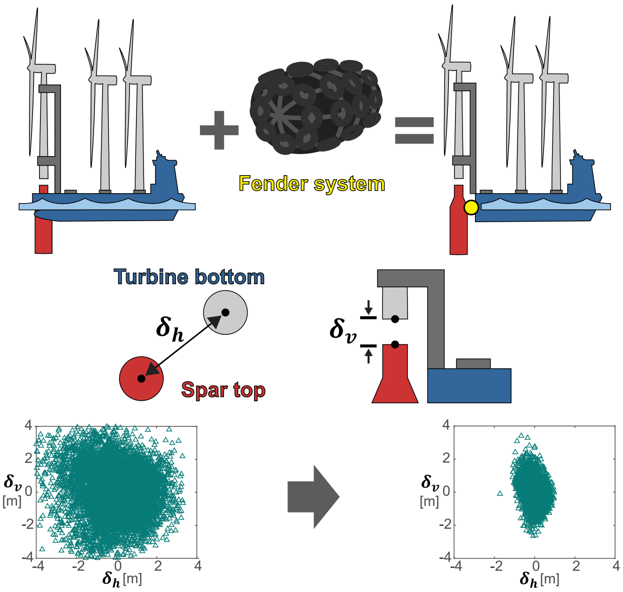


Fig. 15. Effect of a mechanical damping system on the relative motions of the offshore lifting operation (Hong et al., 2022).

Motion compensation systems are widely used in various marine operations, including subsea product lifting and installation and transporting people and cargo for installation and maintenance activities (Xu et al., 2023; Ampelmann, 2024). As a means to mitigate the relative motion between the lifted wind turbine and the floating foundation, Ren et al. (2021) proposed to utilise a hydraulic active heave compensation (AHC) system. The study developed the control algorithm governing the AHC system based on singular perturbation theory and validated through MATLAB/Simulink simulations.

Additionally, Hong et al. (2021, 2022) introduced a mechanical damping system consisting of fenders and wires, with the fenders strategically positioned between the catamaran and the spar, see Fig. 15. The damping system was modelled as a linear damping system and applied to the base multibody numerical model. The numerical analysis revealed the mechanical damping system can effectively reduce the horizontal dynamic response of the system.

Given the inherent complexity of the installation system, previous numerical modelling and analyses have often adopted simplified approaches. To achieve more realistic analysis results, Ataei et al. (2023) and Gao et al. (2023) investigated the influence of structural flexibility of lifting mechanisms on the dynamic response of the installation system using SIMO and RIFLEX software (DNV, 2023f). The study found a noticeable impact of crane structural flexibility on the system's dynamic response. Furthermore, Hong et al. (2023b) presented a detailed numerical modelling method for the onsite installation system utilising a catamaran, leveraging GeniE, HydroD, and SIMO software. The study also examined the influence of hydrodynamic and environmental factors that could potentially affect the analysis results. The findings underscore the importance of considering various hydrodynamic and environmental modelling factors during control system design and the utilisation of diverse wave types to evaluate the weather window for the onsite installation concept.

In order to improve the efficiency of the onsite installation method, Liu et al. (2023a,b) investigated the dynamic response by considering a SWATH vessel and compared the results with the catamaran case, see Fig. 14. The study results showed that the SWATH vessel has a reduced vessel response and can be a promising alternative to improve the installation operability.

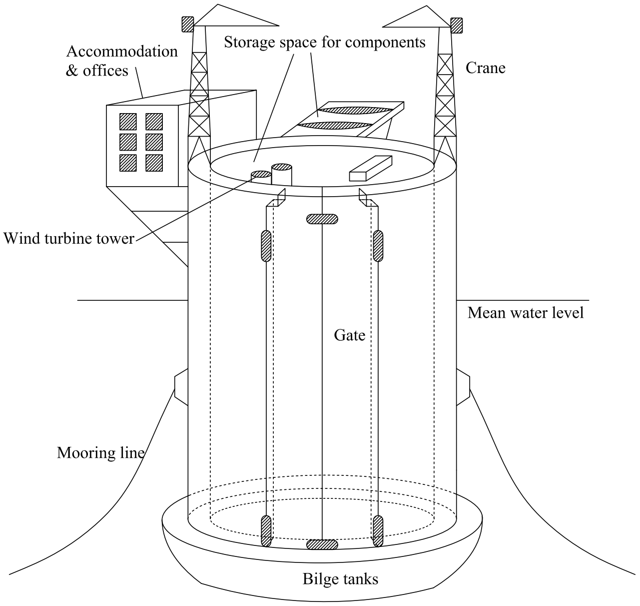


Fig. 16. Floating dock (Jiang et al., 2020).

In addition to the offshore lifting methods utilising catamaran and SWATH vessels, Jiang et al. (2020) designed and analysed a large floating dock specifically for WTG installation on a spar foundation to mitigate the relative motion induced by offshore environmental loads, see Fig. 16. The numerical floating dock was built using SESAM package including SIMO, HydroD, and MIMOSA (DNV, 2023e). The novel floating dock design demonstrated stability, ease of transportation and installation and is expected to provide a safer and more efficient installation method.

Significant progress has been made in research regarding the installation of floating wind turbines. This progress has led to:

- Improved understanding of the dynamic response of the novel onsite installation system with catamaran and SWATH vessels.
- Development of novel control and mechanical damping systems.
- Enhanced knowledge of the influence of environmental and hydrodynamic factors on the installation system.

To further increase efficiency and stability, future research should focus on:

- Developing and evaluating diverse and realistic designs for new installation methods.
- Developing dedicated low-motion WTG installation vessels.
- Continuing the advancement of relative motion reduction methods and control systems.

Incorporating the various structural and hydrodynamic elements, control systems, and damping mechanisms explored in the different studies into a single simulation will yield results that more closely resemble real-world installations. However, modelling and analysis for such a complex model may need to be more computationally efficient, and the trade-off between the fidelity and cost of the analysis should be evaluated.

As the current onsite installation method simplifies the crane design, accommodations, and deck layout of the vessel, collaborations between research institutions with various industrial stakeholders, including operators, installation contractors, ship owners, and crane manufacturers, are essential for a realistic installation method and vessel development.

6. Discussions

This review offers a comprehensive analysis of the current landscape of FOWF installation. It explores both the significant achievements in the field and identifies areas ripe for further development. Key findings, opportunities, and research gaps can be summarised as follows:

6.1. Key findings

- **Surging research activity:** A global surge in research activity is observed, focusing on integrating larger turbines and exploring diverse foundation designs (e.g., barge, semi-submersible, spar, TLP). This signifies a growing international commitment to advancing FOW technology.
- **Unlocking deepwater potential:** Existing FOW projects demonstrate the readiness of technology to tap into vast wind resources in deep waters, where bottom-fixed turbines are impractical. Foundation type selection significantly impacts installation processes, each offering advantages and limitations for specific water depths, environmental conditions, and project needs.
- **Regional variations:** Research trends reflect regional priorities and resources. Europe leads in R&D, while Asia-Pacific nations, with favourable geography and strong industry bases, show vast potential. The US market is poised for significant growth driven by ambitious offshore wind energy targets.
- **Near-shore mating challenges:** Assembling wind turbine components with foundations near shore provides a controlled environment for mating operation but can significantly increase T&I and O&M costs in the future as wind farms are located further away and wind towers increase in size.

6.2. Opportunities and research gaps

- **Enhanced costing and planning:** Current FOWF cost models inadequately capture weather variability and its impact on project timelines. Unforeseen weather events can significantly disrupt schedules and inflate costs. Standardised tools that integrate environmental and economic impact assessments are needed to improve decision-making during the FOW project planning phase. These tools should leverage existing cost estimation and weather forecasting methods but require validation and improvement to enhance their accuracy and mitigate financial risks associated with FOW projects.
- **Expanding installation vessel capacity:** The limited capacity of existing FOWF installation vessels and the slow pace of fleet expansion pose challenges for future large-scale deployments. Research should explore innovative vessel designs capable of handling larger turbines and harsher environments. Upgrading existing vessels and fostering strategic partnerships between project developers and vessel operators are also crucial considerations.
- **Foundation design optimisation:** While spar foundations dominate current research due to their majority in recent operational projects, a more comprehensive understanding of all FOW foundation technologies is necessary. Comparative analyses and multi-disciplinary design approaches can guide informed decision-making for selecting the most suitable foundation type for specific site characteristics. This can lead to significant cost optimisations throughout the project lifecycle. Initial research often prioritises wind resource assessment; however, a shift towards comparative studies focusing on optimal foundation selection based on cost, environmental impact, and site suitability is critical for maximising project viability.
- **Anchor design and installation:** Anchors play a vital role in long-term FOW stability by mooring the floating structures to the seabed. Research on cost-effective anchor deployment methods and an improved understanding of complex anchor-soil interaction mechanisms are crucial for ensuring the long-term integrity of FOWFs and reducing maintenance costs.

- **Comprehensive stability analysis:** Existing research on stability analysis primarily focuses on towing for semi-submersible foundations. Further studies are needed to analyse the stability of spar and TLP foundations across various environmental conditions and throughout all installation stages, including towing, assembly, and power generation. Robust stability analysis is crucial for ensuring the safety and success of FOWF installation.
- **Exploring innovative installation methods:** While towing remains the dominant method for FOWF installation due to its simplicity, innovative methods such as offshore lifting and onsite installation promise efficiency gains and reduced installation time frames. Further research should focus on optimising these methods for cost-effectiveness and wider adoption, considering factors including weather dependency and suitability for different foundation types.
- **Digital twin technology:** Validating the accuracy and reliability of digital twin frameworks in predicting structural responses during FOWF installations requires further investigation. This technology has the potential to revolutionise FOW project planning and execution by enabling virtual simulations of installation procedures, optimising processes to minimise risks and improve efficiency.
- **Bridging the research-industry gap:** Addressing these research gaps necessitates a solid collaborative effort between academia and industry stakeholders. Universities and research institutions can provide valuable expertise in developing advanced cost assessment models, refining digital twin frameworks, and optimising FOWF component designs. Conversely, industry partners can offer real-world data, practical insights, and testing opportunities to ensure the developed solutions are technically sound and commercially viable.

By addressing these knowledge gaps, the FOW industry can achieve significant advancements in efficiency and cost-effectiveness, overcome technical hurdles, and realise the full potential of this promising renewable energy source.

7. Conclusion

Floating offshore wind technology presents a significant opportunity to unlock vast renewable energy potential in deep water regions, potentially contributing to gigawatts of clean energy generation capacity and accelerating global clean energy goals. While successful projects showcase the technology's potential, limitations require attention for broader adoption.

Conventional towing installation methods are vulnerable to harsh weather and remote locations, especially for ever-growing wind turbine sizes. Innovation in FOWF installation and maintenance methods is crucial for overcoming these limitations and reducing overall costs. Research efforts should focus on safe, reliable offshore methods. Achieving this necessitates realistic planning and robust R&D investments.

Floating offshore wind farm installation research is a rapidly evolving field driven by the need to harness offshore wind energy in deep water. While significant progress has been made, critical research gaps exist. These include refining cost estimation models, optimising foundation designs for diverse regional and environmental conditions, expanding and innovating installation vessel capabilities and developing breakthrough installation methods. Bridging these gaps is critical for the successful and efficient deployment of large-scale FOW projects.

The path forward demands a two-pronged approach: technological innovation and industry collaboration. Key technological advancements include advanced mooring systems and optimised vessel utilisation through strategic scheduling and partnerships. Additionally, fostering robust research-industry collaboration through consortiums or knowledge-sharing platforms will accelerate FOW technology breakthroughs.

Overcoming remaining challenges and seizing opportunities for efficiency, cost-effectiveness, and reliability will unlock FOW's full potential as a game-changer for clean energy. This wider adoption will significantly accelerate the transition to a sustainable future.

8. Limitations

This study provides a broad overview of current research trends and limitations in the FOWF installation study, which inevitably excludes extensive analysis of specific installation phases, scopes, designs, or methodologies. In addition, the nascent FOW industry itself has limited available research due to the small number of completed projects and limited sharing of intellectual property. As this study is a systematic meta-analysis of papers retrieved using specific keywords, further searches and investigations in specific areas are needed to understand the evolution of FOWF installation technology from various perspectives.

CRediT authorship contribution statement

Sunghun Hong: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jade McMorland:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Houxiang Zhang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Maurizio Collu:** Writing – review & editing. **Karl Henning Halse:** Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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