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Perspective

Five grand challenges of offshore wind financing in the United States

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ABSTRACT

Offshore wind energy has the potential to play a critical role in fostering a renewable energy transformation in the United States. This owes to its massive technical potential, strategic location near densely populated coastlines, and—relative to onshore wind and solar—high capacity factors and consistent production. The Biden Administration's target to build 30 GW of offshore wind capacity by 2030 (from 0.04 GW today) requires the creation and swift development of a new industry that interlinks the wind and power industries with the maritime sector. Critical to its success is financing. While financial capital is abundant, deploying it for offshore wind faces major challenges. We identify and describe five grand challenges affecting offshore wind finance in the U.S. Failing to address these challenges may put deployment targets at risk. The challenges include (1) Early years financing: navigating the complexities, timing mismatches, and high costs of projects in the development phase; (2) Policy support for project financial solvency: addressing the uncertainty and systematic transfers of tax credits away from offshore wind, characteristic of the U.S. Investment Tax Credit; (3) Workforce development: building a skilled workforce for an emerging market; (4) Transmission and integration barriers: upgrading the power grid to reliably support large scale offshore wind integration; and (5) Floating wind development: financing the development and scale-up of floating offshore wind technologies. The second challenge has already been solved to a large extent by the Inflation Reduction Act.

1. Introduction

Offshore wind (OSW) is a massive renewable energy resource, strategically situated near densely populated coastlines. Technically, OSW power is capable of supplying 11 times the world's projected electricity demand in 2040, and—relative to onshore wind and solar—OSW exhibits significantly higher capacity factors and more consistent production, providing stability for electricity transmission systems [1].

Within the last decade, OSW has developed from a costly decarbonization technology to an economical way to produce bulk electricity without subsidies in mature markets [2]. From 2012 to 2021, global installed capacity increased more than 10-fold from 5 gigawatts (GW) to 53 GW [3]. Europe had long had the highest capacity installed, but in 2022 was overtaken by Asia [4].

OSW's attractive characteristics and success in Europe and Asia warrant the rapidly growing interest and development in OSW power in the U.S. Indeed, the estimated technical potential of OSW in U.S. waters is 2100 GW, nearly twice the country's entire electricity capacity in 2021 [5,6]. In addition, coastal counties account for just 10 % of the country's landmass (excluding Alaska), but nearly 40 % of the population [7].

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A. Offshore Wind Development in the United States

The Biden Administration committed to increasing OSW capacity from 42 megawatts (MW) in 2022 to 30 gigawatts (GW) by 2030—enough to power 10 million homes [8]. Achieving this target will require over $100 billion in new investments [9] and create 80,000 full-time-equivalent jobs from 2023 to 2030 [10]. Policies in eight East Coast states—Massachusetts, New York, New Jersey, Rhode Island, Connecticut, Maryland, Virginia, and North Carolina—target developing 40 GW of OSW capacity by 2040 [11]. In August 2022, California adopted OSW capacity targets of 3–5 GW by 2030 and 25 GW by 2045 [12]. Discussions for additional OSW capacity targets are underway in Washington and Oregon [13,14], the Gulf Coast [15], and Great Lakes states [16]. The pipeline of U.S. OSW projects rose to more than 40 GW by May 2022 [11]. For comparison, the country's onshore wind capacity totals 140 GW [17].

Despite the U.S.'s slow start, Bloomberg New Energy Finance and 4C Offshore forecast that the U.S.'s global share in installed capacity will increase from zero in 2022 to 11 %–13 % in 2031 [11].

Yet, creating an OSW transformation requires coordinated co-developments across technology, policy, and economic systems. With attention on OSW development rising, it is important to consider the challenges. These challenges stem from overall market and supply chain nascency, emerging workforce requirements, and regulatory, policy, and jurisdictional overlaps, among other factors.

B. Financing Offshore Wind

All energy projects need financing, but financing plays a particularly important role for capital-intensive technologies like OSW [18]. The largest share of OSW costs comes from upfront capital expenditures (CapEx), e.g., turbine parts, machinery, and electrical equipment. CapEx need to be financed long before revenues from energy generation are obtained through a combination of debt (loans) and equity (ownership stakes in the project), each of which comes at a cost. CapEx and the resulting financing costs account for around 80 % of a typical Western European OSW project's lifetime cost [19]. The capital-intensive nature of OSW development makes the weighted average cost of capital (WACC)—i.e., the weighted combination of the interest rate on debt and required rate of return on equity—a highly important cost determinant of a typical OSW project [20]. For example, at a WACC of 10 %, financing costs already account for half of the project's lifetime cost [21].

Historically above the WACC of onshore wind or solar PV, the WACC for typical OSW projects has come down dramatically in recent years, ranging from 3 %–6 % in nominal terms for projects financed between January 2020 and June 2022 in Western Europe,[1] the U.S., and China [22].[2] In large part, this can be attributed to a low-interest rate environment and confidence in the technology itself, as evidenced by falling risk premiums in the last decade [20].

With today's inflationary environment and higher interest rates, finance becomes an even more critical component for OSW project development to keep costs of energy down.

C. Perspectives of industry experts on the challenges

We explore the challenges of an emerging OSW industry in the U.S. through the lens of finance, i.e., the sourcing of funds, the conditions under which those funds are provided, and the challenges and opportunities that surround this aspect of OSW development.

Against this backdrop, this paper addresses the following questions:

1. What are the challenges in the next three to five years affecting the financing of a rapid scale-up of OSW energy in the U.S. at a reasonable WACC?
2. Which of these challenges are *grand challenges*, i.e., potential show-stoppers—challenges that, if unresolved, may prevent the massive and rapid scale-up from taking root?

To answer these questions, we organized an intensive, two-day exploratory consultation stakeholder workshop, bringing together academic researchers and industry practitioners active in the OSW finance space. We focused our discussions on challenges that are *controllable* to a large extent by government or industry actors within the offshore wind space.

D. Macrotrends: Inflation and Interest

Since the workshop, questions of offshore wind finance have been dominated by two macrotrends: the highest inflation levels and resulting interest rate hikes that the U.S. and many other countries have seen in decades [24,25]. These trends have hit OSW development particularly hard, for three reasons. First, being capital-intensive, OSW relies heavily on financing, and increasing interest rates mean increasing financing costs. Second, the combination of high inflation and fears of recession (from rising interest rates to stem inflation) steers investors towards safer investments, increasing the premium on risky investments [26–28]. OSW is a nascent industry in the U.S. without an established track record and has long development timeframes. Both factors increase perceptions of risk. When combined with the general rise in material costs, OSW development in the U.S. is nearly 50 % more expensive now than in 2021 [29]. While OSW developers can mitigate inflation risk to some extent by, e.g., inflation indexing in contracts (prices automatically adjust for inflation), this does not solve the overarching problem: costs for OSW development have soared, and someone must pay for it.

Below is a brief overview of examples in four states:

Recent data, however, provide hope of price stability for the foreseeable future. U.S. inflation dropped to 3 % year-on-year in June and July 2023, and interest rate hikes have similarly slowed [40]. We acknowledge the ongoing impacts of these contextual macrotrends, which may delay OSW development. As noted above, in this paper we focus on grand challenges that are largely controllable within the OSW space, that must be overcome to finance a thriving U.S. OSW industry.

E. Five Grand Challenges

We found that, while financial capital is abundant and investors are seeking opportunities in OSW, successfully employing that capital in the U.S. faces at least five grand challenges:

1. Navigating the timing mismatches, high costs, and jurisdictional complexities of the development phase (i.e., all of the processes, such as siting and permitting and securing financing, prior to construction).
2. Addressing the uncertainty and systematic transfers of tax credits away from OSW built in to the U.S. Investment Tax Credit (ITC).
3. Developing a skilled workforce capable of navigating and problem-solving the harsh conditions offshore.
4. Building a transmission network that supports OSW expansion.
5. Financing and scaling up early-stage floating OSW technologies, which are needed to realize the full potential of OSW in the U.S.

The second grand challenge (inadequacies of the ITC) has been addressed to a significant extent by the Inflation Reduction Act (IRA) and is discussed in detail in Section 3.

The grand challenges, in general, imply the need for structural change, alignment across policy and regulatory environments, as well as

[1] Denmark, UK, Netherlands, Germany, Belgium, and France.

[2] See [23] for estimates going back to 2007.

development of the OSW electricity transmission grid. They also imply a future of growing pains experienced by any new industry. The U.S. is an emerging OSW market with its first utility-scale OSW farm scheduled to come into operation in 2023.

This paper is organized as follows: Section 2 outlines the methodology, Section 3 presents the grand challenges, and Section 4 concludes with a discussion on the implications of the grand challenges for OSW development in the U.S. and future research.

2. Methodology

We organized and conducted an intensive two-day workshop, "Offshore Wind Energy Financing: Grand Challenges and Innovative Solutions," held at Columbia University, New York City from June 23–24, 2022 (for a summary report, see Hansen et al. [41]).[3]

A. Participant Selection

Invited participants were selected based on their involvement, experience, and knowledge of OSW finance in the U.S. and Europe. From a web-based search on publications, news mentions, presentations, and participation in events, and through the network of the organizing researchers, we identified 23 relevant research academics, 9 European and 14 from the U.S.

The evidence of previous activity in the field was critical for the selection of academics, alongside other measures to ensure a broad set of viewpoints. We screened 48 industry practitioners and invited 31 with broad representation across companies, interests, and geographies. Through individual conversations, some personal invitations were updated and transferred within companies.

Eventually, 13 academics—ranging from MS and Ph.D. Students, Postdocs, and Assistant/Associate/Full Professors (or equivalent)—and 14 practitioners from some of the leading OSW companies participated in the workshop.

B. Pre-workshop Survey

The research team developed a short survey to identify the challenges and drivers of OSW financing and structure workshop conversations. The purpose of the survey was to identify the most critical discussion points prior to the workshop and maximize the value added by the practitioners by asking the "right questions." The survey was sent to all confirmed participants (i.e., research academics and industry practitioners) two weeks before the workshop and results served to select focus group topics (survey questions and results are detailed in Hansen et al. [41]).

C. The Workshop

The two-day workshop engaged participants in general sessions and dedicated focus groups on risk, siting and permitting, and financing structures. The goal of the focus groups was to determine the grand challenges facing offshore wind financing within the three focus group themes. Researchers took on the role of asking questions and providing context, based on their knowledge of OSW finance, and practitioners took on the role of answering the questions, based on their collective experience.

The composition of each focus group was pre-selected by the workshop organizers to ensure that each group encompassed appropriate areas of expertise and diversity in experience level, work role, and geographical context (U.S. and Europe). A designated chairperson in each group assumed the role of guiding the discussion towards the core questions and ensuring equitable participation.

Following the focus groups, each group presented its results, and the workshop organizers compiled a full list of grand challenges.

D. Data Collection and Processing

The workshop followed Chatham House Rule, meaning that general conclusions can be shared outside the workshop, but not specifics of who said what [42]. This helped to ensure that participants felt comfortable sharing their ideas and opinions.

Three researchers were designated as note-takers for the entirety of the workshop. After the workshop, the notetakers combined their notes, harmonized discrepancies, and coded using NVivo.

The grand challenges, as presented in the next section, emerged and were generally agreed upon by each focus group and during the general discussion in plenum. Researchers conducted additional desk research after the workshop to provide context for the grand challenges and incorporate developments since the workshop.

3. Grand challenges

This section presents the five grand challenges facing offshore wind financing in the U.S. in the next three to five years that emerged from the workshop. Throughout the section, we refer to the views of both practitioners and academic researchers as "participants."

A. The Timing Mismatches, High Costs, and Jurisdictional Complexities of the Development Phase

According to the practitioners, the development phase of OSW is daunting. In this phase, the developer must obtain site access, permits for construction and operation, grid access, and financing [20]. It is characterized by exceptionally high risk, uncertainties, and costs. Participants traced these risks to timing mismatches, high costs, and jurisdictional complexities in at least three areas: (1) seabed lease auctions; (2) permitting and other regulatory processes; and (3) alignment of costs and revenues.

1) Seabed Lease Auctions and Payment Structure

The right to develop offshore energy in the U.S. is allocated through seabed lease auctions. OSW developers submit competitive lease price bids in auctions facilitated by the federal Bureau of Ocean Energy Management (BOEM), and the winner pays the bid price to the federal government. During the past years, the lease prices, i.e., winning bids, have increased drastically. In 2022, six lease areas in the New York Bight—totaling 488,000 acres (1975 km^2) with the potential to supply 5.6 GW of electricity—were auctioned for a combined $4.37 billion [11]. These lease costs amounted to 22 % of average capital expenditures for offshore wind projects [11]. Five lease areas in California and two in North Carolina were auctioned for $757 million and $315 million, respectively; while smaller—potentially due to California's deeper waters necessitating floating wind technologies, and North Carolina's relatively weaker policy environment—they are substantial [43,44].

It is important to note that not all seabed lease auctions have attracted high prices. In August 2023, the first offshore wind seabed lease auctions were held for three areas in the Gulf of Mexico (one in Louisiana and two in Texas). Only one of the Texas areas received bids, and the winning bid was $5.6 million, just above the minimum required [45]. This may reflect a number of factors, including the lower wind

[3] Our research is exempt from IRB approval based on 45 CFR § 46.104 paragraph (d)(2)(i) and (ii). The information obtained from the workshop (1) was collected such that workshop participants cannot be identified directly or indirectly, and (2) would not place participants "at risk of criminal or civil liability" or damage participants' "financial standing, employability, educational advancement, or reputation" (see https://www.ecfr.gov/current/title-45/subtitle-A/subchapter-A/part-46/subpart-A/section-46.104).

resource and less developed policy support (relative to the North Atlantic) [46], as well as the uncertain macroeconomic environment.

In general, however, seabed leases are a major development cost for U.S. OSW projects, and practitioners pointed to the timing and front-heavy lease payment structure as a major challenge. Seabed lease auctions occur early on in the development phase, when risks are highest and before developers have accurate estimates of project costs or future revenues. In addition, the lease payment structure requires the bulk of lease costs to be paid upfront.

Practitioners also noted a structural issue in regulatory design. Seabed leases more than three miles from shore fall under federal jurisdiction, while power purchase agreements (PPAs) and offshore renewable energy certificate (OREC) contracts are under state jurisdiction. The result is that developers must compete in seabed lease auctions with the winning bid being paid to the federal government, and then negotiate with states to try and recoup costs, where the amount that can be recouped is uncertain. This system creates (1) the potential of cross-subsidization from states to the federal government, and (2) advantages for larger developers with greater access to capital and the ability to take on more risk. Both may lead to increased electricity prices for OSW power, potentially reducing its competitiveness and speed of development.

2) Permitting and Regulatory Processes

OSW development falls under federal, state, and local regulatory jurisdictions. Each jurisdiction has its own laws, permitting systems, requirements, and courts, and coordination between jurisdictions and relevant authorities remains challenging. The result is increased uncertainty on whether and when a project will be fully permitted and authorized. This increases risk of major delays or even project abandonment.

3) Revenue and Cost Alignment

An OSW farm must generate enough revenue to recover its costs. Securing finance for OSW development generally requires revenue stabilization, i.e., long-term stabilization of electricity prices so that revenue is known for at least 15 or 20 years, and is often accompanied by subsidies to incentivize investment. This is particularly true for emerging OSW markets [47].

In the U.S., government subsidies come in the form of federal tax credits (see sub-section D below), and revenue stabilization is currently being achieved at the state level through fixed-price PPAs or OREC contracts (depending on the state) [48].[4] Participants generally agreed that PPAs and OREC contracts work well—they stabilize electricity prices at levels high enough to cover costs.

However, there is a timing challenge: PPAs and OREC contracts are generally issued early in the development phase, before all permits have been secured, and before most costs—turbines, balance of plant, steel, etc.—can be accurately projected. This creates a major risk. While some (larger, risk-loving) developers may prefer this setup, practitioners at the workshop preferred reducing the time gap, and therefore risk. The examples in Table 1 (Introduction) show the risks of long development timeframes, especially during times of price instability

4) Navigating the Development Phase as Grand Challenge

The exceptionally high risk and costs of the development phase constitute a major barrier to entry into OSW development. For firms that do enter OSW development, the high risk and costs increase the likelihood of major delays, cost overruns, high financing costs, and—therefore—project abandonment. Additionally, practitioners agreed that there are relatively few financial experts currently able to manage the complexities of OSW finance risk, which in itself increases the risk of, for example, cost overruns (discussed further in Section 4E).

Table 1
Examples of effects of high inflation and interest rates in four states.

State	Description
Massachusetts	In October 2022, two projects (Commonwealth Wind, 1.2 GW; South Coast Wind (formerly Mayflower Wind), 400 MW) requested to re-negotiate power purchase agreements (PPAs) due to increasing costs; the requests were rejected [30,31]. Both projects are paying penalties (Commonwealth Wind: $48 M; South Coast Wind: $60 M) to exit contracts, and plan to re-submit in future MA procurements with new pricing requirements [32].
New Jersey	Passed legislation in June 2023 allowing Ørsted (developer of Ocean Wind, 1.1 GW) to keep federal tax credits that would normally be returned to ratepayers (does not impact other NJ OSW projects). Ørsted nonetheless chose to delay project, is considering abandonment, and announced possible $2.3 billion impairment on U.S. assets [33,34].
New York	In July 2023, developers of the state's four projects filed petitions with the Department of Public Service asking for ~50 % more money from ratepayers to address cost increases and transmission delays [35,36]. NY rejected requests [37].
Rhode Island	In October 2022, the state put out a solicitation for an OSW project (600 MW-1 GW) [38]. After receiving a single bid, the state cancelled the solicitation (July 2023), arguing that the bid received was too high and therefore bad for ratepayers [39].

B. The uncertainty and systematic transfers of tax credits away from OSW built into the U.S. federal Investment Tax Credit

Federal financial support for OSW development comes in the form of the Investment Tax Credit (ITC), providing project owners with a tax credit of 30 % of the project cost (or 40 % if local content requirements are met) [49]. The full amount of the tax credit can be deducted from the owner's tax liability the year the OSW plant starts commercial operations. OSW project owners, however, generally do not have sufficient tax liability to take full advantage of the tax credit, which is non-refundable.

As noted in the Introduction, the IRA addresses this challenge to a large extent.[5] As such, we describe the challenge as formulated prior to the IRA and how the IRA addresses it.

1) The Challenge (Pre-IRA)

Prior to the IRA, there were two ways to deal with the lack of sufficient tax liability on behalf of the project sponsor. First, the ITC could be used over multiple years until the developer's tax bill was high enough. However, as explained by Mormann [51], "in the case of a standalone wind project…this lack of current tax liabilities would cost [the developer] up to two-thirds of the net present value of her project's tax benefits." This is due to (1) inflation and (2) the time value of money (a dollar earned today is worth more than a dollar earned in the future because the dollar earned today can be invested).

The second solution was the tax equity market, where a developer would sell the unused portion of the tax credit to an entity with a large tax liability in return for an equity investment in the OSW project. However, as noted by Mormann [51], "Historically, fewer than two dozen highly profitable and sophisticated entities…have been willing and able to support renewable energy projects through their tax equity investments." This led to two challenges:

[4] For an overview of PPAs, ORECs, and revenue regimes used in other countries (feed-in-tariffs and contract for differences schemes), see Tables 1–6 in Beiter et al. [48].

[5] See [49,50] for a detailed assessment of the IRA's impacts on OSW.

1. Due to the small number of tax equity investors, they were able to demand higher rates of return, leading to a larger portion of the tax credit—15-25 % [52]—being permanently transferred away from the OSW project.
2. The total supply of tax equity in any given year was uncertain and particularly low in economic downturns (i.e., when it is most needed) [51]. Some practitioners noted that project developers tended to overestimate the level of tax equity, causing financial problems later on (e.g., needing to cut costs or raise additional capital).

Given the large size and high costs of OSW projects, this was particularly challenging.

2) How the IRA Addresses the ITC Challenge

The IRA addresses these problems to a large extent by making the tax credits transferrable to any entity with corporate income tax liability [52]. These entities are no longer required to become equity investors in the OSW project. This greatly increases the pool of entities that can purchase unused tax credits and simplifies the transactions. In theory, this change could solve much of the tax equity supply problem and increase competition.

C. Developing a skilled workforce capable of navigating and problem-solving the harsh conditions offshore

Practitioners identified the inexperienced workforce as a grand challenge on two levels: (1) the OSW workforce in general, and (2) the finance workforce in particular.

1) General OSW workforce

Developing, constructing, and operating OSW farms is inherently challenging due to the harsh conditions offshore, and the many interfaces between industries and competencies (wind, power, and maritime) that have not historically worked together in the U.S. Building an OSW farm *always* entails problems and setbacks [20]. According to practitioners, these realities require a highly skilled and experienced workforce, from construction workers and mariners to engineers, from project managers and risk analysts to finance specialists, and more. The nascent state of the OSW market in the U.S., as well as the lack of comparable industries in the region from which to draw and the limited skilled-labor market, make developing the necessary workforce a major challenge. An inexperienced workforce increases risk of OSW development, and therefore financing costs.

This challenge increased in relevance with the recent debate over crewing provisions in U.S. H.R. 7900, requiring each crew member working on offshore energy projects to either (1) be a U.S. citizen or permanent resident, or (2) have a nationality matching the country where the vessel is flagged [53]. Those in support wanted to protect U.S. workers, while those in opposition expressed concern about straining an already scarce resource: offshore workers [53]. While the provisions did not become law, they passed the U.S. House of Representatives and highlight a key point of contention for OSW development.

2) Finance workforce

In the area of finance, practitioners noted a significant lack of experience and expertise in structuring project finance deals for OSW projects. Project finance is a financing structure where the provided funds are backed by the projected cashflows of the project itself, and that incorporates a series of risk-reducing checks and balances. It was critical for the success of early OSW projects in Europe and continues to rise in importance for OSW development, accounting for well over half of installed capacity from 2018 to 2020 [20]. However, according to practitioners, very few people (a few dozen) across the globe, working at even fewer financial institutions (10–15) have the experience and expertise necessary to structure smart project finance deals for OSW development.

D. Grid Transmission and Integration Barriers

With the first utility-scale OSW farm scheduled to come online in 2023, the U.S. lacks the necessary transmission infrastructure and market coordination mechanisms to support the scale of OSW development planned in many regions. According to practitioners, availability and quality of transmission infrastructure is the most important factor in siting OSW farms. Without significantly improving the planning and coordinating of transmission infrastructure, with the explicit goal of supporting OSW expansion, OSW energy will provide less value to the grid and energy markets, and thus to investors. Investors require some level of certainty that the power generated will flow to and be purchased by consumers, with minimal curtailment.

Coordination and planning of transmission infrastructure is already happening in several European countries, which are (among other things) responding to the need to reduce public opposition by optimizing onshore transmission connection points, and it is beginning to happen in some U.S. states, especially in the North Atlantic [54–57].

One potential issue jeopardizing transmission upgrades is that in the U.S., the project developer is currently responsible for transmission infrastructure and connection to the grid. The OSW project developer must work with the transmission system operator to coordinate transmission upgrades, significantly delaying the interconnection process. In comparison, in Germany and the Netherlands, for example, this is a task of the transmission system operators, who guarantee access and levy costs onto general grid tariffs [47].

Participants also pointed to grid-scale battery storage and hydrogen production and infrastructure as options for alleviating interconnection stress and integrating OSW energy in particular. However, energy storage units are privately owned in the U.S., and participation in electricity markets will require new incentives and frameworks with an explicit (but not exclusive) focus on OSW integration.

E. Financing and Scaling Up Floating OSW Technology

Globally, 99.94 %[6] of utility-scale OSW farms in operation (as of the end of 2022) use turbines on fixed-bottom foundations (i.e., turbines are installed on foundations set on/into the seabed), which limits OSW deployment to water depths of less than 60 m. Much of the seabed in the U.S.—especially off the West Coast—is too deep for fixed-bottom projects. Thus, floating OSW technologies, where turbines are installed on floating structures, are necessary for realizing the full potential of OSW in the U.S.

Floating OSW technology is at an early stage of commercialization. Globally, most floating wind farms are considered pilot projects [58]. The risks of floating OSW technology, therefore, are not as well understood as with fixed-bottom OSW technology. Until this changes, lenders and investors will consider floating OSW projects relatively high risk, leading to a higher cost of capital.

Some participants drew a connection between the challenges faced by floating OSW development today and those faced by the early fixed-bottom projects in the 2000s. Transferring knowledge and skills to floating OSW technology will likely be crucial.

4. Discussion and conclusions

Current macrotrends aside, conditions in the U.S. are favorable for a rapid scale-up of OSW energy, but successfully deploying hundreds of

[6] Hywind Scotland totals 30 MW [58]; 30 MW/53 GW = 99.94 %.

billions of dollars in investments in the U.S. OSW sector requires overcoming five grand challenges: (1) Early years financing; (2) Policy support for project financial solvency; (3) Workforce development; (4) Transmission and integration barriers; and (5) Floating wind technology development. Challenge (2) has already been solved to a large extent by the IRA.

These challenges point to structural shifts in policy and regulatory environments, the workforce, and the physical infrastructure in electricity transmission systems. They also point towards growing pains in a new industry. The U.S. currently hosts just seven operating OSW turbines. Scaling up OSW development in a nascent market at an unprecedented pace is risky for financial actors and presents major logistical challenges for developers and regulators.

We also appreciate that these grand challenges are not the only major challenges facing OSW finance. Recent reporting, for example, highlights efforts—funded in part by fossil fuel interests—to undermine social acceptance and political support for OSW projects [59,60]. Such efforts—even with moderate success—can increase project risk and cost of capital.

The grand challenges suggest future research directions. Domain-specific research topics such as OSW design and deployments, transmission system planning, and financing models, will continue to be critical. Interdisciplinary research detailing the evolving infrastructure, economic, regulatory, policy, and social environments will help policymakers, regulators, and developers develop coordinated solutions. Specific research topics include:

1. Analyzing policy impacts on financing and cost of capital in general.[7]
2. Identifying regulatory and policy solutions to streamline and reduce risk of OSW development.
3. Assessing the impacts of inflation and high interest rates on OSW and other capital-intensive technologies.
4. Mapping and analyzing the stakeholders of OSW, their influence, and the political-economic relations between them.
5. Exploring how coordinated planning of transmission (power and hydrogen) and storage build-outs affect and can improve OSW profitability.
6. Further specifying the near-term workforce challenge and potential solutions, drawing on existing resources and past experience.

Researchers are also well-positioned to discern and analyze longer-term challenges, including:

1. Domestic workforce development to support long-term OSW capacity targets.
2. OSW integration solutions, e.g., demand response, electricity storage, and sector coupling (electrifying transport, coupling the power and heating sectors, and using power to generate green fuels, known as Power-to-X [62,63]).
3. Supply chain constraints in light of global energy transitions and the effect of local content requirements on project costs and critical bottlenecks.

Our work presented in this paper provides context for creating solutions for OSW development. We are hopeful that collaborations between researchers, practitioners, policymakers, and regulators can support the development of solutions and enable rapid decarbonization of the energy sector in the U.S.

CRediT authorship contribution statement

T.A. Hansen: Conceptualization, Methodology, Investigation, Data curation and analysis, Writing original draft, Review and editing; **E.J. Wilson**: Conceptualization, Methodology, Investigation, Review and editing, Funding acquisition; **J.P. Fitts**: Conceptualization, Investigation, Methodology, Review and editing; **M. Jansen**: Conceptualization, Investigation, Review and editing; **P. Beiter**: Conceptualization, Investigation, Review and editing; **B. Steffen**: Conceptualization, Investigation, Review and editing; **B. Xu**: Conceptualization, Investigation, Review and editing; **J. Guillet**: Conceptualization, Investigation, Review and editing; **M. Münster**: Conceptualization, Investigation, Review and editing; **L. Kitzing**: Conceptualization, Methodology, Investigation, Review and editing.

[7] See [61] for example in European context.

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

The authors do not have permission to share data.

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