Breaking wind: A comparison between U.S. and European approaches in offshore wind energy leadership in the North Atlantic region

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May 31, 2023

Abstract

The United States has only recently begun investing in commercial-scale offshore wind energy (OWE). Although the United States is slow to progress, it is uniquely positioned to build on the existing knowledge that coastal European countries have applied for their own energy transitions. In this study, we analyze how federal and regional plans for expanding the OWE sector in the United States brought to the surface decade-long tensions related to multi-scale governance mismatches, jurisdictional conflicts, and unclear pathways for implementing national industrial policies. Drawing upon the European experience with OWE, we employ a dynamic multi-level perspective framework enriched by socio-ecological elements to examine the United States energy transition through its most promising technology. From our framework we identify six categories of OWE developments characterized by both unique and shared elements between the United States and European coastal countries. These elements are: (1) role of local communities, (2) governance structures, (3) multi-scale government interactions, (4) regional socioeconomic structures, (5) socio-ecological impacts, and (6) relationships with existing industries. Drawing upon our analysis, we identify and conceptually map four research areas in need of further development for the United States and the research community— (1) knowledge, (2) potential, (3) adaptation, and (4) learning. These insights provide critical information to ensure that the United States expansion into offshore energy generation is characterized by elements of justice, equity, and inclusive regional economic development.

Highlights:

- Drawing from the European OWE experience, the U.S. is poised to rapidly expand their own OWE sector.
- International comparison of North Atlantic countries and their pathways to OWE development.
- The multi-level perspective provides a holistic evaluation of the success and failure of OWE across four North Atlantic countries.

Keywords: Offshore wind energy, just energy transitions, blue economy, multi-level perspective, comparative analysis

Word Count: 8,410

Abbreviations:

BOEM: Bureau of Ocean Energy Management

FERC: Federal Energy Regulatory Commission

GDP: Gross Domestic Product

GW: Gigawatt

GWh: Gigawatt hour

ISO-NE: New England Regional Independent System Operator

MLP: Multi-Level Perspective

MOPR: minimum offer price rule

MW: Megawatt

MWh: Megawatt hour

NOAA: U.S. National Oceanic and Atmospheric Administration

OWE: Offshore Wind Energy

PTC: Production Tax Credit

PURPA: Public Utility Regulatory Policies Act

R&D: Research and Development

1. Introduction

As the post Covid-19 pandemic recovery evolves, nations worldwide have begun outlining methods for rebuilding their economies. In the United States (U.S.), the Biden Administration has outlined a course for tackling climate change, boosting the economy, and reducing vulnerability to global supply chains [1,2]. The transition towards a decarbonized electricity infrastructure through the development of offshore wind energy (OWE) plays a pivotal role in this plan (figure 1). In 2021, President Biden announced a federal initiative to deploy 30,000 megawatts (MW) of OWE by 2030 [2], while in July 2022 the Administration spearheaded the Inflation Reduction Act [3]. By 2022, 22,431 MW were at the initial stages of approval ("site control" or "permitting") 800 MW were awaiting construction, and 42 MW were operational [4]. Such an ambitious plan is expected to create over 30,000 jobs, generate electricity for millions of residential homes, and substantially curb carbon emissions [2]. Yet OWE remains contentiously debated with public opposition being one of the most significant barriers to implementation [5–7], as was illustrated in the Cape Wind Project in Massachusetts, a failed 420 MW offshore wind development that was canceled when concerns about decreasing local tourism were raised [8]. Furthermore, the development of the OWE sector in the U.S. brought to the surface decade-long issues related to multi-scale governance, jurisdictional conflicts, and unclear pathways for implementing national industrial policies.

OWE is not new to the U.S., in 2016, the Block Island Wind Farm became the first offshore wind farm operating in U.S. waters, four years later in 2020 a second offshore wind farm became operational off the coast of Virginia [9,10]. Comparatively, OWE in Europe has a longer history with the first commercial offshore wind farm constructed in 1991. The Vindeby wind farm built off the coast of Denmark was a pilot project, intended to test the capability of OWE. With a nameplate capacity of 4.95 MW, it remained operational until 2017, at which point Vindeby was decommissioned due to its expiring consent [11]. Since Vindeby, Europe's OWE developments have risen exponentially. As of 2021, worldwide cumulative capacity of OWE reached 54,257 MW, a majority of which is supplied by China, a rapidly emerging player in OWE, followed by the United Kingdom (U.K.), Germany, the Netherlands, Denmark, and Belgium [12].

As the U.S. expands OWE to meet low carbon energy goals, it is well-positioned to build upon the existing knowledge and development that European coastal countries have applied for their own energy transitions. Moreover, renewed interest in OWE has the potential to transform the U.S. electricity supply industry similar to, if not at a larger scale, than what other countries (e.g., Germany) experienced in the early 2000s [13]. All the while, it has the additional effect of adding to the broader effort of materializing the Blue Economy (see e.g., [14]), which centralizes inclusion, equity, and participation at its core [15].

Our goal in this study is to identify priorities for learning from and areas of further research for ensuring that the U.S. expansion into OWE generation is characterized by practices of justice, equity, and inclusive economic development at the local, state, and national levels. Drawing upon the deployment of OWE in Germany, Denmark, and the U.K., we employ a common socio-technical transitions frameworks, the multi-level perspective (MLP), to examine the potential growth of OWE in the U.S. The MLP allows us to take into consideration actors and interactions that are operating at different governance scales (i.e., local, national, federal). Our work expands on the existing literature of international comparisons of energy transitions, which is necessary, in spite of variations across countries, to better inform alternative low carbon energy policy (see e.g., [16,17]). Methodologically, we develop a systemic comparative analysis that utilizes a dynamic MLP framework enriched by socio-ecological elements (see e.g., [16]). While the countries represented in this study have unique histories, governance models, and geographic landscapes, we see the merit in drawing generalizable lessons that can inform future OWE development in the U.S. Rather than make specific comparisons across countries, we articulate these lessons in six thematic areas characterized by both unique and shared elements between the U.S. and European coastal counties. These are as follows: (1) role of local communities, (2) governance structures, (3) multi-scale government interactions, (4) regional socioeconomic structure, (5) socio-ecological impacts, and (6) relationships with existing industries. We conclude with a discussion on how the U.S. can employ principles adopted in Denmark, Germany, and the U.K., while also identifying four research areas in need of further development for the U.S. and the research community – 1) Stakeholders' identification and engagement; 2) Data availability; 3) Jurisdictional management; and 4) OWE as regional economic development.

The remainder of the work continues as follows. Section 2 contains a broad overview of the MLP framework, contextualizing OWE and the role technology plays within each level of the MLP: niche-innovations, socio-technical regime, and socio-technical landscape. Section 3 then provides an overview of the identification of each European country evaluated in this study. Section 4 refines the methodological approach used and discusses how the MLP draws out key elements of success and failure as well as similarities and differences as they relate to experience with OWE over time. Section 5 discusses how the six thematic areas can be strategically utilized as lessons to inform priority areas of research. We conclude with section 6, a brief summary on the direction of OWE research.

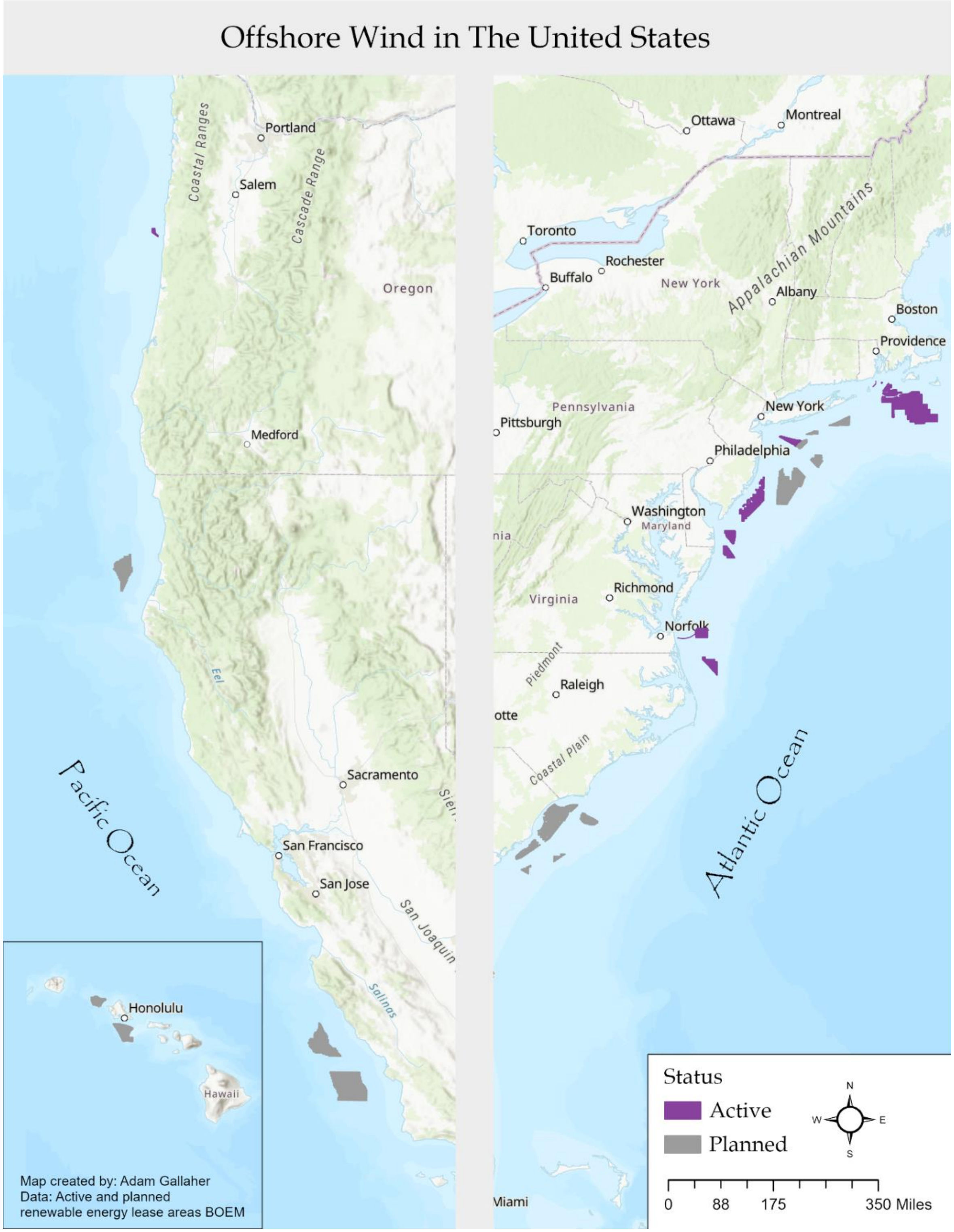

Figure 1: Active and proposed offshore wind energy lease zones in the United States. Lease zone GIS data obtained from the Bureau of Ocean Energy Management's Marine Cadastre National Viewer.

2. Overview of the Multi-Level Perspective in relation to OWE

We draw upon the MLP[1] [18,19] to explain the larger socio-technical transitions occurring within the electricity sector across multiple counties (figure 2). Studies examining transitions within the socio-technical system context garnered attention starting in the 1980s; the MLP emerged as the one of the more prominent theoretical frameworks in the early 2000s [20-22]. The MLP has been applied to understanding various socio-technical transitions including transportation, electricity production, and agri-food systems (see e.g., [23–29]). The MLP contains three different spatio-scalar heuristic analytical concepts, from top to bottom they are as follows: socio-technical landscapes, socio-technical regimes, and niche innovations forming a nested hierarchy (see e.g., [18,19,30]). Despite the widespread applicability of the MLP, some aspects of the framework have been criticized; such as a lack of agency, operationalization of regimes, bias towards bottom-up change models, and overall methodology among others (see e.g., [31] for a review and response to those criticisms). Nevertheless, the MLP remains a useful framework for exploring and analyzing by what means, and when, large scale socio-technical transitions occur [25].

2.1. Niche-Innovations

Niches are ‘protective spaces’ where innovations are spun out of Research and Development (R&D) laboratories, subsidized demonstration projects, or small markets whereby specific users support emerging innovations [31]. Along with innovations, there are niche actors who work on, and support, radical innovations with the goal of placing pressure on the existing regime to change, or even replacing it all together [31]. However, this is easier said than done, at times resulting in incremental innovations rather than those emerging from a radical breakthrough [25,31]. Such incremental development is

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[1] For a detailed description and visual of the MLP see Geels (2002) [18]. Our adaptation of the MLP is presented in figure 2.

visible in the slow expansion of OWE, which only began expanding in the mid-2000s due to the opening of resource-rich markets with large demand (U.K.) outside the home markets of leading companies (Denmark) [13,32].

There are three core processes in niche development— the articulation and/or adjustment of expectations or visions, a building of social networks (largely for the development of actors), and learning and articulation processes [31]. There are many technical challenges hindering, or at times, slowing OWE development such as, harsh offshore environments, development in deep waters, high voltage direct current transmission system development, and manufacturing and installation of reliable OWE systems [33]. Many of these challenges are contributing factors in the learning and articulation process within the development of OWE. As OWE expands, beyond shallow waters, different turbine foundations will continue to emerge. For example, currently there are four bottom-fixed foundations (gravity, monopile, tripod, and jacket) and three floating turbine concepts (semi-submersible, spar, and tension leg) [34]. These technological developments directly impact the resource potential of OWE. For example, within the U.S. there is an estimated 2,059 gigawatts (GW) of technical OWE potential: however, nearly 58% is in waters 60 meters or deeper and jumping to 95% when considering the Pacific coastline [35,36]. If the U.S. rapidly expands OWE development, technological advancements in floating OWE has the potential to emerge as a niche innovation contributing to the broader interplay of OWE and the existing socio-technical regime. When landscape pressures such as climate change and social support for renewable energy bear down upon the existing socio-technical regime, niche innovations are given a window of opportunity to emerge into the market and attempt to disrupt the socio-technical status quo [33,37].

2.2. Socio-technical regime

The socio-technical regime is an extension of what Nelson and Winter [38] referred to as the "technological regime", which defined a set of shared cognitive routines in an engineering-centric community used to explain pattern development along technological trajectories [18]. However, scientists, policy makers, users, and special interest groups also contribute to the evolution of technologies. Thus, the socio-technical regime - which accommodates this broader community - emerged from the original "technological regime" [18]. It is within the socio-technical regime that existing trajectories are stabilized, through routines by engineers and users, regulations and standards for various technologies, and investments in existing systems [18,39]. For example, in the U.S. the New England Regional Independent System Operator (ISO-NE) implemented a minimum offer price rule (MOPR) in 2013 to comply with a Federal Energy Regulatory Commission (FERC) ruling aimed at addressing inefficiencies in on-call energy markets. MOPR applies to power plants entering the market for the first time. After which electricity transactions take place in the on-call market where independent power producers can bid optimal prices. Since states operating within ISO-NE maintain their own Renewable Portfolio Standards [40], renewable energy projects (such as OWE) have a legal obligation to interconnect. Given that MOPR requires an unsubsidized bid price, the policy can effectively render a project uncompetitive thus placing the price burden on the consumers [41]. However, as of March 31st, 2022, ISO-NE filed a proposal to FERC requesting the removal of MOPR from the on-call energy market opening the door for future renewable energy development.

Similar interactions between niche innovations and the socio-technical regime are present across the entire U.S. East Coast. Russel et al. [9] provides four case studies of OWE developments, of which two failed and two succeeded. Among those that failed, the more notable Cape Wind project in Massachusetts faced opposition from politicians, business figures, local commercial fishing groups, the local municipalities, and environmental groups [9]. The main grievances cited as possible visual impacts, potential environmental damage, interaction with existing commercial fishing spots, and impacts to recreation and cultural resources [42]. While the project failed due to strong opposition from multiple socio-technical regime actors, Cape Wind paved the way for future projects. For instance, Massachusetts created zones in state waters for potential OWE developments and initiated a siting review process to facilitate future development [43]. Unlike Cape Wind, Bluewater Wind, in Delaware received strong community support [42]. However, given the infancy of OWE in the U.S., financial and regulatory inadequacies led to investors pulling out of the project and ultimately the power purchase agreement leading to the abandonment of the proposed Bluewater Wind project [9]. Yet new OWE projects have emerged, most notably the Vineyard Wind 1 project, which began construction in 2021, an 800 MW OWE farm 15 miles off the coast of Martha's Vineyard, Massachusetts. While the project continuously faces opposition, mainly from commercial fishers, previous projects helped pave the way for the latest round of OWE developments in the U.S., showing signs of institutions' ability to adapt.

2.3. Socio-technical landscape

The socio-technical landscape influences niches and regime dynamics [19], containing broader demographic trends, political ideologies, macroeconomic patterns, and societal values [31]. It is through the variation of these trends, under ideal conditions, that a 'regime shift' can occur. This happens when downwards landscape pressures provide a window of opportunity for niche technologies to enter the regime and begin integrating with existing regime dynamics [16]. Typically, downwards landscape pressures are exogenous factors such as climate change, energy crisis events, and wars [37].

There are a few key examples of downward landscape pressure on the socio-technical regime that have had direct impacts on the energy sector. Following the 1970s oil crisis, Denmark rapidly switched from being 95% dependent on oil for electricity to only 5% within five years [44]. Denmark's rapid transition contradicts the widely held assumption that energy transitions are long "protracted" affairs [44, 45]. Denmark's trajectory, albeit was initiated by external pressures, indicates that energy transitions can and do occur within more contracted timeframes. Denmark had accessible resources and the political will to make a rapid shift whereas OWE in the U.S. is only recently a potential reality due to a mix of resource endowments, prices, and sociopolitical preferences [13]. Similarly, Germany's anti-nuclear movement initiated after the 1986 Chernobyl, and strengthened after Japan's 2011 Fukushima nuclear disaster prompted permanent closure of several nuclear facilities in Germany and a rapid phase out of the remaining by 2022 [46]. Both Denmark and Germany's shifts were motivated by external pressures—Denmark to maintain domestic energy security, and Germany for risk reduction, yet they both exemplify the socio-technical landscapes in which transitions occur.

Exogenous pressures have the capacity to influence endogenous energy transitions. Recent external shocks in the global energy sector and disruptions in the global supply chain (e.g., COVID 19 pandemic and Russian invasion of Ukraine) have strengthened the U.S.'s political motivation to transition its energy source. Policies aimed at shifting electricity production in the U.S. have become a priority due to the impacts of climate change and impending energy security concerns. [47].

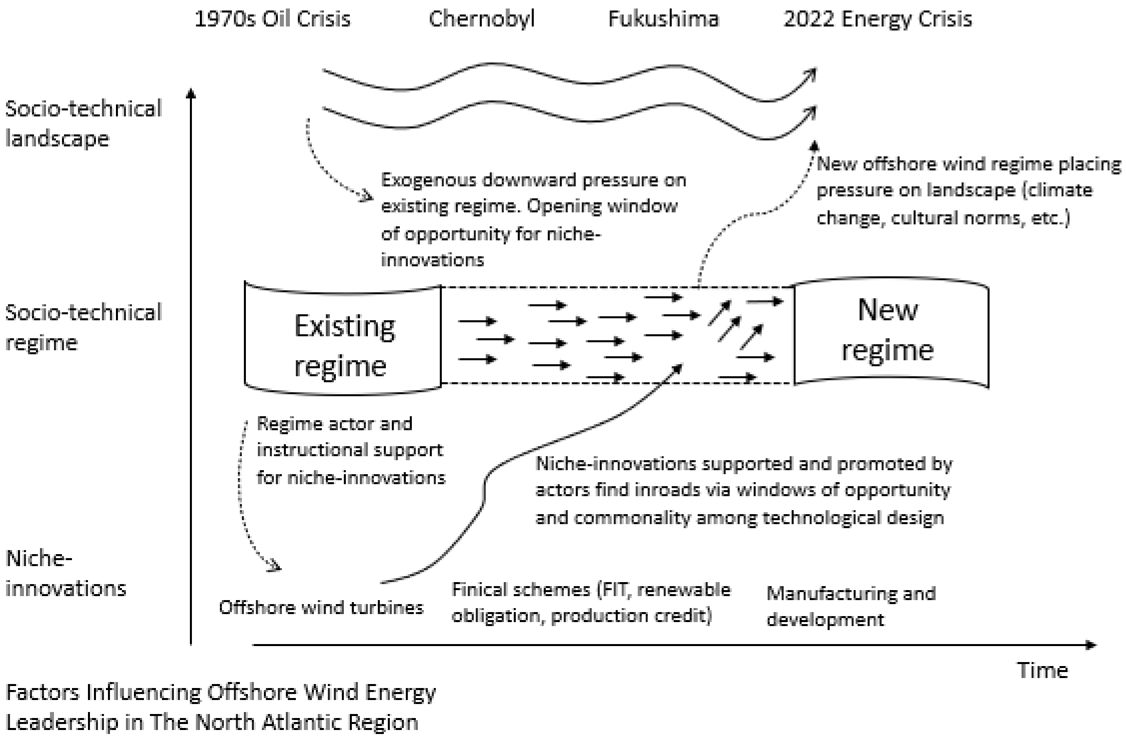

Figure 2: The multi-level perspective (adopted from figure 5 in Geels 2002 [18]) updated to reflect OWE transitions as they relate to the three North Atlantic countries.

3. OWE, Transitions Management, and Energy Security and Justice

Denmark, Germany, and the U.K. are ideal case studies to draw generalizations from to inform U.S. OWE development. As highly industrialized nations that share similar consumption trends for domestic consumer goods and services, environmental and social standards, and with industrial and political institutions, these countries are comparable (see e.g., [13,48,49]). Additionally, there are contrasting contextual circumstances that provide opportunity for valuable considerations with respect to renewable energy policy, energy security, and transition studies. These differences illustrate why, for example, the U.S. has lagged in OWE developments when Denmark experienced early adoption of OWE in the 1990s. Also, following the oil crisis of the 1970s, all four countries responded by crafting energy policies aimed to increase domestic energy production by exploring alternative energy options or reformulating concepts of energy consumption. Yet, even under the downward pressure of an exogenous socio-technical landscape level shock, not all solutions maintained longevity. Three European countries, Denmark, Germany, and the UK, demonstrate different approaches to energy security[2]. Denmark achieved energy self-sufficiency through consistent energy policies, emphasizing availability and reliability [44]. Germany prioritized sustainability by implementing strong renewable energy policies and focusing on wind energy exports for availability [13, 50]. The UK, however, lagged behind in exploring wind energy and instead pursued an "all of the above" approach focused on affordability [13,44,48]. The United States can learn from these approaches, especially in sustaining long-term energy security policies, particularly through offshore wind energy (OWE).

The development of OWE both supports and bolsters a nation's energy security and independence while bringing to the surface emerging complexities related to energy justice. There is a growing body of literature centered on the idea of incorporating ideas of energy justice into energy transitions research typically referred to as the “just energy transition” [51–54]. Energy justice has been summarized by five elements: 1) distributive justice, 2) procedural justice, 3) restorative justice, 4) recognition justice, and 5) cosmopolitanism justice [51,55]. Dwyer and Bidwell [55] point to procedural and distributive justice as key considerations in, what they refer to as the “chain of trust”, which was built during the development process associated with the first U.S. OWE farm. Moreover, resistance to OWE exports points towards issues and concerns related to distributive justice [56,57]. While both procedural and distributive justice lend themselves to incorporating justice within OWE development, additional forms such as recognition and restorative justice must also be included. This is particularly evident within the U.S. context whereby

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[2] We draw our use of the term energy security from Sovacool’s [58] adaptation of Elkind’s [59] four elements of energy security: availability, reliability, affordability, and sustainability.

OWE development encounters local groups and has the added potential for interactions with Indigenous American communities and federally-recognized tribal nations. These interactions were evident during the planning of the Block Island Wind Farm when developers learned that part of the original lease block was part of the Narragansett's tribe's oral history [60]. While concepts of energy security and energy justice are typically presented separately, Jenkins et al [61] argue, within socio-technical systems undergoing transitions these two concepts can be combined to reach a holistic evaluation of socio-technical transitions. We do not aim to replicate previous work, yet building upon their work, we apply the MLP to draw out the various elements of energy security and justice to not only evaluate and compare our case study countries by also outline a research agenda for the U.S. specific to OWE.

4. Methodology and Study Area

We employ a case study approach similar to Cherp et al. [16] to analyze how federal and regional pushes for expanding the OWE sector in the U.S. brought to the surface decade-long issues related to multi-scale governance, jurisdictional conflicts, and unclear pathways for implementing national industrial policies. Drawing upon the European experience on the development of OWE, we employ the MLP to examine the U.S. energy transition pathway and identify elements of learning and areas of future research. Much of the literature informing this research is that of sustainability or sustainable transitions through a justice lens [22,62–64]. In an effort to ensure U.S. OWE is characterized by elements of justice, equity, and inclusive regional economic development while aiding in the decarbonization of the nation's grid. Research related to comparative international analyses of energy transitions are a rare affair among the energy transitions literature [16,17]. However, they still serve as important contributions to better understand how countries are implementing low carbon energy systems (e.g., OWE) as they tend to exhibit patterns of development via policies, technologies, or spatio-temporal patterns [17,44,48], in lieu of exogenous shocks to the socio-technical landscape [46,65,66].

This research examines four countries Denmark, Germany, the U.S., and the U.K. (see table 1). These countries are evaluated with respect to their OWE development in contrast to the U.S. Globally, the U.K., Germany, and Denmark are the second, third, and fifth largest markets for installed capacity of OWE with 11 GW, 7.7 GW, and 2.3 GW [12]. Denmark leads in OWE development followed by the U.K., Germany, and finally the U.S. (figure 3). Both the U.K. and Denmark have been the largest markets at different times (Denmark in 2000-2007 and the U.K. in 2008-2020). Each of these countries represent a different combination of market and policies implemented (see table 2), which can offer pathways of growth to the U.S.

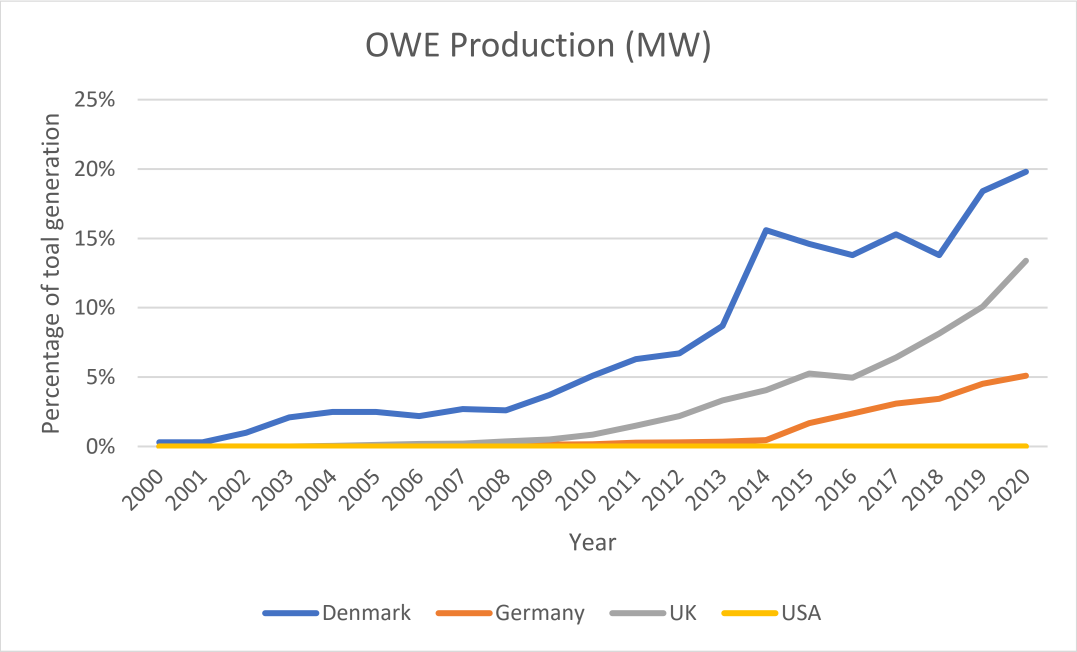

Figure 3: Timeline of OWE expansion from 2000 to 2020 as a percentage of overall electricity generation. Data obtained from [12].

Table 1: Country level summary information for each study site. Information related to energy consumption and production are for all forms of energy. 2022 is the reference year for all data contained in table 1.

Country	Population	Electricity Production (GW)	Electricity Consumption (GW)	GDP Per Capita	Energy Consumption Per Capita (MWh)
Germany	83,111,000	33.4	33.7	$46,252.69	5.7
Denmark	5,851,000	573.71	584.9	$61,063.32	6.4
United Kingdom	67,503,000	305.53	317.3	$41,059.17	4.5
United States	333,376,000	4157.1	4186.7	$63,206.52	12.3
Ref. [67,68]					

4.1. Denmark, Germany, and the United Kingdom: three different OWE powerhouses

The ways in which Denmark, Germany, and the U.K. have risen to be leaders in OWE developments vary considerably and offer insights for paths the U.S. could take as it seeks to fill a role of technological and deployment leadership, as summarized in Table 2. Prior to the 1973 oil crisis, Denmark did not have a formal national energy policy. From 1955 to 1974 nearly 85% of electricity came from imported oil [44]. This lack of domestic energy policy reflected the fact that Denmark was not a primary energy producer prior to 1972 [69]. However, following the 1973 oil crisis, Denmark headed down a path of energy security despite the discovery of sizable offshore fossil fuel reserves [69,70]. As a result, oil accounted for only 5% of total electricity in 1983, down from 64% in 1973 [68] through the 1976 Danish Energy Policy [44,69]. By adhering to energy policy and not markets, Denmark became a pioneer in wind energy, through cooperative and grassroots movements along with support from the government which ultimately paved the way for Danish leadership in the global wind energy sector [69,70].

The Danish story of wind energy can offer lessons not only from a technical but also social perspective on how to integrate wind energy into the broader socio-technical system [70]. Along with grassroots efforts and a cooperative structure of ownership, the wind sector was largely supported by two main actors, the Organization against Nuclear Power and the Organization for Renewable Energy. The efforts of both non-governmental organizations helped formulate public awareness campaigns which shaped wind energy during the early growth stages in Denmark [58]. In the context of the MLP, both the Organization against Nuclear Power, the Organization for Renewable Energy, and the Wind Turbine Owners Association worked within the socio-technical regime to sustain and facilitate the window of opportunity provided by the oil crisis of the 1970s for wind energy to flourish. Additionally, the introduction of a feed-in-tariff scheme bolstered up renewable energy, combined heat and power, along with district heating during the destabilization of the existing socio-technical regime [44]. Beyond the feed-in-tariff, investment subsidies and tax exemptions for wind power owned by households played a supportive role in the development of wind energy [70].

From 1970 to 2016, Germany's electricity sector was fueled primarily by coal and nuclear power. By 2016, shares of nuclear energy were surpassed by wind and natural gas generation [68]. Nuclear energy began to decline at the turn of the century, initially catalyzed by the Chernobyl disaster in 1986, but following Fukushima in 2011, the German government announced the closure of Germany’s nuclear power plants by 2022 (figure 4) [45,50]. However, as of March 2022, nuclear generation still accounted for approximately 10% of net electricity generated [71].

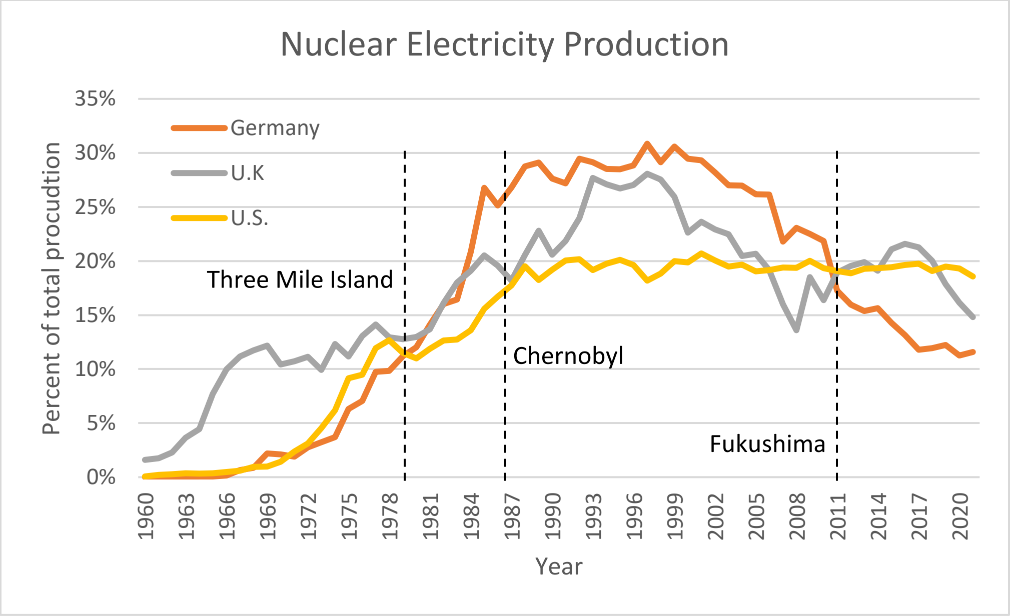

Figure 4: Timeline showing the share of nuclear electricity generation from 1960 to 2021 as reported by the International Energy Agency. The three major nuclear reactor meltdown events have been marked with a dashed line and labeled accordingly.

When considering energy transitions within the German context, *Energiewende* is found throughout the literature and policy documents [72]. Passed in 2011, "*Energiewende*" is a comprehensive legislative package composed of 120 measures designed to bolster domestic sources of renewable energy along with reducing overall greenhouse gas emissions from the electricity sector [73]. The policy calls for a reduction in greenhouse gas emissions by 40% in 2020 compared to 1990 levels, furthermore Germany is aiming for 55% reductions by 2030, 70% by 2040, and 80 to 95% by 2050 [72]. Similarly, the share of renewables is set to expand 35% by 2020, 50% by 2030, 65% by 2040, and 80% by 2050 [72]. As of 2020, 56.3% of electricity produced in Germany was powered by renewable energy, representing a 26.9% increase over 2010 levels [68]. Germany, in comparison to the other European countries in this study, initiated OWE developments much later. It was not until 2009 when the first OWE turbines came online with a cumulative installed capacity of 35 MW. However, given the strong onshore wind industry Germany experienced rapid growth thereafter. By 2014 installed capacity reached nearly 994 MW representing a 2,740% increase in OWE development. From 2015 onward to 2020 growth in OWE slowed, during that time OWE only grew 135.9%. However, as a result of strong political support and favorable financial incentives, in 2021 German cumulative OWE installations totaled 7,774 MW placing them second, to the U.K., in OWE developments. Expectations are that Germany will continue to represent a large market for wind energy in Europe as a whole. Estimates show OWE installations from 2022 to 2026 to total 5,400 MW, nearly doubling the current capacity [74]. Socio-technical landscape level interactions drastically influenced actors (e.g., community organizations, Greens Party, Coalition of Social Democrats) decision making within the context of the German electricity sector. While fossil energy sources remain (e.g., coal and natural gas), largely a result of incumbent pushback leading to a 'fit-and-conform' transition pathway [17]; Germany has still experienced an influx of alternatives (namely, wind and solar), largely as a result of strong consistent political support [75].

In 1970, U.K. energy consumption was dominated by solid fuel use (e.g., coal) and petroleum that accounted for 91% of total energy consumption [76]. From the 1980's, the energy mix had diversified with North Sea gas coming online, reducing the proportion of solid fuel consumption and petroleum to 36% and 37% respectively. While the 1990's mirrored the 1980's, from 2000 onward, changes in electricity generation primarily through natural gas becoming the dominant fuel source, responsible for 41% of energy consumption in the U.K. [76]. In 2014 however, more renewable fuels had entered the energy mix for both electricity and bioenergy consumption, accounting for 19% of total energy consumption. The U.K. has a long history of passing energy-related legislation into law. The Clean Air Act of 1956 restricted the use of solid fuel in urban areas, while at the same time new processes for developing gas from petroleum emerged [77]. The Thatcher Government decided to sell off the British Gas Corporation in the 1980s and the coal mining industry was later privatized in 1994 [78]. Despite landscape-level pressures such as the oil price shocks in the 1970's, fossil fuels continue to be the main source of domestic energy consumption. Tepid responses to the energy crisis of the 1970's resulted in the U.K. lagging behind other European nations in the transition to low-carbon energy sources, particularly wind [13].

However, numerous regime-level policies and technologies have shaped the U.K.'s energy strategy and direction. The Climate Change Act of 2008 and the Low Carbon Transition Plan of 2009 began the U.K.'s commitment to addressing climate change and transition towards a low-carbon energy future. Renewable energy use grew by 21% between 2012 and 2013 which equated to nearly four and a half times the level it was in 2000 [79]. The Energy Act of 2013 indicated that both onshore and offshore wind power become a substantial part of the U.K. energy mix, yet the Conservative Government in 2015 ceased subsidies for onshore wind and that OWE would only be financially supported if the cost of the technology were to be reduced. Given that the Conservative Party has been in government since 2010 and energy policy towards wind power shifted in November 2015, the growth of the low-carbon energy sector including offshore wind, new nuclear, and gas has grown to ensure domestic energy security [76].

Despite any ebbs and flows in energy policy and incentives, the U.K. is, however, a global leader in OWE generation. In 2016, there were 28 offshore wind farms with a total of 1,465 wind turbines across U.K. waters [78]. This rose to 40 offshore wind farms with a total of 2,297 offshore turbines in 2022 [80]. As of 2021, the U.K. has 11,256 MW of offshore capacity [12]. OWE will continue to expand as the U.K. Government seeks to increase offshore wind generation to 50 GW by 2030, with 5,000 MW coming from floating OWE [81]. This secures the role of OWE as a prominent component to the future of the U.K. energy mix supported by primarily regime-level components for example, Energy and Industrial Strategy 2022, increased efficiency of offshore wind technology, increased finance from the U.K. Government, and higher recorded levels of public support for wind energy [13,82,83]. The Energy Security Strategy solidifies the position of the energy transition, and by extension the role of OWE, in the U.K. supported by three mutually reinforcing goals: security, affordability, and sustainability [81].

4.2 The U.S. context

Prior to the 1970s, U.S. energy production, similar to the U.K., was dominated by coal, accounting for around an average of 52% net electricity production between 1949 and 1970 [84]. During that same time, natural gas, oil, and conventional hydro contributed 19%, 7%, and 21% respectively. The events of the 1970s along with favorable policies and expansion of natural gas extraction shaped the energy landscape currently operating in the U.S. Following the 1973 oil crisis, U.S. energy policy dramatically reformed existing regime structures within the electricity sector. The Public Utility Regulatory Policies Act (PURPA) of 1978, an act which was part of the broader National Energy Act of 1978 radically reformed power plant ownership and sales of electricity [85,86]. PURPA enabled independent power producers to sell their electricity to the utilities while also generating favorable conditions for the expansion of renewable energy [85]. Moreover, the National Energy Act of 1978 along with the Energy Policy Act of 1992 helped pave the way for renewables in the U.S. However, while inroads within the existing regime were created for renewables, the majority of electricity production as of 2021 continues to rely on fossil fuels. Coal used to produce electricity however, reached a peak of 56% of net production in 1988; and as of 2021 only accounted for 22% [84]. Of the generating capacity set to retire in 2022, coal will account for 85% of retirements largely a result of transitioning to natural gas [84,87]. Wind and solar accounted for only 12% of net electricity production in 2021, leaving room for continued expansion going forward. It is expected that the share of renewables, particularly wind, will increase as continued investments are placed in OWE developments to meet the goal of 30 GW of OWE by 2030 [2]. However, given the current geopolitical climate (Russia-Ukraine war) and surging demand for petroleum, U.S.

energy policy in the short term is backpedaling in an effort to curb the burden placed on consumers [88].

The U.S. has access to vast offshore wind resources, nearly 4,000 GW of potential energy is available or nearly four times the current generating capacity of the U.S. electricity sector [49]. A laggard in OWE, the U.S. has only installed 42 MW of OWE, as of 2022. Additionally, there is currently 22,431 MW of OWE between the “site control” and “permitting” process, both of which still require approval from the Bureau of Ocean Energy Management (BOEM) and other federal agencies [4]. With respect to onshore wind developments, the U.S. has the second most installed capacity of onshore wind energy contributing 21% of global wind electricity generated in 2020, second only to China who generated 30% of total wind electricity [89]. Transitioning from 6.73 gigawatt hours (GWh) in 2001 to 379.7 GWh in 2021 the U.S. has a strong foothold in onshore wind energy development and production. While this represents a 5,809% increase over 20 years, wind energy only accounts for around 9.2% of total net electricity production.

Moving forward, the U.S. has implemented multiple energy policies which have supported the development of OWE and other renewable energy technologies more broadly. During the 1980s, energy prices began to rise once again forcing congress to reevaluate U.S. energy policy [90]. Along with the above mentioned passing of PURPA and the National Energy Act of 1978, deCasto et al. [49] outline eight more policies influencing the development of OWE farms. Missing from their list however is the Energy Policy Act of 1992, which set forth the US production tax credit (PTC), a federal tax credit available for eligible renewable energy projects, most notably wind, which provides 1.5 cents/kilowatt hour produced during the first 10 years of a projects life [86]. Prior to the PTC, renewable energy financing throughout the 1970s took the form of tax credits that subsidized the purchase of equipment needed to build the projects [50]. The PTC along with state policies provided the much-needed financing crucial to renewable energy projects and can be attributed to much of the growth the U.S. saw in wind energy from the 1990s onward [50,91]. From the 1990s on, the PTC expired and renewed in a boom-and-bust cycle creating uncertainty for investors in renewable energy and more specifically wind energy (onshore and offshore) [86,49]. Firestone et al. [92] highlight the importance of continued investment along with appropriate technology specific tax structures designed to spur development.

Table 2: Country comparison with respect to OWE development adopted from Graziano et al. (2017) [13]. Data comes from the International Energy Agency (2022) [68] and the International Renewable Energy Agency (2022) [93].

	Strategy	Installed capacity (MW) (2020)		Share of wind (onshore and offshore) by total electricity consumption (all sources) (2019)	National Companies
		Onshore	Offshore		
DK	Feed-in tariffs (1991); constant R&D development (1970s onward); export-oriented (US market) social and political support	4,558.66	1,700.80	49.03%	Vestas
DE	Feed-in tariffs (1991); constant R&D development (1970s onward); export-oriented strong social and political support after 1986 Chernobyl	54,414	7,774	24.66%	Siemens Enercon Nordex Senvion E.on Dong
UK	NFFO, then ROCs, Feed-in-Tariff only from 2013 - CfDs no development of local industry for onshore wind; creation of the Offshore Renewable Energy Catapult for offshore wind research center (2013); until recently no social support	14,101.94	10,383.05	24.8%	N/A
US	PURPA (1978) opened door for renewable energy interconnection market-based incentives; tax credits (production tax credit for wind) State led renewable portfolio standards; until 2021 all OWE was state led; OWE faces opposition from incumbent industries; Mixed support at state level	118,702.70	42	8.42%	GE

5. Implications for OWE development in the U.S. and areas of learning from across the pond

One of the more complex barriers to large scale adoption for OWE is found at the nexus of a “green dilemma” [94]. The “green dilemma” is characterized by support for a global transition towards renewable energy, but opposition to localized projects. At the macro level, transition to low-carbon energy sources is critical to mitigating the impacts of climate change. Particularly, when considering the interrelated climate and health benefits that OWE can provide given its potential scale in comparison to other low-carbon energy sources [95]. At the micro level, this highlights conflicting agendas and interest amongst multiple stakeholders, developers, governmental agencies, communities, and utilities. Additionally, OWE is expanding to new areas of energy production [96], and often faces local opposition because of its *perceived* aesthetic and environmental impacts on seascapes (see e.g., [94,97]), or uses (see e.g., [98]). These issues often find fertile ground in the multi-scalar and multi-jurisdictional nature of these projects, which may create conflicts within public agencies (see e.g., [99]). Such micro level tensions and concerns will most likely continue to evolve as more OWE farms are deployed, becoming a part of the socio-cultural and historical development of seascapes, which are perceived in multifaceted ways for example, industrial heritage, coastal cultural heritage, fragile ecosystems, and culturally sensitive areas [100].

5.1. European lessons for an emerging U.S. OWE industry

The ability to advance the development and deployment of OWE in the U.S. to the scale proposed will require communication and engagement across multiple governmental scales and communities. As additional OWE developments proliferate the U.S. coast lines, new case studies and lines of inquiry will emerge allowing for meaningful international comparison studies deepening our understanding of OWE and its place in our societies [9]. The U.S. offers a unique opportunity to fill several gaps in the current research and practice of sustainable transitions as it relates to OWE. In Table 3, we identify areas where additional research can enhance the efficacy of OWE and its relevance to low-carbon socio-technical energy transitions. These priority areas can be further distilled into four themes: 1) Stakeholders' identification and engagement; 2) Data availability; 3) Jurisdictional management; and 4) OWE as regional economic development. For each of these themes, the U.S. displays both peculiarities and commonalities with the three leading cases: each theme has been at least identified by existing literature based on decades-long practices and tools, especially in the European North Atlantic region. Overall, these themes reflect the broader instance of avoiding maladaptation through holistic approaches, reformulated definitions, and competing problems [101].

Table 3: Priority areas and gaps in socio-technical research related to OWE

Priority research	U.S. context	Gaps in research	Methods & Data	Relevance to low carbon transition	Relevant reference
Role of local communities	Pressure on institutions; Exclusionary communities; Equity planning.	● Identifying myths and perceptions around OWEs. ● Outlining and addressing tensions between developers, communities, government, and utilities ● Role of 'ins' and 'outs' in highly segregated regions. ● Identifying the meanings of seascapes and 'placefulness' of marine/coastal environments.	● Qualitative methods	● Proactive support for transition process. ● Understanding regional, informal power relations. ● 'Just' element in clean energy transition	[5, 90, 102]
Governance structure	Multi-layered governance: federal vs local governments;	● Outlining and addressing interactions between competing jurisdictions; ● Historical rights vs. national interests;	● Rural and Urban Planning;	● Understanding role of incumbents in varying	[99, 103]

	indigenous rights.		● Regional Science applications	jurisdictional landscapes. ● Identifying relevant policy stakeholders and decision makers.	
Governance interactions	Balance of interests and objectives among different agencies.	● ‘Parallel’ plans between different agencies within across levels of governance ● State land use oversights vs federal jurisdiction of OWE siting	● Policy analysis	● Implementing workable and meaningful regional plans while eliminating inter- and intra-institutional conflicts.	[97, 104-107]
Regional socioeconomic structures	Expansion in non/minimal resource extractive regions that are new to the energy value chain.	● Community engagement with energy systems ● Emergence of OWE value chain to communities/states/regions	● Equity analysis of OWE ● Socioeconomic data harmonization	● Altering cultural/societal interactions with energy systems ● Reforming opposition to OWE and low-carbon transitions	[108]
Socioeconomic & ecological impacts	Lack of federal, state, and local data harmonization	● Non/minimally invasive construction processes. ● Environmentally conscious supply chains. ● Uncertainty of ecological effects on marine life. ● Regional economic benefits from OWE	● Quantitative ● Structured Decision Making ● Data clearing houses	● Access to tools for making informed decisions based on appropriate (by type, format, and scale) socioecological data.	[109, 110]
Relationships with existing industries	Interaction with subsidized fisheries and successful fisheries; Interaction with existing offshore energy extractive industries.	● Commercial and recreational fisheries ● Impacts of OWE grid integration and overall state/regional energy portfolio ● Shared knowledge between OWE and offshore drilling	● Technical assessments ● Energy sector/supply chain economic analysis ● Assessment of onshore wind and farmers	● Offsetting retiring coal fired power plants ● Spillover financing from OWE to offshore drilling ● Mutualistic relationships between incumbent/existing industries and emerging OWE	[108, 111]

5.2. Stakeholders' identification and engagement

The first two elements in Table 3 belong to the long-standing issue of identifying and engaging with relevant stakeholders. This 'relevance' becomes increasingly complex within frameworks such as the Blue Economy or Blue New Deal, where social justice is a fundamental pillar [112]. Within this theme, the U.S. is both a learner and, if not a unique, certainly an extreme case. From the learning side, developers and policymakers in the U.S. can rely on the existing works and tools developed in the UK (see e.g., [113–115]) and Germany (see e.g., [116–118]). However, the identification of stakeholders and community engagement remains a major issue in the U.S. A historical legacy of residential redlining in the U.S., has led to socioeconomic segregation along racial lines throughout coastal states, particularly along the North Atlantic leading to contentious opposition when it comes to approving OWE projects and developing coastal infrastructures [119]. Fundamental questions of inclusion and participation such as 'who gets to decide?' and 'what is representation?' can raise inquiries into how conceptualizations of justice and equity are put into practice. Assumptions of public participation without reflexive attention to existing power dynamics between stakeholders has the potential to lead to maladaptive outcomes in the form of increasing social vulnerabilities [120]. Further complicating stakeholder dynamics are local level hierarchies that often ignore the heterogeneity in local spaces themselves, this includes divergent interests and agendas amongst multiple stakeholders.

The richness in diversity in the U.S. highlights the role of place for coastal communities and the intrinsic value that the coast and seascapes provide for people across class and cultural lines. By exploring and understanding the differing roles of seascapes and placefulness within the context of coastal communities can enhance relationships between these communities, developers, and governments [5]. It is known that factors influencing OWE development include visual impacts, perceived effects on wildlife and tourism, along with integration of OWE into existing seascapes, and fairness [121]. Fairness, or distributive justice is one example that could explain opposition to OWE projects, specifically when framed as energy exports and not used locally [56,57]. Similar sentiments were found when asking New England residents on proposed OWE projects located in federal lease plots in the Long Island Sound. Bidwell et al. [121], found opposition to projects exporting electricity to neighboring regions as opposed to use locally. Such regionalism is represented in the environmental benefits of renewable energy projects as well, such as local air quality vs overall global air quality when supporting renewable energy [102]. A better understanding of factors influencing attitudes towards regionalism with respect to OWE projects could lead to less opposition and increased local support for OWE.

5.3. Data gaps in existing OWE research

Similar to other innovative adaptation measures, OWE, requires a transition to a culture of learning through data sharing of what works, and what does *not* work [112,122]. Whilst the existing know-how still requires fine-tuning because of the complex seascapes-inland interactions of the OWE supply chain, and the cross-sectoral impacts of these developments once deployed [14,104]. Needs will emerge routinely as OWE development expands, creating the necessary preconditions for a national analytical capacity to continuously monitor development— a characteristic common to all sectors involved in the sustainability transition process in coastal regions [113]. Moreover, analytical capabilities will support decision-making for pairing sound environmental planning with beneficial economic uplifting, thus fostering a balanced transition process throughout the entire OWE supply chain. By building upon the integration of multiple tools: from geographic information system-informed analysis to environmental impact assessments, we can further our understanding of environmental interactions with OWE than is currently available [123], while macroeconomic models can help understand societal effects over multiple time horizons (e.g., [13]). For ex-ante planning and ex-post evaluation tools, however, building national accessible databases with fine-scale data is pivotal [124,125]. The Marine Cadastre National Viewer, a joint venture between BOEM and the National Oceanic and Atmospheric Administration (NOAA) provides one example of such national databases. Within this theme, the U.S. is probably better-suited than the other countries: this is exemplified by the partnership between Ørsted Wind Power North America and NOAA whereby Ørsted will share physical and biological data related to OWE within their lease plots in U.S. waters [126]. However, for the U.S. to fully embrace the Blue Economy there needs to be a robust framework for data collection, sharing, and analysis unlike the NOAA Economics National Ocean Watch program which maintains a limited database of only six economic clusters compared to the 27 identified [122]. Most importantly, is the usefulness of building datasets and facilitating a framework to disseminate such information to the proper channels [125].

Developing proper definitions will be required to advance and streamline OWE development as they relate to the Blue Economy. Definitional ambiguity remains a knowledge barrier, particularly as it relates to environmental frameworks such as adaptation (see e.g., [101] and Blue Economy (see e.g., [14]). Developing a sound national level definition of the Blue Economy that allows regional definitions to draw from, enable building informed decision making related to relevant stakeholders and their engagement with the Blue Economy and OWE development [122]. Furthermore, a cohesive definitional understanding of the Blue Economy allows for better integration with OWE development that also delineates from other forms of economic development [101].

5.4. Harmonized government structures designed to streamline development of OWE

Due to the hierarchical governance structure of the U.S., conflicting interest needs to be addressed before moving forward, both between different jurisdictional levels, and among agencies within the same level of governance [104]. For example, project siting is the most time-consuming aspect of the entire development process. Developers need to adhere to multiple federal regulations, such as those outlined in the National Environmental Protection Act, among others in addition to various state and local regulations. The crosscutting of these various governmental levels can lead to delayed processing, redundancies, and in some cases project failure [9]. In an effort to alleviate these challenges, the Departments of Energy and Interior published a report aimed at providing a framework to streamline development of OWE [127]. Despite these efforts, in the U.S. the current structure and allocation of responsibilities within the same jurisdictions (e.g., states) and between different jurisdictions (e.g., states vs federal level) remain unsolved, especially in relation to energy projects and ocean management/development [99]. Tools such as Marine Spatial Planning have been of little help: at the root of the issue, is the lack of a hierarchical structure of both decisional/planning powers responding to checks and balances. These gaps have been emerging quite significantly over the last decade: in Massachusetts, the state's marine spatial plan has been consistently modified to reflect power relations among state agencies [128]. Most recently, the Northern Pass and its evolutions have been consistently defeated by referendums launched at the state level, which effectively impaired the energy system design of entire electricity regions [129]. These events suggest that the scale of decision must be identified: in this case, other countries offer relatively few 'best practices' or learning experience. The U.K. has had issues with the continuous contrast between Scottish Government (state-level) and the UK government [13], whilst Germany and Denmark have relied on planning mechanisms, which still incorporate current power biases [99].

5.5. OWE as a tool for economic development.

The last theme relates to the ways in which OWE can contribute to the economic development of the U.S., at what scale, and through which channels. Denmark and Germany have embraced an export-oriented approach as a way of using OWE for economic development, while the U.K. has focused on a mix of research and development attractiveness, resource abundance, and linked-industries know-how [13]. The differences among these countries have been driven in part by the (lack of) abundance of wind and market size. The U.K. most closely resembles the U.S. both in terms of resource potential and planning approach. The U.K. decided not to impose local-content mandates, but rather used existing industries (e.g., underwater cable industry) to attract investors for developing wind farms. At a larger scale, the U.S. shows strengths similar to the U.K., in addition to existing offshore wind manufacturers: however, most recently the U.S. Congress is attempting to strengthen a unique form of local content, by imposing a nationality mandate on workers employed in OWE projects in an attempt to build out U.S. OWE compliant vessels [130]. By taking a nationalistic approach, the U.S. risks delaying a transition to OWE, rather than supporting the sector as a whole. Similar issues arose during the construction of the first U.S. OWE project, Block Island [130].

6. Concluding discussion

In this study, we analyzed how federal and local efforts for expanding the OWE sector in the U.S. brought the surface decade-long issues related to multi-scale governance, jurisdictional conflicts, and unclear pathways for implementing national industrial policies. Through a dynamic MLP framework enriched by socio-ecological elements, we identified six categories of OWE development characterized by both unique and shared elements between the U.S. and European coastal countries. By exploring the following shared and unique elements: (1) role of local communities, (2) governance structures, (3) multi-scale government interactions, (4) regional socioeconomic structures, (5) socio-ecological impacts, and (6) relationships with existing industries, we were able to link four priority research areas ((1) Stakeholders’ identification and engagement; 2) Data availability; 3) Jurisdictional management; and 4) OWE as regional economic development) the U.S. and the research community to draw from the European experience.

OWE development efforts integrate themselves across multiple United Nations Sustainable Development Goals, specifically those linked to low-carbon transitions (e.g., affordable and clean energy), economic development (e.g., decent work and economic growth and industry, innovation, and infrastructure) and social justice (e.g., reduced inequalities and climate action). Each of the above elements within the United Nations Sustainable Development Goals framework speaks to a broader call of a 'just transition' or 'just energy transition' specifically in relation to low-carbon economies [64,51]. With respect to the ongoing energy transition, all four counties presented have explored distinctive paths to OWE generation but faced different regime-specific challenges over various timelines (see figure 2). For example, all enjoy a mix of renewable energy powering their respective grids and all have pledged to reduce greenhouse gas emissions and continue to expand shares of renewable energy. However, shares of and approaches to OWE development are not uniform. Denmark can be characterized as a pioneer in OWE having enjoyed consistent development with little rapid expansion from 1991 till today, largely facilitated by strong community support and ownership along with favorable energy policies. Additionally, Denmark has experienced the full life cycle of OWE thereby fortifying a holistic knowledge other countries can draw from [11]. Germany, much like Denmark has, since the events at Chernobyl, maintained strong community, political, and economic support for renewable energy and pioneered a benchmark for energy transitions policy, *Energiewende.* From laggard to leader, the U.K. has demonstrated leadership in OWE development throughout Europe. Transitioning from Tepid responses to the energy crisis of the 1970's to increased interest and finical incentives such as the 2002 renewable obligation policy, an energy policy mechanism similar to that of the renewable portfolio standards in the U.S. only at the national level. When considering the U.S., such structures (e.g., strong public support, community ownership) do not exist, potentially explaining strong opposition and NIMBYism to local renewable energy developments, particularly wind. While the U.S. has started making progress in OWE development, much remains to be seen. In both the U.S. and Europe however, regionalism remains to play a strong role in shaping attitudes towards renewable energy projects, particularly wind and specifically in relation to the end use of electricity, namely remaining local. As the U.S. and others face the current energy crisis ignited by Russia's invasion of Ukraine [47], many have temporarily turned away from clean energy goals in favor of suppressing economic hardship [131]. As economics rebound from the Covid-19 pandemic and employ recovery packages designed to spur economic development, specifically within the energy sector, the need for a ‘just energy transition’ is more urgent now than ever [132].

Unlike with onshore wind, if the U.S. is to become a leader in OWE there needs to be strong political support for OWE and sound economic structures. Additionally, by streamlining a process for identifying, approving, building, and producing electricity via OWE, much like Germany who has a standing innocent until proven guilty policy for OWE developments, the U.S. could facilitate consistent interest and investment from OWE developers and make considerable progress towards energy security, clean energy goals, and energy independence.

Acknowledgements & Funding

This work was supported in part by the program Team-TERRA at the University of Connecticut, which is supported by the National Science Foundation under Grant DGE-2022036.

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