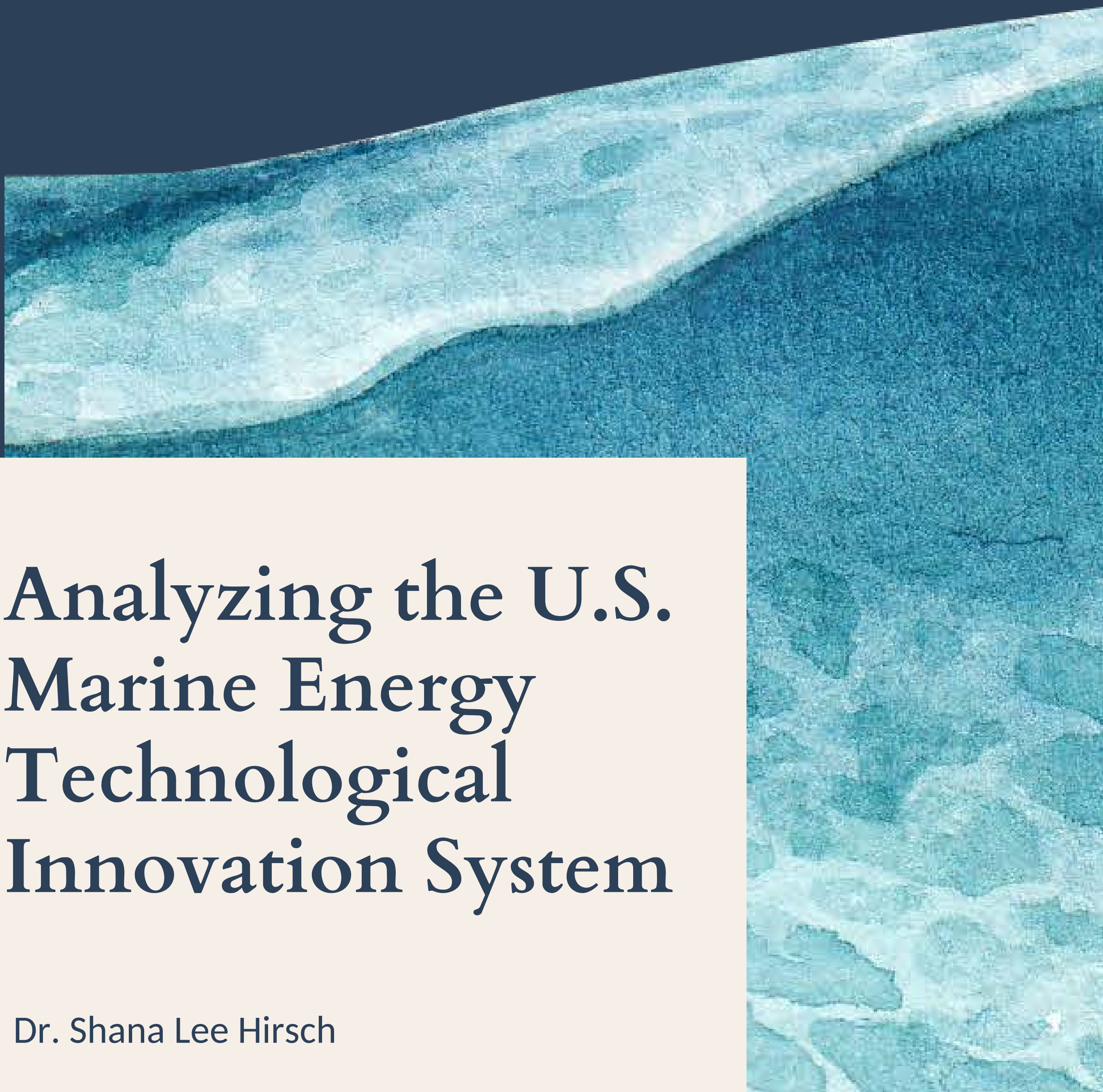

Analyzing the U.S. Marine Energy Technological Innovation System

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Executive Summary

This report uses the Technological Innovation System (TIS) framework to provide a systematic analysis of the marine energy research and innovation system within the United States. (US). A TIS includes the *the actors, institutions, networks, infrastructures, and relationships that influence the speed and direction of innovation* (Bergek et al., 2008; Hekkert et al., 2011). The report describes the current state of the TIS, its structure and its functionality, and draws on other research in innovation systems and policy to provide recommendations for strengthening the TIS to support innovation in the US marine energy sector.

Executive Summary

Rationale & Methodology

At the root of the innovation ecosystem perspective is the understanding that innovation is a collective activity that takes place within the context of a wider system, which is constituted by a complex network of relationships. By understanding the structure and functionality of the innovation system, recommendations for how to improve it can be made. Methods for analyzing innovation ecosystems have been applied to a variety of innovation contexts by science policy researchers since the early 2000's. This study focuses on the TIS that supports innovation in marine energy in the United States through 2022.

Research Questions

1. What is the structure of the Technological Innovation System (TIS) that supports foundational research for marine energy in the US?
2. How has the marine energy TIS in the US changed over time?
3. How is the TIS in the US supporting foundational research on marine energy?
4. How could the TIS in the US be strengthened to support foundational research on marine energy?

Results

Structure

This analysis finds a complex structure of networks supporting collaboration and interaction across universities, government laboratories, and industry. The actors and organizations that form the structure upon which the marine energy TIS in the US rests are highly regarded internationally, and include the US National Laboratories, research and teaching universities, and federally-supported programs that are aimed at fostering innovation. The infrastructure that supports marine energy testing and knowledge production has also been rounded-out and strengthened by recent investments in open-water testing sites and access to testing and expertise through the Testing and Expertise for Marine Energy (TEAMER) program. The complexity of institutions such as the regulatory landscape could potentially produce a blocking mechanism in the TIS, and steps to support movement through the regulatory process such as the Triton Initiative and the Marine Energy Regulatory Toolkit will be critical. Network and organizational ties to other marine sectors such as offshore wind and blue economy applications could be hampered, however, due to the organizational structure and complexity of research funding mechanisms in the US. A more coordinated effort between these structures could strengthen the TIS.

Table 1: Strengths and Weaknesses of the TIS Structure for Marine Energy in the US

Structural Component	Strengths	Weaknesses
Actors	Complex, highly regarded	Lack of actors that cross markets and sectors
Institutions	Strong universities and government laboratories	Complexity of regulatory institutions
Networks	Complex, many connections	Lack of connections with adjacent topics/sectors
Technologies and Infrastructures	Recent investments in testing infrastructure and access/Increased support for modeling and data	Delays in open-water testing, difficulty navigating funding support through all TRLs

Executive Summary

Function

The functional analysis finds that the system is functioning well for a “pre-development phase,” but several functions need to be strengthened for it to thrive and move fully into commercialization. Knowledge development within the TIS is robust, with high quality research and collaboration taking place across the country. This will need continued support if the US is to remain a strong player in the sector. Knowledge exchange is also fairly robust, with a complex network of collaborations spanning academia, industry, and national labs. If the sector is to progress to the next innovation phase, entrepreneurial experimentation must be supported. The small size of the sector and the high risk for developers could block the system from moving on to commercialization. Similarly, the sector needs guidance and vision to develop value propositions and create opportunities for markets. Legitimization is also hampered by the highly complex regulatory process. Thus, the functional analysis highlights a number of places where the TIS requires support.

Table 2: Strengths and Weaknesses of the TIS Functions for Marine Energy in the US

Function	Strengths	Weaknesses
F1: Knowledge Development	Robust, high quality and quantity of research	Decreasing compared to global competitors
F2: Knowledge Exchange	Complex networks of researchers, especially internationally	Few "boundary-crossers" between institutions and fields
F3: Entrepreneurial Experimentation	Increasing diversity of application	Small size of firms, few in number, high risk
F4: Guidance of the Search	Diversification of value propositions	Lack of cohesive strategies or roadmaps
F5: Resource Mobilisation	Evolving testing infrastructure	Difficulty accessing financial resources; lack of trained workforce
F6: Market Formation	High-value markets	Low number of firms, time to commercialization, lack of cross-fertilization with adjacent sectors
F7: Legitimation	Public support, IEC Standards	Lack of regulatory pathways and coordinated public support

Challenges and Barriers to Reach Next Phase

Marine energy technologies are diverse, and thus are at different stages of development. Focusing on pre-development, development, and take-off stages will be dependent on the technology, but strengthening the development stage will help all technologies. During the development phase, entrepreneurial experimentation is the most important function, however, this function is not strong due to high risk of entry, unstable support to commercialization, and a complex and slow regulatory process. The US TIS also needs to strengthen resource mobilization through cohesive, technology-specific and cross-cutting innovation strategy and support. In addition to supporting this function, all functions need to be growing in strength at this phase of development if it is to progress to the take-off phase of development.

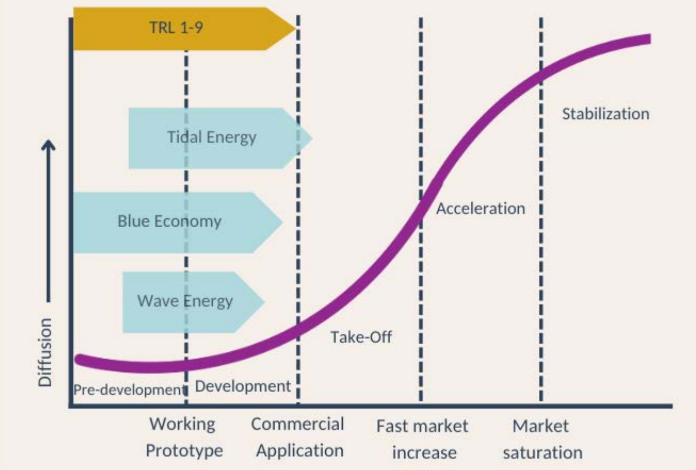

Figure 1: Phases of Development (following Hekkert et al., 2011)

Recommendations

The following recommendations for strengthening the US marine energy TIS are drawn from the previous structural and functional analyses and previous TIS Analyses including: Hannon et al., (2017) and Hekkert et al., (2011). Many of the recommendations span multiple organizations and scales, and so each actor will have different capacities for implementing the changes. Therefore, all actors within the innovation ecosystem will need to address them in different ways, whether through innovation policy or other structural means.

1 Create cohesive, realistic, and focused strategy that provides a roadmap for innovation in the sector.

The US marine energy TIS is entering a new phase of innovation: a development phase that requires support from all functions in order to succeed. This phase must be supported by cohesive, technology-specific and cross-cutting innovation strategy. This strategy also needs to be realistic in terms of the time that it takes for technology to innovate. Putting too much pressure on fast-tracking innovation has been problematic in the context of early UK wave energy development (Hannon et al., 2017). Further, each scale and niche of marine energy application will require different (if sometimes overlapping) pathways and strategies. One speed and one size will not fit all.

2 Provide predictable support to reduce risk and build entrepreneurial experimentation.

Entrepreneurial experimentation was one of the least robust functions of the US marine energy TIS. This is especially concerning because this is the most important function for the development phase and must be strong in order for the TIS to move into the take-off phase. Although funding is inevitably constrained due to the nature of public funding, it should be acknowledged that marine energy has not garnered the level of regular funding and support for R&D as other renewable sectors such as solar or wind. This fact has, in turn, hampered the ability for entrepreneurs to move to commercialization, and has led to a small number of viable US firms. The loss of firms, in turn, leads to loss of tacit knowledge and skilled workforce, as individuals leave the sector. Support will be needed to reduce risk and allow entrepreneurs to move through development phases at a reasonable pace, especially because private sector funding (such as match funding) will not necessarily be available to entrepreneurs at this stage of development. Support for early stage commercial deployments in terms of production tax-credits or energy pricing policies have been successful in other contexts and countries.

3 Align with adjacent sectors to draw in relevant knowledge and talented workforce.

At this stage of development, collaboration and competition must be balanced (Hannon et al., 2017), yet relevant knowledge from other fields can be drawn into the sector without hampering competition within it. The siloed nature of marine energy R&D in the US is stifling the ability to innovate, and most importantly, to draw on previous knowledge from adjacent sectors such as oceanographic sensing, offshore wind, oil and gas, marine operations, and others. With an increasing focus on "blue economy," "ocean internet of things," and offshore renewable energy, the marine energy sector has an opportunity to seize on an important narrative which can draw in knowledge, research funding and support, and talented workforce from adjacent sectors and programs. The time to do this is now.

4 Continue to support knowledge production and exchange.

Knowledge production and knowledge exchange are currently robust in the US. However, both of these functions are leveling off, and becoming less competitive when compared to other countries. These functions must continue to be supported by strong networks including already-existing networks that are shown to have high levels of interaction and knowledge production, such as the National Marine Energy Centers. Not only will this support the development of knowledge, it will also provide a skilled workforce, a lack of which could create a blocking mechanism to moving to the next phase of development.

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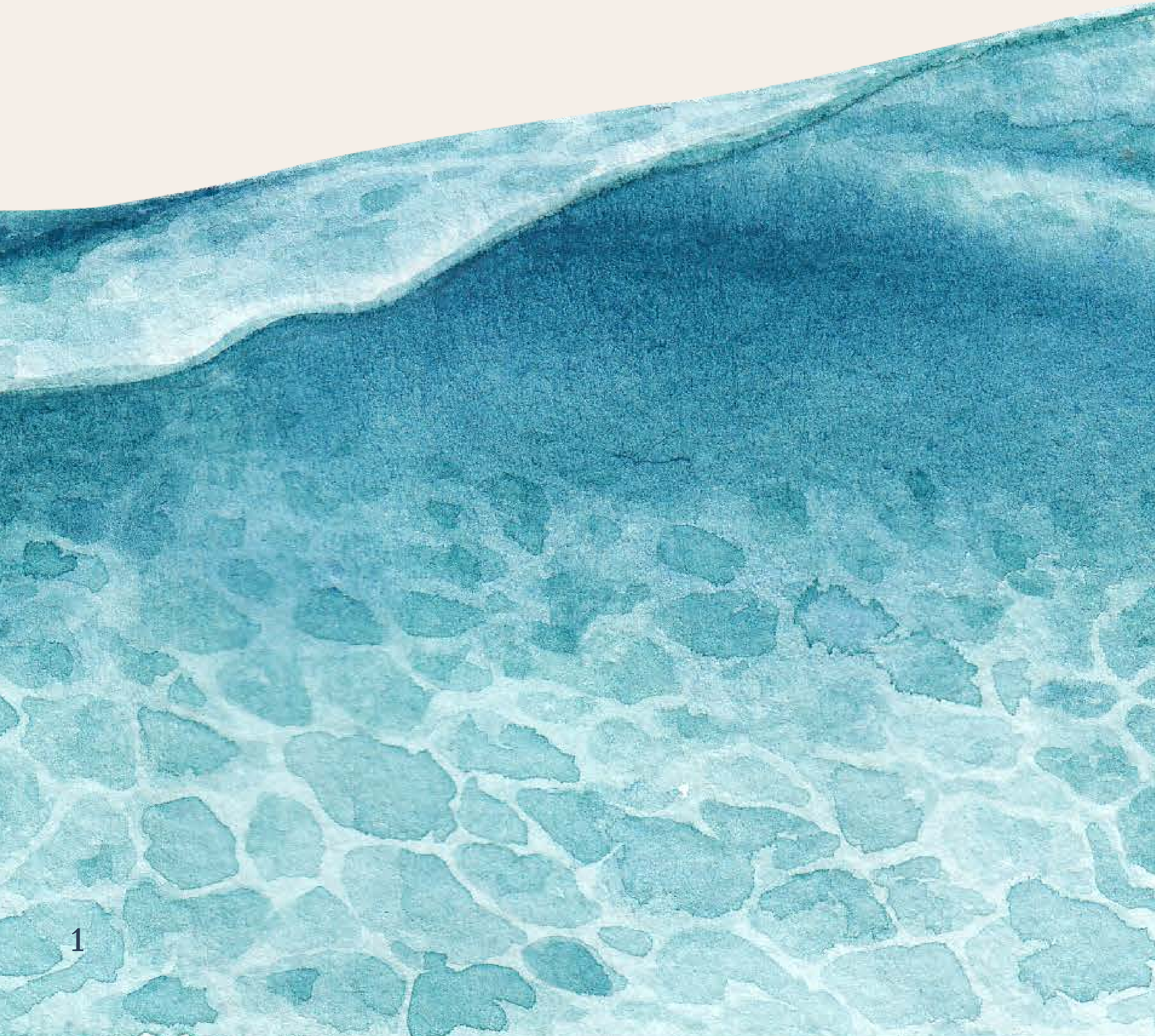
Abbreviations and Acronyms

AMEC	Atlantic Marine Energy Center
APL	Applied Physics Laboratory
BOEM	Bureau of Ocean Energy Management
COE	US Army Corps of Engineers
DOE	US Department of Energy
EERE	Office of Energy Efficiency & Renewable Energy
ETIP-Ocean	European Technology & Innovation Platform for Ocean Energy
EU	European Union
FERC	Federal Energy Regulatory Commission
GW	Gigawatt
HINMREC	Hawaii National Marine Renewable Energy Center
IEA	International Energy agency
IEA-OES	International Energy Agency Ocean Energy Systems
IEC TC-114	International Electrotechnical Commission Technical Committee 114
kW	Kilowatt
LCOE	Levelized Cost of Electricity
MECC	Marine Energy Collegiate Competition
MW	Megawatt
NHA-MEC	National Hydropower Association Marine Energy Council
NMEC	National Marine Energy Center (formerly NMREC)
NMFS	National Marine Fisheries Service
NOAA	National Oceanographic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
OCS	Outer Continental Shelf
OTEC	Ocean Thermal Energy Conversion
PI	Principal Investigator
PMEC	Pacific Marine Energy Center
PNNL	Pacific Northwest National Laboratory
POET	Pacific Ocean Energy Trust
PRIMRE	Portal and Repository for Information on Marine Energy
Sandia	Sandia National Laboratory
SNMREC	Southeast National Marine Renewable Energy Center
TEAMER	Testing & Expertise for Marine Energy
TIS	Technological Innovation System
TWh	Terawatt Hour
UK	United Kingdom of Great Britain and Northern Ireland
UMERC	University Marine Energy Research Community
US	United States of America
WETS	US Navy Wave Energy Test Site
WPTO	Water Power Technologies Office
WWPTO	Wind and Water Power Technologies Office (now WPTO)

1 Introduction



Introduction

Marine energy is a renewable energy source that includes ocean and tidal currents, tidal elevation, waves, and temperature or salinity gradients. In some instances, it can also include other water currents such as estuarine or river currents. Wave and current energy technologies have been shown to produce power ranging from watts to megawatts. Marine energy technologies also have a range of applications at these different scales. Further, wave energy resources are significant both in the US and globally. Although marine energy technologies are still emerging, they are on a path to commercialization, and with many applications for power both at sea and on land and the high potential of the marine renewable energy resource, supporting innovation in this sector is important and timely.

Rationale

Marine energy resources have the potential to provide renewable, carbon-free, and predictable power. In the US, the total marine energy technical resource is 2,300 TWh/yr. This amounts to approximately 57% of US electricity generation (Kilcher et al., 2021). Wave energy resources alone are estimated as 1,400 TWh/year, and tidal an additional 220 TWh/yr, of which 210 TWh/yr is located in Alaska. Gulf Stream current resources include around 49 TWh/yr, and riverine hydrokinetic potential adds an additional 120 TWh/yr (EPRI, 2012). Ocean thermal (OTEC) resources located in US territories add an additional 4,100 TWh/yr potential (Kilcher et al., 2021). In an era of energy transitions, the size of these numbers cannot be ignored.

In 2021, the US Department of Energy's (DOE) Water Power Technologies Office (WPTO) funded the Pacific Ocean Energy Trust (POET) to establish the University Marine Energy Research Community (UMERC). The goal of this new organization is to assess the existing research network in marine energy, foster collaboration and coordination across the US marine energy research community, and amplify research impacts both nationally and internationally. As such, one of the primary objectives of UMERC is to understand marine energy research in the US, with a special emphasis on university research activities in order to align them with industry needs. This will allow UMERC to recommend ways to improve research coordination, collaboration, and impact in the sector.

In order to understand how to support relevant research in the marine energy sector, we first need an understanding of what research is taking place, where, and the effectiveness of this research in supporting the marine energy sector. Fortunately, there are tested and proven social scientific methods and concepts to support this effort. Many of these methods have been developed and applied by the Copernicus Institute for Sustainable Development and Innovation in the Netherlands, where researchers created and tested the **Technological Innovation System (TIS) Analysis** framework (Hekkert et al., 2011, Hekkert et al., 2007; Bergek et al., 2008). Since the early 2000's, researchers throughout Europe and the world have used this framework to understand how to influence the speed and direction of technological innovation. Case studies on renewable energy technologies have been conducted in the UK (Hannon et al., 2017), the Netherlands (Suurs et al., 2010; Kieft et al., 2021), Norway (van der Loos, 2021), Asia (Huang et al., 2016), and other places. These case studies have helped science and technological innovation policy makers and analysts understand and address gaps in innovation ecosystems in diverse sectors.

Research Questions

1. What is the structure of the Technological Innovation System (TIS) that supports foundational research for marine energy in the US?
2. How has the marine energy TIS in the US changed over time?
3. How is the TIS in the US supporting foundational research on marine energy?
4. How could the TIS in the US be strengthened to support foundational research on marine energy?

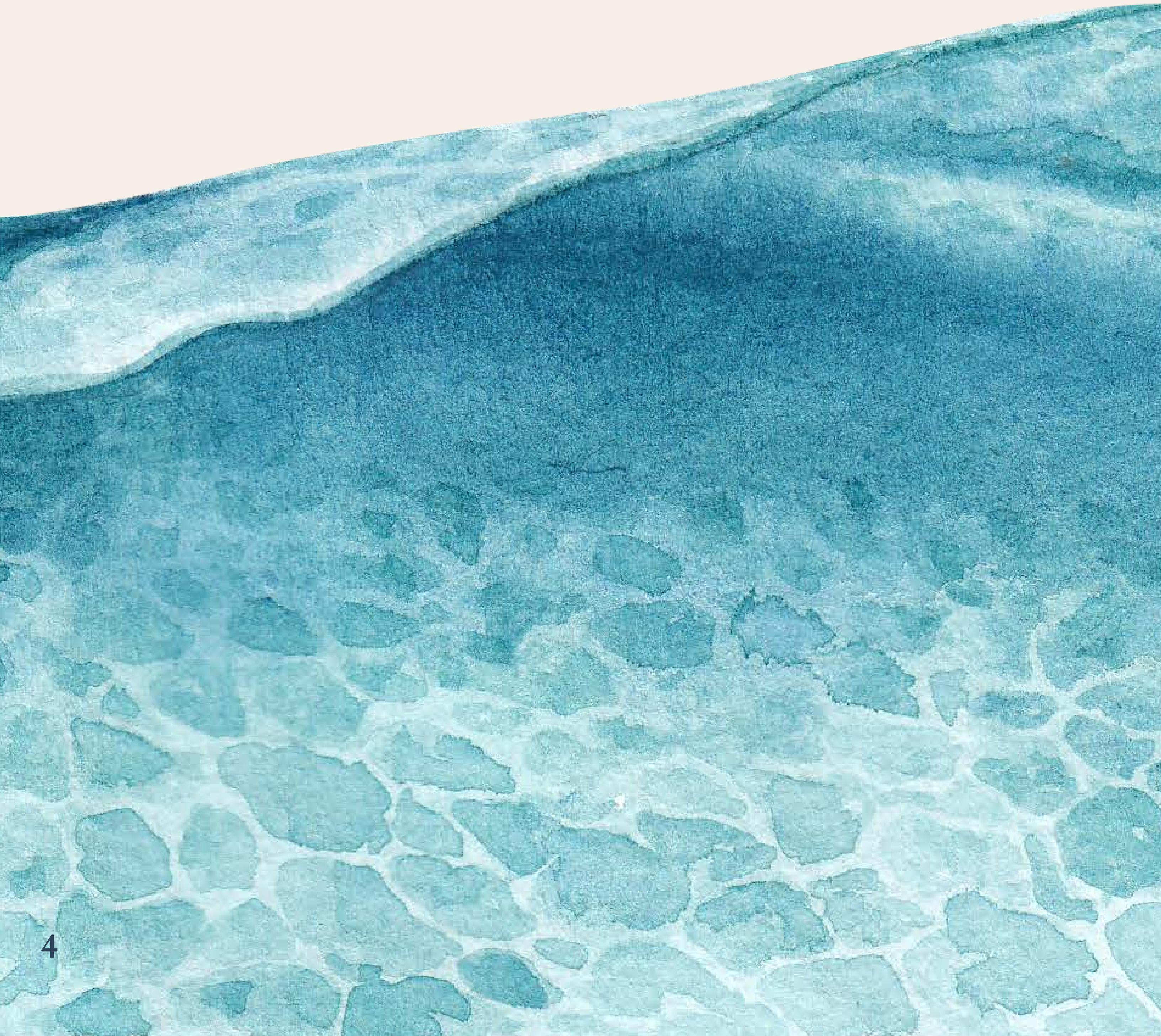
Research Objectives

This report describes the existing marine energy related research activities in the US, analyzes the effectiveness of the research ecosystem, and follows its evolution over time. This TIS Analysis was carried out to identify the current state of knowledge exchange and innovation in the marine energy sector within the US. The **objective** of the TIS Analysis is to provide a baseline for understanding what research has recently occurred, is ongoing, and gaps in the research infrastructure. The following report provides an understanding of how the TIS is functioning (or failing) and provides a basis for innovation policy recommendation to support foundational research in the sector.

As part of this ongoing research, an annual survey will continue to be administered to all UMERC members (membership is open to anyone interested in the marine energy sector). The annual survey is designed to verify current information and completeness and evaluate knowledge transfer and collaboration within the marine energy community. The goal is to capture both qualitative and quantitative metrics that can track changes in the U.S. marine research community over time. The results from the survey will inform future directions and identify gaps for UMERC to help overcome. The outcomes of the first annual UMERC survey (2022) are contained in this report, and will form a baseline for future surveys.

02

State of Marine Energy Research and Innovation



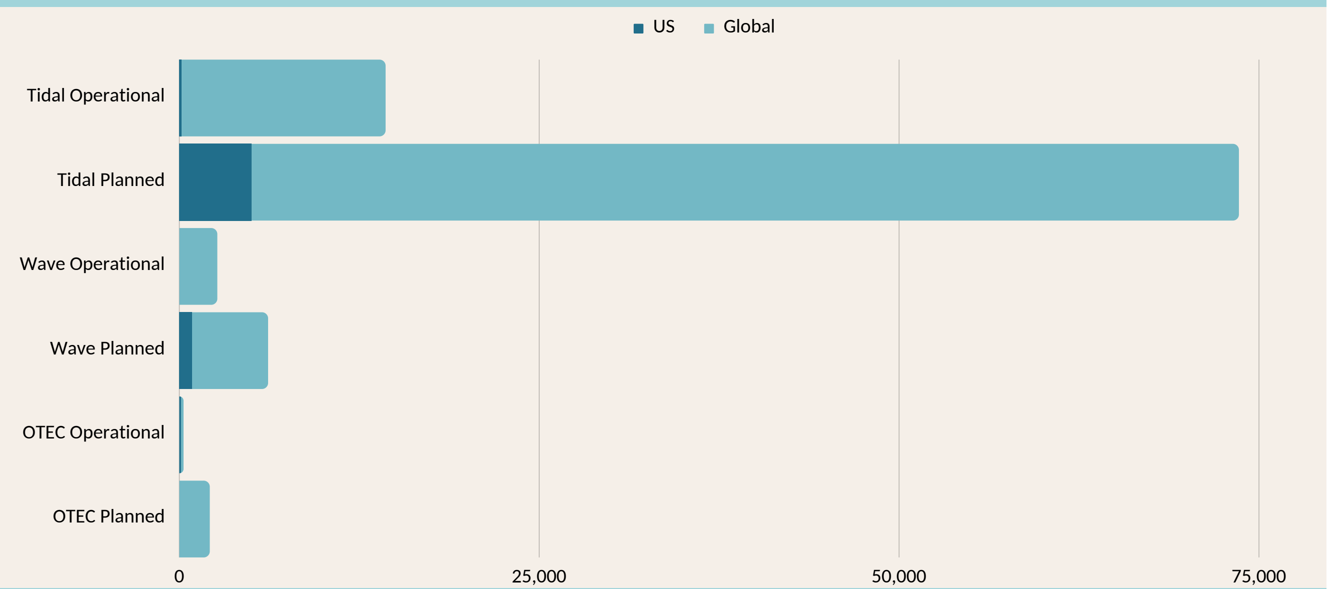
State of Marine Energy Research and Innovation

Marine energy technologies are rapidly emerging, innovating, and transforming. Although the sector is in a dynamic stage of development, some marine energy devices are reaching later stage TRLs, with tidal energy approaching full commercialization. Yet fundamental knowledge about impacts to the marine environment, resource characteristics, and hydrodynamics are still being described, and there is much room for efficiencies in these technologies to be realized. Further, diverse applications and pathways for commercialization for marine energy are still being recognized and discovered, especially in terms of generating power for the blue economy (LiVecchi et al, 2019). For innovation to occur, the marine energy sector therefore requires foundational research, and this foundational research requires support and coordination as part of a functioning Technological Innovation System (TIS).

Where are we now, and where are we going?

Marine energy is now on a path to commercialization, with research, validation, and demonstration projects being funded by the DOE, the US Navy, and others. Marine energy resources in the US are known to be large and predictable, and a recent report found that harnessing only 1/10 of the technical resource in the US would provide 6% of electricity needs (Kilcher, 2021). However, the marine energy sector within the US is falling behind Europe, where tidal energy is "on the verge of industrial roll-out" (Villate et al., 2020). The marine energy sector in the US is at a stage where it requires coordination and support to reach commercialization. At the same time, researchers must continue to answer foundational questions to push the technology forward.

Figure 2: kW of Marine Energy in the US and Globally 2022



*Data combined from various sources, including PRIMRE, IEA, OES, and desk research

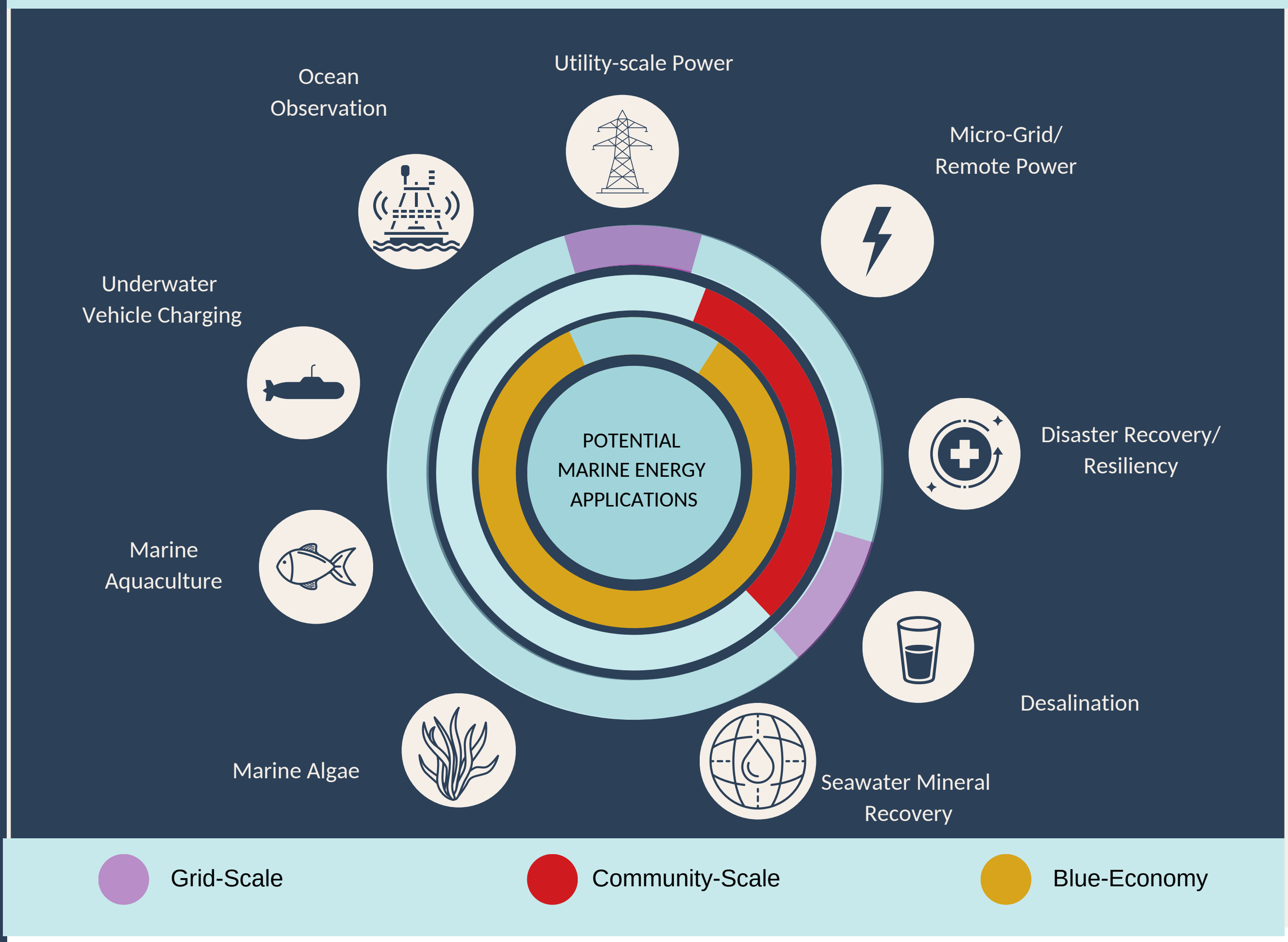
Key Challenges Identified in High-Level Reports

Recent high-level reports include: NHA-MEC's (2021) "Commercialization Strategy for Marine Energy," DOE EERE's (2022) WPTO "Multi-Year Program Plan" and "Powering the Blue Economy," (LiVecchi et al., 2019), OES's "white paper" on OTEC, and ETIP OCEAN's (2020) "Strategic Innovation Agenda for Ocean Energy." In these reports, several overlapping challenges and barriers are discussed. These include: reliable financial support for research, demonstration, and validation; a need to reduce cost; the need for a trained workforce; complex regulations and long permitting times; engineering challenges, especially around installation and reliability; long design and test cycles; and lack of data.

Key Drivers Identified in these reports

Additionally, several key potential or actual drivers are identified in these reports, including: developing international standards; financial incentives; infrastructure upgrades to grid and distribution networks; and incentives for deployment. Further, the critical need to decarbonize energy sources by creating a mix of complementary renewable energy technologies is a clear driver, especially when paired with government targets for renewables. Finally, the cross-cutting applications of marine energy technologies in high-value niche markets could also potentially drive innovation.

Figure 3: Potential Scales and Applications for Marine Energy

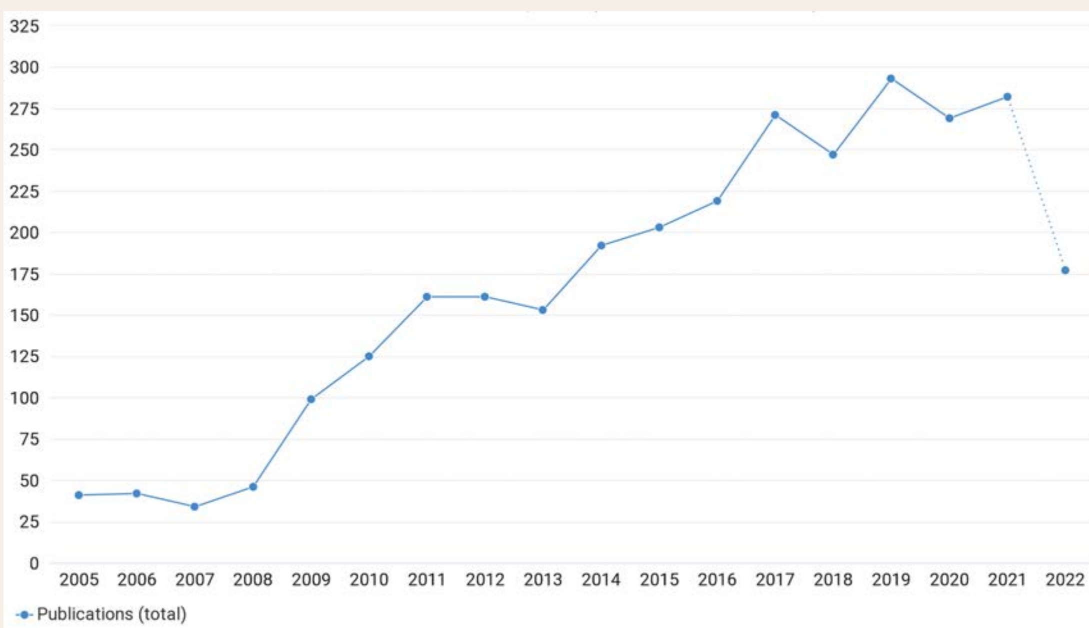


Multiple Scales of Application

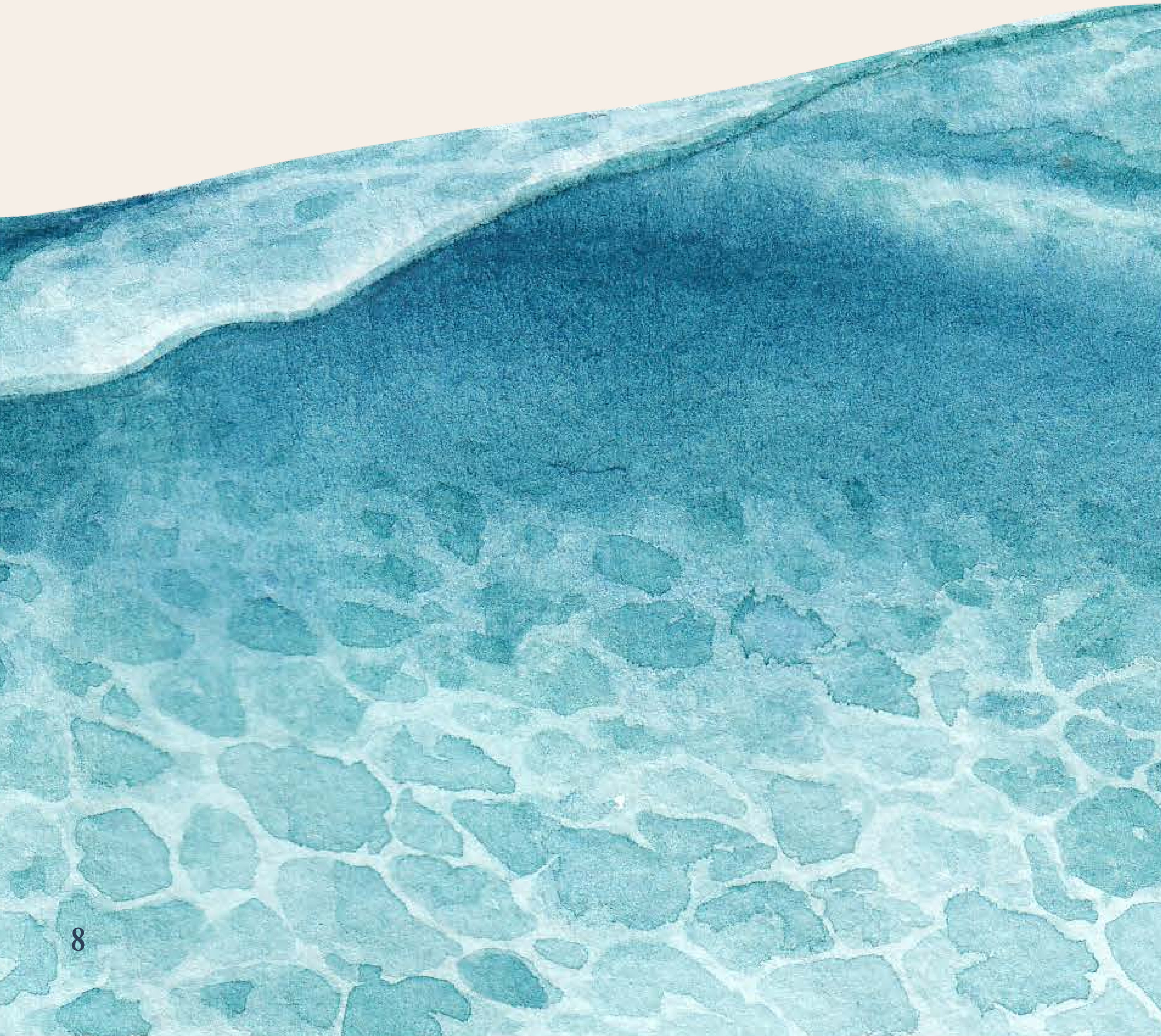
Marine energy is now commonly conceived as having multiple scales of application. The DOE-EERE WPTO report (2019) "Powering the Blue Economy," presented the first comprehensive evaluation of broader applications for marine energy technology. More recently, the International Energy Agency's Ocean Energy Systems (IEA-OES) released their own report focused on the blue economy and its "promising markets" for marine energy. These emerging and potential applications, or what are referred to as "blue economy" applications include niche, and likely high-value markets that require energy at sea. These include: ocean observation, marine algae, marine aquaculture, underwater vehicle charging, seawater mineral recovery, desalination, and other applications for power at sea.

Scaling up to another niche market, marine energy can also provide power to remote communities, either for distributed power or micro-grids, or for disaster recovery. In the largest scale of application, wave and current energy, as well as OTEC, could not only complement wind and solar in the electricity mix at grid-scale, but also provide reliable and predictable power to isolated island communities and national grid infrastructure in the form of arrays. Conceptualizing marine energy at these multiple scales and broad applications has created a complex innovation system with new synergies between and among researchers and innovators. This framework has also increased the variety and possibilities of marine energy technologies both in the US and globally, necessitating foundational research collaboration across disciplines, which has been increasing steadily over the past two decades (Figure 4).

Figure 4: US Publications Related to Marine Energy 2005–2022



03 Analytical Framework and Methodology



Analytical Framework and Methodology

The TIS is an analytical perspective that facilitates a systematic description of innovation at all technology development stages. It includes consideration of actors (including government, industry and research organizations), institutions, networks and the feedbacks and drivers between them (Hekkert et al., 2017). This report explores the marine energy sector in the US through a TIS analysis, characterizing scientific work and technology development. The report includes a structural analysis as well as measures of performance indicators and functions of the TIS (Hekkert et al., 2007 and 2017). This chapter explains what a TIS Analysis is, and outlines the methods and data that were gathered and used for this analysis.

Methodology

The remainder of this section details the research purpose and scope, data sources and limitations, and methods and analysis for the four main parts of the study. The four subdivisions of the study are: 1) Structural Analysis, 2) Functional Analysis, 3) Analyses of System Failures/Health, and 4) Recommendations. The methods include both qualitative and quantitative measures, outlined below.

Table 3: TIS Definitions

Technological Innovation System	The actors, rules, structures, and processes that support or influence the speed and direction of technological change in a specific technological area. (Hekkert et al., 2011).
Innovation System	"networks of actors and institutions that develop, diffuse, and use innovations" (Markard and Truffer, 2008, p. 597; Carlsson and Stankiewicz, 1995)
Networks	"agents working within a "particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology" (Carlsson and Stankiewicz, 1991, p. 93)
Institutions	"Institutions are the rules of the game in a society, or, more formally, are the humanly devised constraints that shape human interaction" including regulations, laws, and informal norms (North, 1990, p. 3).
Actors	Individuals involved in knowledge production in government, industry and research organizations
Functional Analysis	A stage of a TIS analysis that diagnoses specific processes that are important to the performance of an innovation system (Bergek et al., 2008).
Foundational Research	Cross-cutting and early-stage research needed to support innovation in a field.

What is a TIS?

A TIS includes the the actors, institutions, networks, infrastructures, and relationships that influence the speed and direction of innovation (Bergek et al., 2008; Hekkert et al., 2011). Innovation systems are “networks of actors and institutions that develop, diffuse, and use innovations” (Markard and Truffer, 2008, p. 597; Carlsson and Stankiewicz, 1995). Thinking with innovation systems means recognizing the importance of knowledge exchange, dissemination, and creation between actors, organizations, and institutions as a critical determinants of technological change (Hekkert et al., 2007). Meanwhile, technological systems focus on networks of agents working within a “particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology” (Carlsson and Stankiewicz, 1991, p. 93). Analyzing a technological system highlights knowledge flows between resources and clusters of resources such as hubs; economic support; social networks; data; and institutional infrastructures (Carlsson and Stankiewicz, 1991).

Researchers in the field of sustainability transitions have bridged work on innovation systems and technology systems by adopting a Technological Innovation Systems (TIS) approach (Markard and Truffer, 2008). This approach provides a systemic and interactional perspective for analyzing the successes and failures of innovation, rather than a purely hierarchical approach. This is particularly important when considering technology transformations that do not unfold in a linear way, cross national boundaries, or require novel policy instruments and approaches (Weber and Truffer, 2017).

The Technological Innovation Systems perspective has also provided a way for academia and policy-makers to discuss research policy (Sharif, 2006). It has been successfully translated into practical policy guidelines through a schematic for applying functional thinking that looks at the roles that actors and institutions fulfill. These functions are used in this report to analyze the health of the TIS through a functional analysis (Bergek et al., 2008; Hekkert et al., 2017).

Although this study is focused on a national innovation system—that of the US—the TIS approach does not stop at national borders, and instead considers global influences and connections. The nation/state clearly plays a role in facilitating innovation through policy, especially in the energy domain. At the same time, innovation itself often defies these boundaries through knowledge exchange and international standards that may or may not be sanctioned or encouraged by the state. Thus, national innovation systems are important to understand in order to develop effective policy.

Step 1: Structural Analysis

This step includes mapping the TIS and knowledge infrastructures of the US marine energy sector over time. TIS structures include 1) individual actors and government, academic, and private organizations; 2) institutions, including regulations, laws, and informal norms (North, 1990, p 3) networks that facilitate knowledge exchange between actors; 4) the technological infrastructures, including facilities and physical networks. Knowledge infrastructures include these categories in addition to the resources and services that actors draw on to create knowledge. These are both “concrete,” as in test sites, instruments, and demonstration projects, and cyberinfrastructure; as well as “abstract,” as in data, protocols, standards, and memory.

Step 2: Functional Analysis

A functional analysis evaluates “how” the innovation system is performing by assessing seven “functions of innovation systems” (Hekkert et al., 2007). A functional analysis highlights what different actors are doing within a given ecosystem, as opposed to the structures that exist.

Functional TIS Analyses rely on both qualitative and quantitative methods. While much of the structural analysis can be accomplished through quantitative data, qualitative data must be collected in order to understand functionality of the system. This is because functions are evaluative, and consider “how” the innovation system is performing. This means that experts within the system must be consulted in order to evaluate the efficacy of the system (Hekkert et al., 2011). This context is critical to understanding the functionality of a TIS.

This analysis measures the effectiveness of innovation by measuring the performance of seven TIS functions (Hannon et al., 2017; Hekkert et al., 2017; Bento and Wilson, 2016). These include: 1) knowledge development, 2) knowledge exchange, 3) entrepreneurial experimentation, 4) guidance of the search, 5) resource mobilization, 6) market formation, and 7) legitimation. This quantitative and qualitative analysis assesses the barriers and challenges to innovation in the sector (Markard and Truffer, 2008; Hekkert et al., 2007). The datasets for each of these functions were gathered from available data from government databases, surveys, and interviews. This data will also allow for analysis of absolute changes through time, and, when possible, relative comparison with other nations (for example, comparison of spending on R&D with other countries).

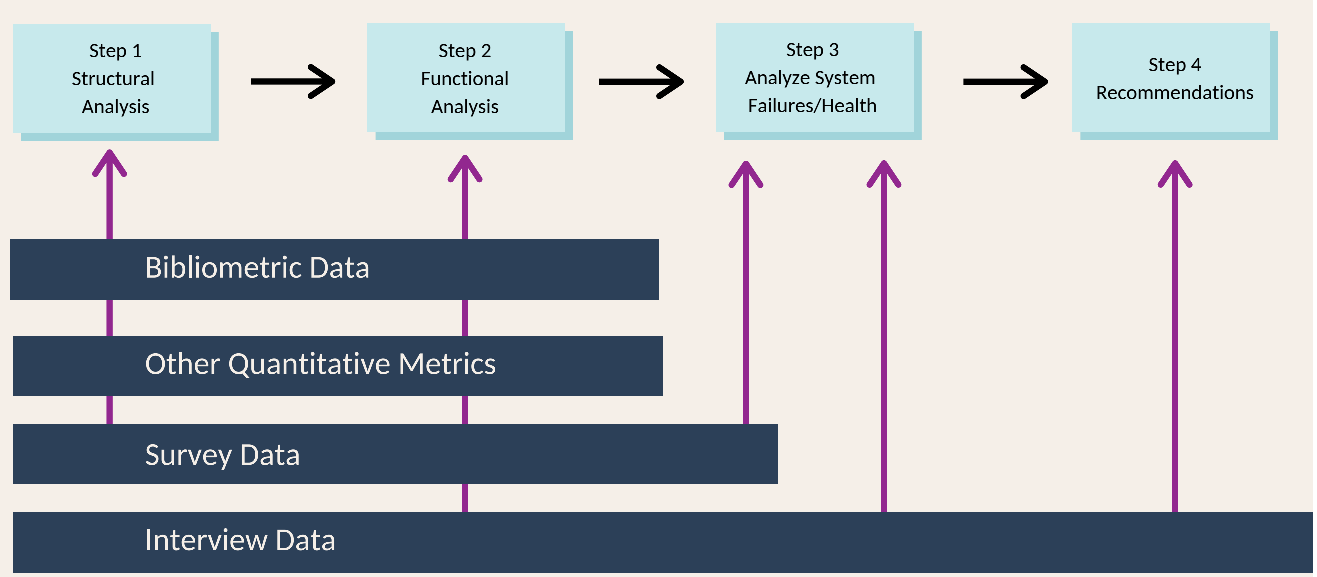
Step 3: Analyze System Failures and Health

After the structural and functional analyses were completed, an overall analysis of system failure, blockages, and challenges was completed. This analysis relies on triangulation, or verification of the initial findings through interviews with experts in industry and research. The result is a multi-layered analysis of the TIS that considers structure and function, and uses expert opinion to verify these findings and add nuance to the understanding that they provide.

Step 4: Develop Recommendations

Finally, recommendations that are relevant to the report audience (policy-makers, innovation specialists, academics, researchers, and developers) were developed. These recommendations are based on the findings of the TIS Analysis, and compared with findings from other TIS Analyses of energy and other technologies. While some of these recommendations may be policy-relevant, they are meant to be more expansive in that they are not all necessarily possible or pragmatic today, but may be in the future. This is important when thinking about innovation in technology, as the field should be dynamic and emergent, not stagnant in one scope and time.

Figure 5: TIS Analysis Workflow and Data



Bibliometric Data

Bibliometric analysis includes a set of quantitative research methods that are used to analyze scientific research publications as a proxy for research. The purpose of the bibliometric analysis is to understand what kinds of research are being conducted, the location of this research, and the productivity of research in the sector. This proxy is valuable because a rich and fairly complete dataset is accessible and can be analyzed using rigorous and tested methods. The scope of the analysis will include marine energy-related research within the United States.

The main data source for the bibliometric, spatial, and network analysis is the Dimensions AI Database. Dimensions AI is the largest linked research information dataset in the world, with 129m publications, 6m grants, 12m datasets, 743k policy documents, and 147m patents. The real power of the Dimensions AI database is in its links between publications, grants, researchers, funders, and patents. Access to this database allows a comprehensive perspective on research and outcomes across the US, as well as researcher links to the rest of the world. The database is current at the time of the search: publications and researcher profiles are updated daily and appear 2-3 days after publication, grants are updated monthly, patents weekly, and organizations are reviewed quarterly.

The search included “full data”, which includes The following filters were used to construct a corpus of relevant data from the Dimensions AI database:

- Publication Year: To keep the analysis less historical and more focused on current research (we are interested in what is happening now, not so much what has happened in the past), we filtered out any data previous to 2005.
- Location of the research organization: the country in which the research organization is based was restricted to the US. NOTE: some research organizations outside the US will still be included because of co-authorship between US and non-US authors of publications.

Search Terms

- Search Terms: Search terms used to gather the initial dataset were: (“marine energy”) OR (“marine power”) OR (“ocean power”) OR (“tidal energy”) OR (“tidal power”) OR (“marine hydrokinetic energy”) OR ("ocean wave power") OR ("ocean hydrokinetic energy") OR ("ocean thermal energy conversion") OR ("marine renewable energy") OR ("cross-flow hydrokinetic turbine")
- NOTE: “wave energy” and “wave power” were not used because of the large amount of unrelated research that these terms include. We also used a number of search terms to exclude research that was not relevant to marine energy. These search terms are listed in Appendix A.
- Fields of research: a number of fields were excluded from the corpus, in order to refine the data. For example: Astronomical and Space Sciences and Quantum Physics. A complete list of these fields can be found in Appendix A.

The resulting corpus includes:

- Publications: 3,015
- Grants: 184
- Patents: 1,761
- Policy Documents: 81

Limitations of Bibliometrics

It should be noted that, because of the large dataset of the bibliometric analysis, it was necessary to exclude some data based on search terms, research areas, and source title. While every effort was made to ensure that no relevant data was excluded, and each set was screened manually before exclusion, the dataset cannot be considered extensive, but can be considered representative. Further, the data could include some sources that are not specifically related to marine energy. This is because some data may relate to marine energy, but may not be "marine energy research" per se (for example: noise from offshore wind development). In cases like these, we erred on the side of inclusion instead of exclusion, due to the way that this research may become more relevant to marine renewables in the future.

Survey Data

The Annual UMERC survey was conducted online, and included both qualitative and quantitative measures. The survey was open for a period of 30 days, and was publicized to appropriate industry and research networks. The survey was also available for people to respond at the UMERC Annual Conference. Survey questions are provided in Appendix B. The survey was conducted confidentially. In total, 50 full surveys were filled out.

Interviews

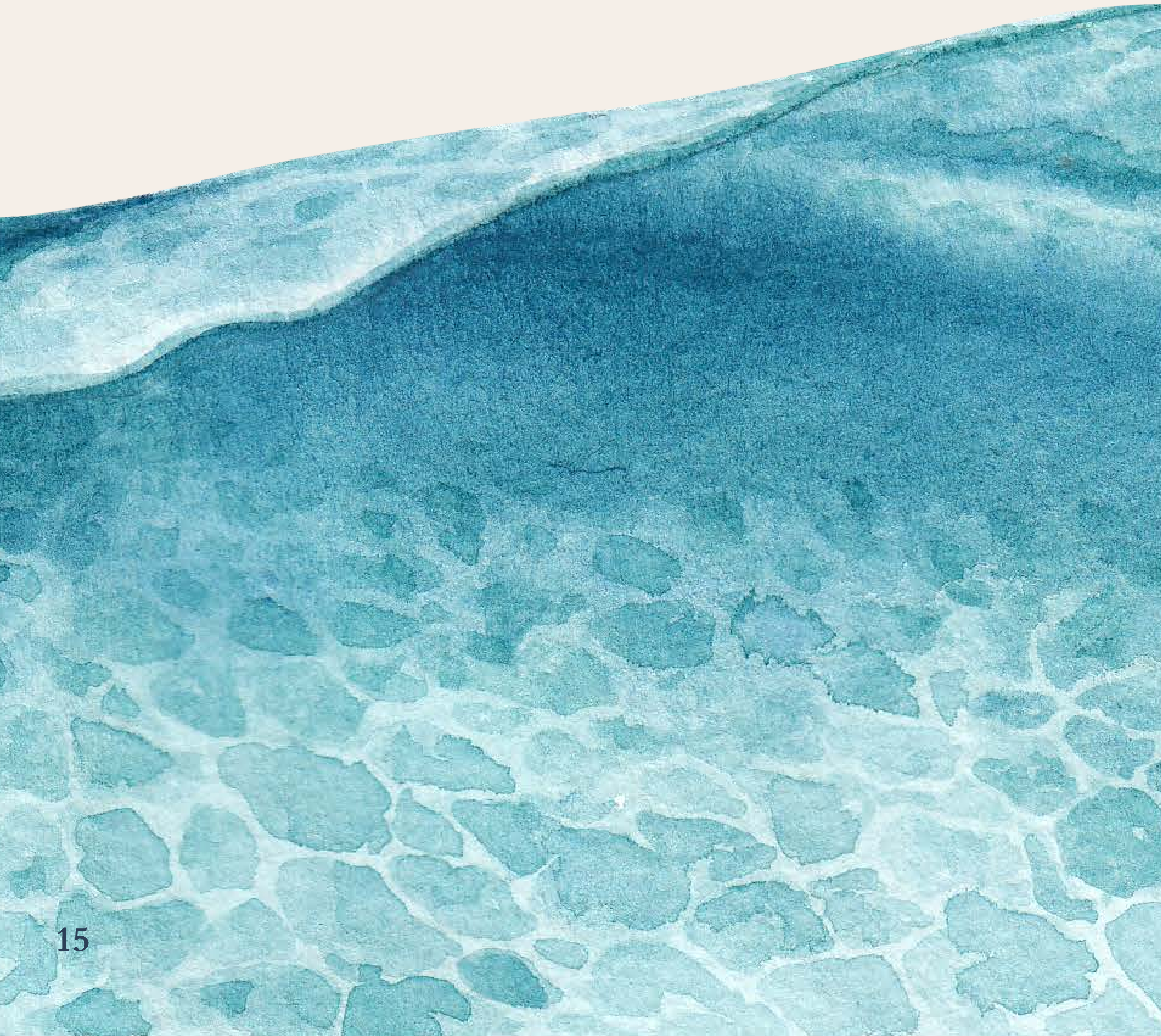
The purpose of interviews is to add context and perspective on the functionality of the TIS, especially interaction between universities and industry. Much of this information is highly qualitative and cannot be collected through survey methods. Because individual perspectives from those that rely on a TIS are critical to understanding its function, semi-structured interviews are a necessary source of data for a TIS Analysis. Confidential interviews were conducted with 20 individual researchers, developers, and others within the sector. A list of type of interviewee is found in Appendix C. The interviews were conducted virtually and were 30 minutes in length.

Other Data

Documentary and desk analysis provided background information and serves as a large qualitative dataset. The documents analyzed will include websites, technology assessments, state, regional, and federal reports, and other available documents. In addition, databases and tools created by the Dept. of Energy such as PRIMRE and the MHK Toolkit provided a resource for information on the current state of the industry. Some of this information was validated through web searches. All of the data that was used in these analyses are described in the individual sections that follow.

04

Structure of U.S. Marine Energy Innovation Ecosystem



04 Structure of Marine Energy Innovation System

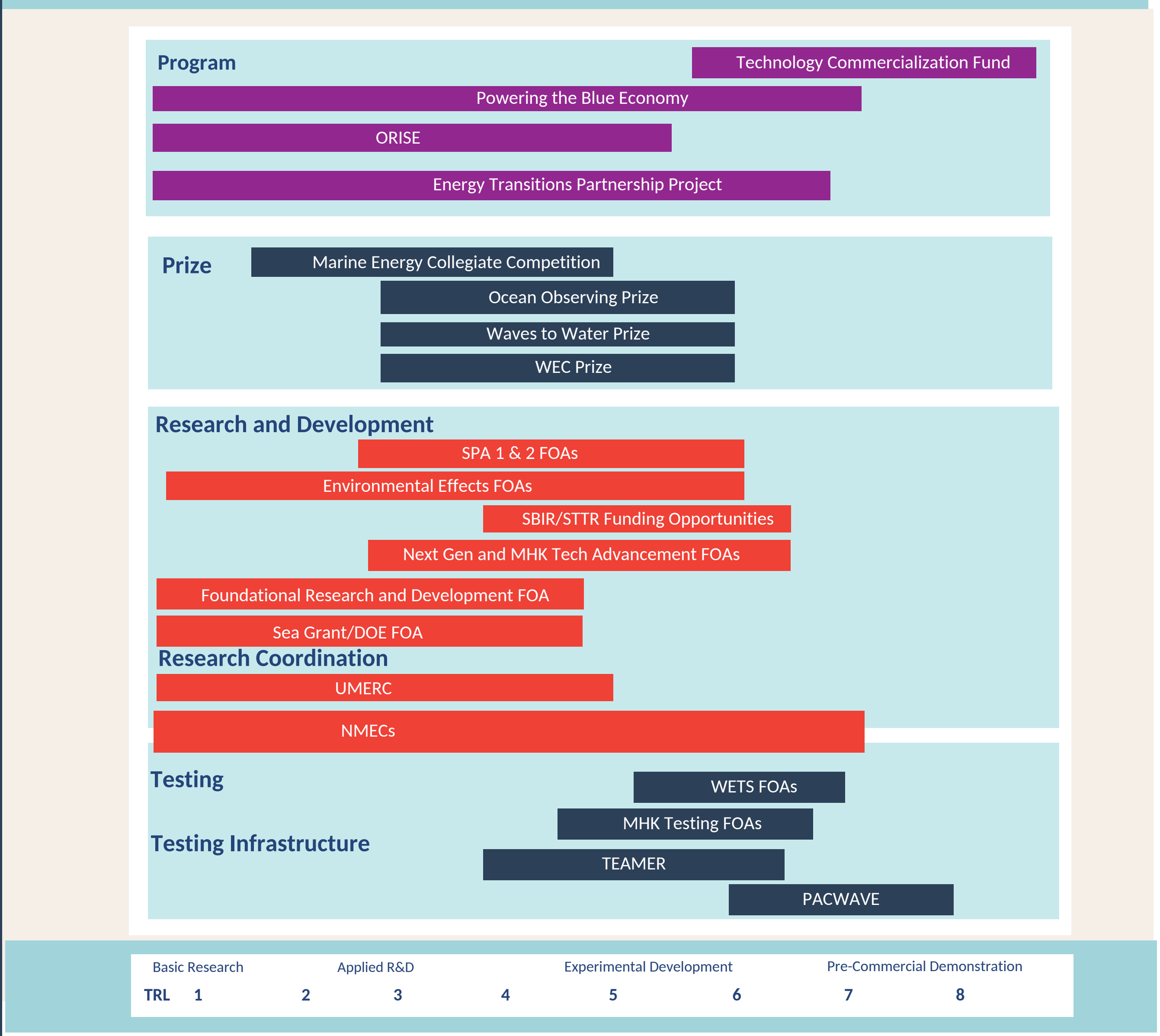
This section describes the structure of the marine energy innovation system in the US. The structure of a TIS includes the actors, institutions, networks, and technologies and infrastructures that support innovation in the system. Since interactions within a system are dynamic, the functional analysis in the next section will build off of this structural analysis. The structural analysis emphasizes the resources within which a system interacts. It is important to remember that the structures are not necessarily physical and include institutions and networks that may not be clearly visible.

Figure 6: US Marine Energy Actor Landscape

Government	IEA-OES (International Energy Agency--Ocean Energy Systems) FERC (Federal Energy Regulatory Commission) DOE EERE-WPTO (Department of Energy Water Power Technologies Office) ARPA-E (Advanced Research Projects Agency for Energy) (DOE) DOD (Department of Defense) NOAA (National Ocean and Atmospheric Administration) BOEM (Bureau of Ocean Energy Management) Department of Energy National Laboratories State Level Incubators and Initiatives
Industry	NHA-MEC (National Hydropower Association Marine Energy Council) Developers Suppliers Environmental Monitoring Consultants Maritime Logistics Labor and Workforce International Electrotechnical Commission (IEC) TC 114
Knowledge	Universities, Colleges, Technical Schools UMERC (University Marine Energy Research Community) NMECs (National Marine Energy Centers) University-based research laboratories such as APL (Applied Physics Laboratory) Non-Profit based research centers such as MBARI (Monterey Bay Aquarium Research Inst.)
Organizations	International Network on Offshore Renewable Energy (INORE) Pacific Ocean Energy Trust (POET) TEAMER (Testing and Expertise for Marine Energy)

This analysis finds a complex structure of networks supporting collaboration and interaction across universities, government laboratories, and industry. The actors and organizations that form the structure upon which the marine energy innovation system rests are highly regarded, such as the US National Laboratories, research and teaching universities, and federally-supported programs that are aimed at fostering innovation. The infrastructure that supports marine energy testing and knowledge production has also been strengthened by recent investments in open-water testing and access to testing and expertise through the TEAMER program. Barriers include the complexity of regulatory institutions could produce a blocking mechanism in the TIS. Network and organizational ties to other marine sectors such as offshore wind and blue economy applications are also hampered due to the organizational structure and complexity of research, development, and funding mechanisms in the US. A more coordinated and less siloed effort between these structures could strengthen the TIS.

Figure 7: DOE WPTO Programs Related to Marine Energy



Government Actors

There are many government actors that interface with the marine energy sector at multiple scales from global to state and local entities (Figure 6), Due to this complexity, only the most prominent will be outlined here.

The International Energy Agency's Ocean Energy Systems (IEA-OES) program supports and coordinates research in the ocean energy sector globally. The US is one of 25 member states. At the national level, the US Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) includes the Water Power Technologies Office (WPTO), whose purpose is to support R&D and testing in both marine energy and hydropower. WPTO remains a major source of funding and direction for the sector.The WPTO also supports the IEA-OES program through its leadership on the PRIMRE knowledge portals and databases and the OES-Environmental program. Funding for research and development is also facilitated by the Department of Defense through the US Navy and Applied Physics Laboratory (APL) and the ARPA-E program through DOE.

The National Oceanic and Atmospheric Administration (NOAA) and its State-level SeaGrant extension services also support research into environmental and coastal impacts and benefits in the sector, including analysis required for the National Environmental Planning Act (NEPA). The Bureau of Ocean Energy Management (BOEM) regulates seabed leases whereas the Federal Energy Regulatory Commission (FERC) is responsible for licensing in state waters and on the Outer Continental Shelf (OCS). Authorization from US Army Corps of Engineers (COE) is also usually required and any structure placed in navigable waters must be authorized by COE.

Finally, the Department of Energy National Laboratories are important facilities for research and testing for the marine energy sector. They also serve as locations where industry interfaces with scientific expertise through the TEAMER program. The National Laboratories that are most heavily involved in marine energy research are:

- Pacific Northwest National Laboratory (PNNL), especially the Sequim, WA campus, which is developing open water test sites for marine energy and environmental instrumentation
- Sandia National Laboratory
- National Renewable Energy Laboratory

These laboratory facilities are a unique asset of the US marine energy sector, and are not replicated in most other countries.

Finally, there are many state-level incubators and initiatives that interface with marine energy in differing ways. Some examples include: The Port of Los Angeles' AltaSea, Washington Maritime Blue, the Coastal Studies Institute of North Carolina, and others.

All of these government actors, each with their own capabilities, fill niches and needs at different scales.

Industry Actors

The "marine energy industry" is often referred to as a monolithic entity, but in reality it is complex, diverse, and emerging. Many parts of the industry are not yet developed or are at various stages. Other parts of the supply chain are only beginning to be discussed now that parts of the sector are approaching commercialization. Five types of actors are discussed here, although others will be more or less present as the system matures: developers, suppliers, environmental monitoring consultants, marine logistics, and labor and workforce.

Developers are probably the most public-facing element of the marine energy industry. In terms of numbers of developers, it is difficult to make an exact count for two reasons: first, some developers may be "inactive" for a period while they await funding or permitting, and second, some developers are innovating in areas adjacent to marine energy, such as marine observation or AUVs, and may not be counted in databases. Regardless, the number of active marine energy firms at this time is small (10-20), although there may be far more entrepreneurs and researchers working on developing commercial technologies in the marine energy space. The small number of firms is concerning because a concentrated pressure on few firms can create a tentative workforce that could easily leave the sector if a firm does not survive. To strengthen this part of the innovation structure, more should be done to encourage entry into the sector and support developers across all stages of development. This will likely be an ongoing weakness until commercialization.

As the sector matures, the industry actors will need to further diversify and increase, engaging with more suppliers, marine logistics firms, labor and workforce. At this point, there is little formal coordination of this nexus, and most connections are made informally or on an as-needed basis. Organization of cross-sector industry actors could strengthen the TIS. One industry actor that has developed more fully are environmental monitoring consultants, partly due to the early work of OES-Environmental in characterizing environmental impacts. Several firms are heavily involved in the sector.

Organizational Actors

There are many organizations that interface with the marine energy sector, only a few major ones will be discussed here. The National Hydropower Association Marine Energy Council (NHA-MEC), a trade organization, is classified as an industry actor, yet its membership includes private sector companies, academia, and government partners. Its goal is to facilitate commercialization and promote the marine energy industry. There are also several programs that are supported by a mixture of non-profit and government funded grants, including the Pacific Ocean Energy Trust's (POET), and the WPTO-funded TEAMER and UMERC projects, which are administrated by POET. Other organizations such as INORE, the International Network on Offshore Renewable Energy are impactful in the US, providing opportunities for workforce development to students and early career individuals. Organizations and networks that cross marine sectors such as offshore wind and blue economy applications for marine energy are uncommon, and could strengthen the TIS.

Knowledge Actors

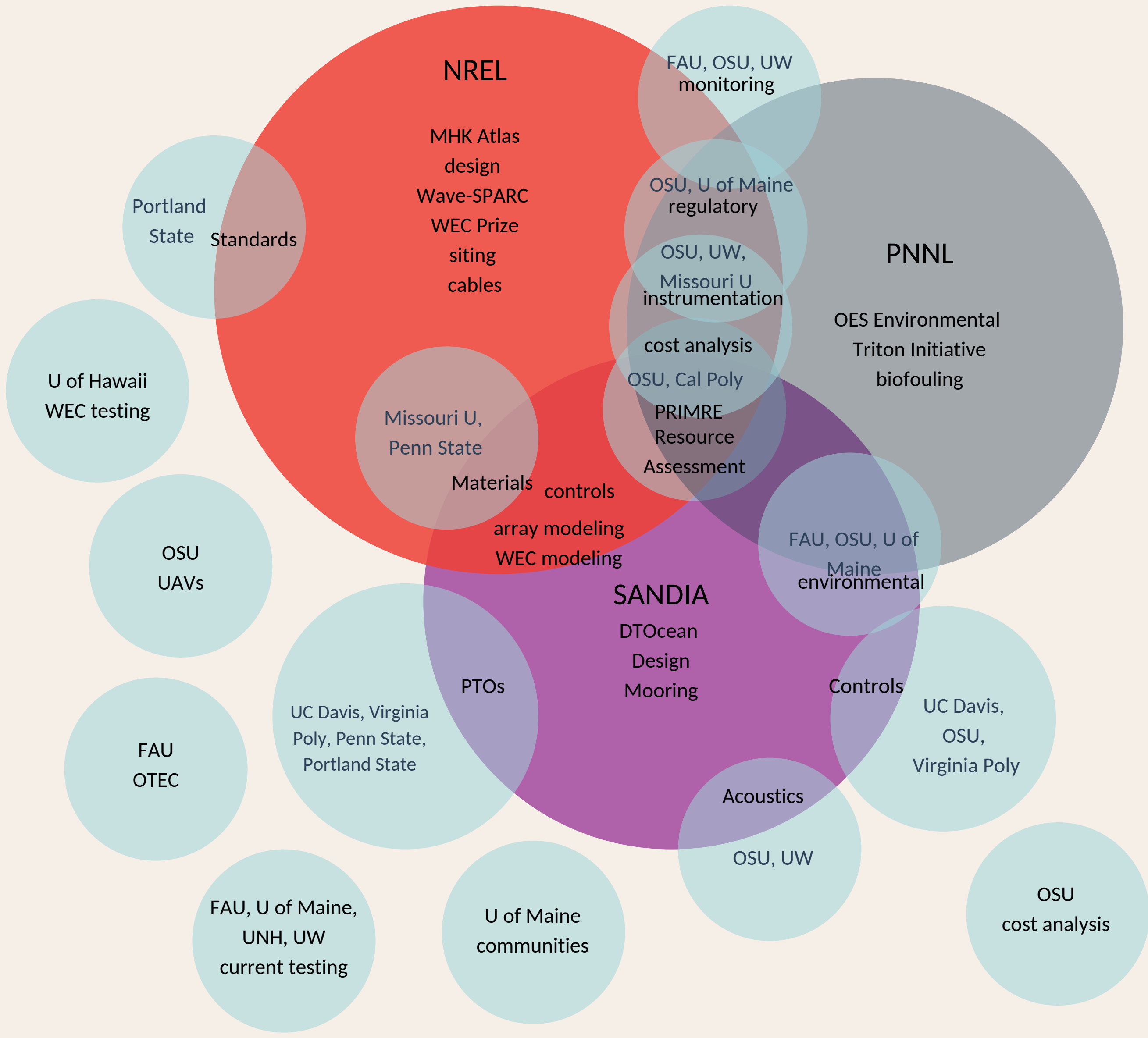
There are many state and private universities and colleges in the US that host researchers involved in marine energy, some of these are listed in Table 14 (p. 56). These knowledge actors are diverse in their capacities and the ways that they interact within the knowledge ecosystem. Universities range from hosting a single researcher who may become involved in a marine energy related project as a Principle Investigator (PI) or Co-PI on a single grant, to universities with single or multiple researchers that host marine energy labs and infrastructure, to universities that have long-term funding and organizations that are dedicated to marine energy research. Some of the collaborations between National Laboratories and universities are represented in Figure 8. Knowledge actors are also diverse in terms of the their resources, for example, some universities have little or no testing infrastructure, some have small or large lab facilities, and others have grid connected, open-ocean, or full-scale test sites. This means that their needs and capabilities vary vastly, and they should not be viewed as monolithic.

Some of these Universities are members of National Marine Energy Centers (NMECs). There are four NMECs across the US. Three were created in 2008 by the DOE WPTO to support marine energy R&D in the US: Pacific Marine Energy Center (PMEC), Hawai'i National Marine Renewable Energy Center (HINMREC), and Southeast National Marine Renewable Energy Center (SNMREC). A fourth center, the Atlantic Marine Energy Center (AMEC) was added in 2021. The University Marine Energy Research Community (UMERC) was also created by a DOE WPTO grant in 2021. UMERC serves to foster collaboration within the U.S. marine energy research community and amplify the impacts of foundational research.

Other universities host research centers that are integrally involved with marine energy research, such as the Applied Physics Laboratory at the University of Washington (APL-UW), the Alaska Center for Energy and Power (ACEP) or the Advanced Structures and Composites Center at the University of Maine. Finally, non-profit organizations, such as the Monterey Bay Aquarium Research Institute (MBARI) also contribute to knowledge production in the marine energy sector.

These knowledge actors are referred to throughout this report. The many individuals and the diverse organizations supporting knowledge creation in the marine energy sector in the US forms a robust and complex network, which is recognized for its leadership and expertise across the globe. However, knowledge and learning processes can vary greatly within and between a TIS (Malerba and Orsenigo, 1997). Opportunities to access knowledge can be more or less accessible or closed and opportunities to innovate can vary (Hekkert et al., 2011). Individuals and firms can now access knowledge through the WPTO's TEAMER program, which facilitates access to testing and expertise at universities or National Laboratories. Access to knowledge is also facilitated through the NMECs, which provide a gateway to research expertise and technical support for those looking to enter the field, either as a student, graduate student, or entrepreneur. Both TEAMER and the NMECs were often referred to as important facilitators of knowledge in the sector in surveys and interviews for this study.

Figure 8: Laboratories and Universities funded by WPTO 2015–2020 grouped by topic and identified by location of grant PI
(NOTE: does not include all collaborators or projects)



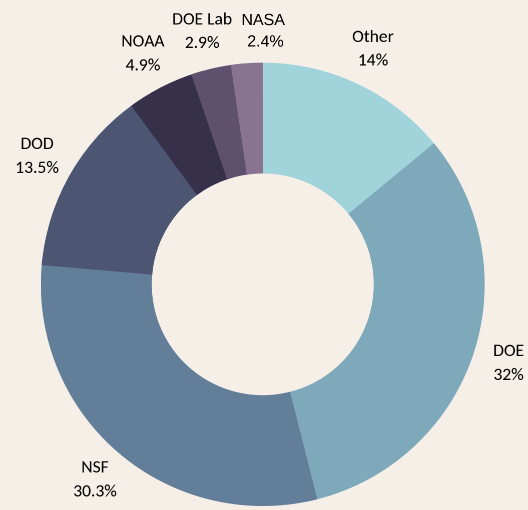
Institutions

Institutions include norms, laws, and regulations. They need to be purposefully aligned in order for a technology to commercialize (Bergek et al., 2008). If institutions are not aligned, firms can compete over the institutional arrangement, stifling innovation in the sector as a whole (Jacobsson and Lauber, 2006).

Energy and marine policy operates at multiple national and state levels in the US, creating a complex pathway for permitting. As discussed above, BOEM regulates seabed leases, FERC is responsible for licensing, inspecting, and overseeing hydrokinetic activities and has jurisdiction over hydrokinetic projects in state waters and on the Outer Continental Shelf (OCS), therefore projects on the OCS also require authorization from BOEM. Authorization from US Army Corps of Engineers (COE) is also usually required and any structure placed in navigable waters must be authorized by COE. But, depending on the location and the use, permitting agencies can also include National Marine Fisheries Service (NMFS), US Coast Guard (USCG), and many other tribal, state and local government authorities. To navigate these regulatory issues, the DOE has invested in the creation of an "MHK Regulatory Processes Handbook" (DOE WPTO, 2020), as well as a marine energy regulatory and reporting toolkit. These tools will assist developers and researchers in navigating the complex regulatory landscape, although very few permits have been issued to this date.

Innovation support policies are also complex, forming networks for funding R&D as well as loan programs to support early stage commercialization. Many of these funding support mechanisms are discussed throughout this report. A review of publications by funder in the figure below (Figure 9) demonstrates the diversity of funding for foundational research, although funding for demonstration and commercialization for later-stage TRLs would not be represented here.

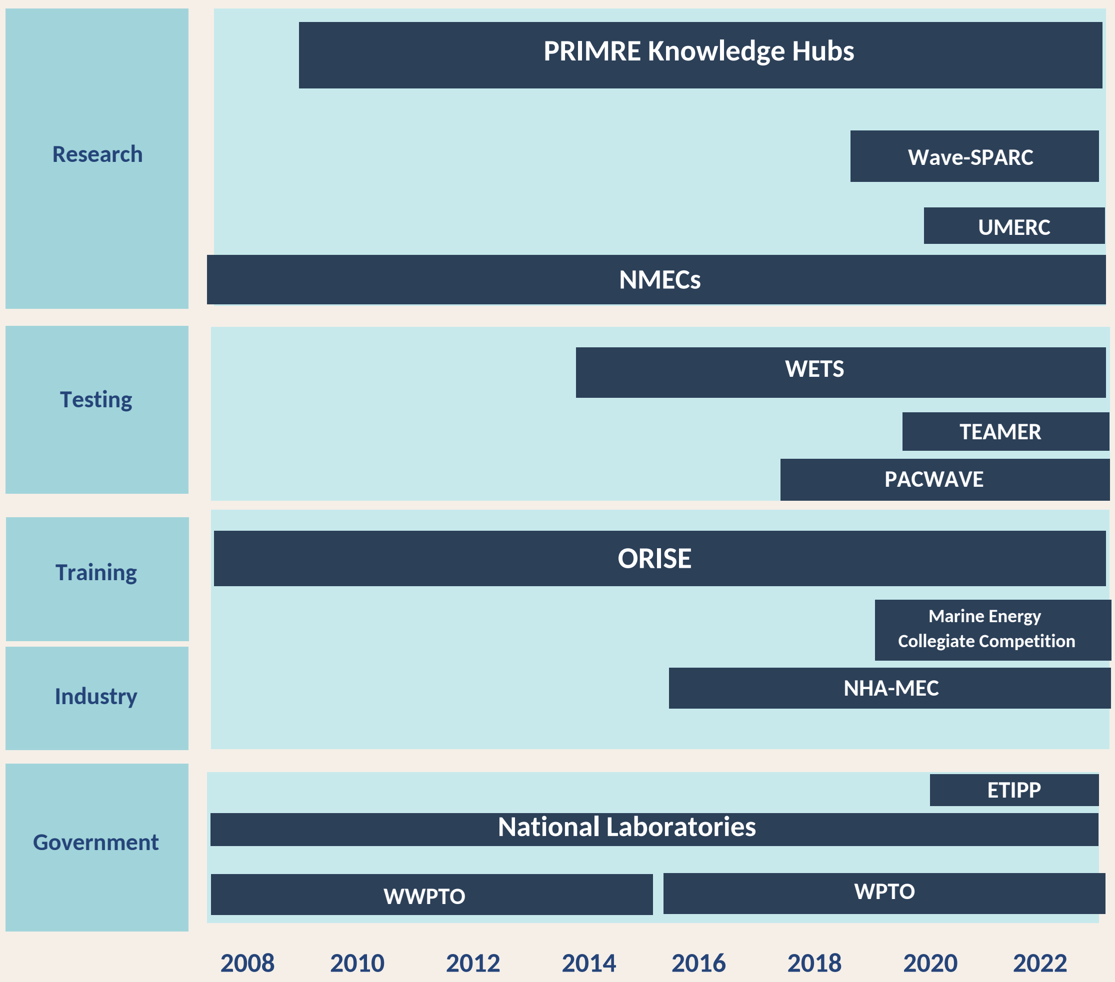
Figure 9: Percent Publications by Funder in US 2005-2022



Networks

Networks can be either formal or informal. They can be initiated to solve a problem, such as IEC TC-114, which was created to develop standards for marine energy, or they can occur organically such as university-industry links that might arise through the needs of a funding opportunity. Many of these formal networks are discussed throughout this report, and some are included in the organizations section above. A timeline of innovation networks that have been formalized by the DOE WPTO is illustrated below (Figure 10). However, it is important to recognize that even less formalized networks still contribute to innovation in the TIS. Some of these are recognized in the following chapter, in the network maps that show linkages between co-authors in research publications. Other informal networks will exist between alumni and co-workers, sometimes on an international scale.

Figure 10: Timeline of Innovation Networks and Programs



Infrastructure

The research and testing infrastructure that supports the marine energy sector in the US is in an evolving state. Major infrastructures for marine energy include the testing and laboratory capabilities at universities and laboratories across the US. Coordination of access to these infrastructures was supported in 2019, with the creation of the TEAMER program by the WPTO. Open-water testing infrastructure has been slow to come online, especially for grid-connected wave energy, with a permitting delay of almost a decade for the PacWave South test site, which is currently under construction. Infrastructure also includes software and modeling access and expertise, which have both been invested in by WPTO through the National Laboratories, including NREL and Sandia. Finally, infrastructures for monitoring and instrumentation are also critical, and are currently being facilitated by the Triton Initiative at the PNNL Laboratory facility in Sequim, WA.

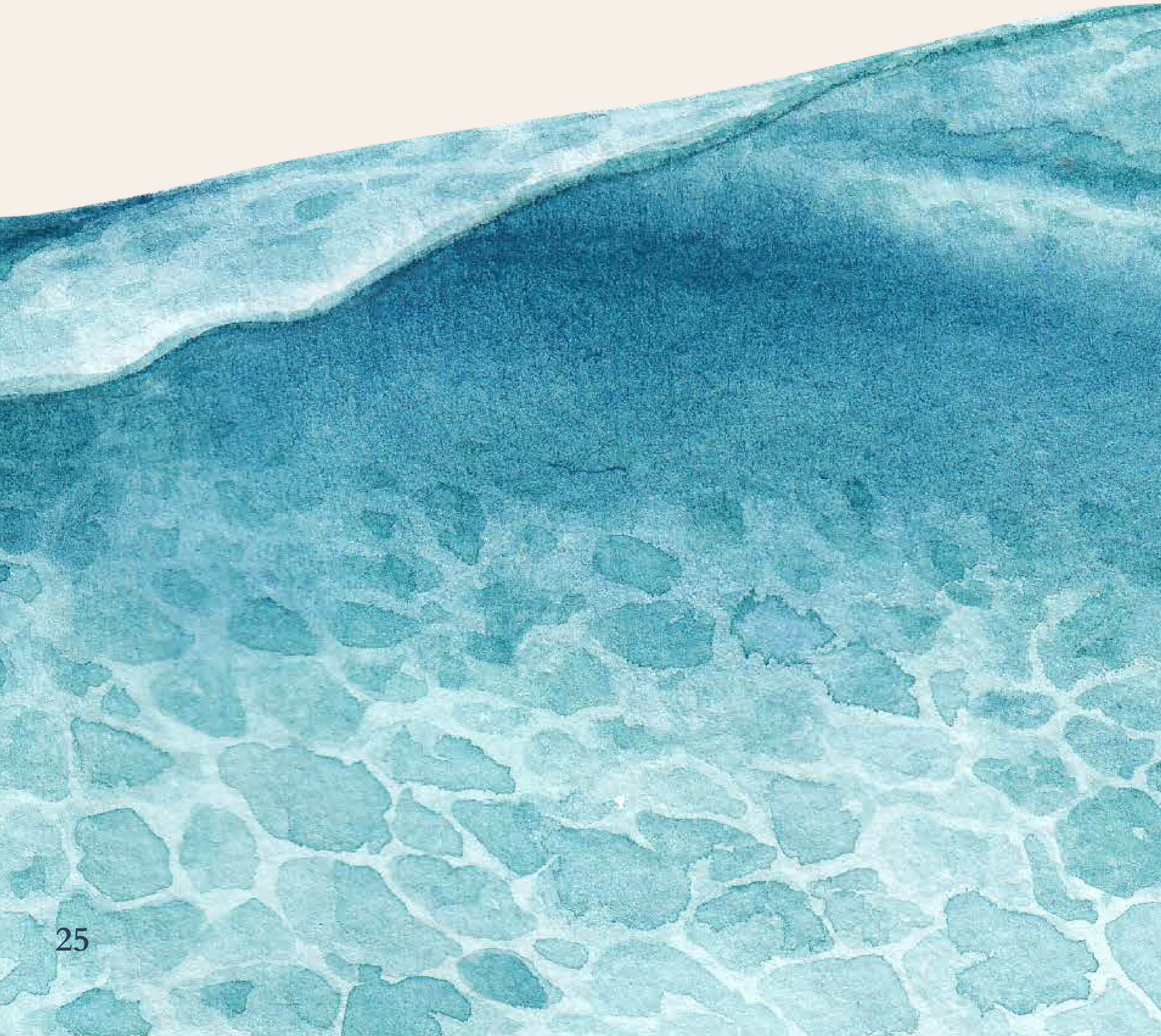
Table 4: Marine Energy Test Sites in the US

Name	Status	Permit Status	Resource
Igiugig	Active	Permit 2019	Riverine
Admiralty Inlet	Inactive	Permit 2014	Tidal
Cobscook Bay	Active	Permit 2012	Tidal
RITE	Active but Decommissioned	Permit 2012 Re-license 2019	Tidal
OPT Reedsport	Inactive	Permit 2012	Wave
PacWave North	Active	Environmental Assessment 2012	Wave
PacWave South	Active	Permit 2021	Wave
WETS	Active	Environmental Assessment 2014	Wave

From: Marine Energy Reporting Tool (Accessed 2022: https://marineenergy.app/)

05

Functionality of the U.S. Marine Energy Innovation System



05 Functionality of the US Marine Energy Innovation System

This section describes and analyzes the functional health of the marine energy innovation system. This requires examining seven key processes, or functions, which have been used by TIS analysts to assess the functionality of innovation in a given sector (Bergek et al., 2008). Each function is outlined below, and appropriate qualitative and quantitative indicators and available data are described in each subsection. The functions are then qualitatively assessed on a scale of 0-5, using a series of standard questions. These questions, based on Hekkert et al. (2011), are highlighted at the beginning of each section.

TIS Functional Analysis

The TIS Functional Analysis examines the "functional pattern" of an innovation system. Innovation systems can either enable or constrain technological change, and the dynamics of these systems are just as important as the structure of the systems (Hekkert et a., 2007). Because processes can be more difficult to assess than structures, the TIS "functional analysis" was developed to help researchers systematically assess the processes taking place within an innovation system. In order to do this, researchers have developed seven functions, outlined below in Table 5 (Hekkert et al., 2007).

Table 5: Description of TIS Functions adapted from: Hannon et al. (2017) and Hekkert et al. (2007)

F1 Knowledge Development	Creation of technological variety by broadening and deepening knowledge through R &D.
F2 Knowledge Exchange	Exchange of information between actors facilitated by networks.
F3 Entrepreneurial Experimentation	Reduction of uncertainty by commercial experimentation, either through success or failure.
F4 Guidance of the Search	Appropriate pressure and incentives for actors to undertake innovation activities, such as targets and roadmaps.
F5 Resource Mobilization	Input of financial, human, and physical resources to support the system.
F6 Market Formation	Support for the creation of niche markets to help incumbent technologies compete.
F7 Legitimation	Support from existing institutions enabling competitiveness within the existing regime.

Overview of Functional Analysis

The analysis below is an overview of the results based on the data that is detailed in the remainder of this chapter.

F1 Knowledge Development

Knowledge development within the marine energy TIS in the US is robust. The amount and quality of knowledge is high, with overall increasing publications and citations by researchers across the US. The level and complexity of the research networks are also strong, with many collaborations and connections across institutions both nationally and internationally. Despite the strength in US publication and citation, the amount of research being published in China results in a falling share of US research globally. Patents follow a similar pattern, although they have leveled off, with the US patenting much less than China and South Korea. Overall, the quality and quantity of knowledge development could be more globally competitive, but it does not form a barrier to the TIS moving to the next phase of innovation.

F2 Knowledge Exchange

Functionality of knowledge exchange between research institutions and industry is fairly strong in the US marine energy sector. This can be seen in the complexity of the networks, the high number of international co-authorships, and the strength of US research institutions and collaborations across the field. In addition to being an important factor in the survey data, university-industry research collaborations and university spin-off companies were consistently cited in interviews as being strengthened by existing networks, including NMECs. In assessing the amount and consistency of knowledge exchange across the US and internationally, the network appears complex and dynamic. However, the number of researchers who serve as "boundary-crossers" between different fields and institutions is small, and could become a weak point, if they were to leave the sector.

F3 Entrepreneurial Experimentation

The marine energy sector in the US is largely in the pre-commercialization stage. While the actors present within the sector are engaged in experimentation, these firms are very small and volatile, with many of the early firms moving overseas or ceasing operations. This includes some that have been fairly far along in their commercialization efforts. While the sector is diversifying its focus in terms of application and scale, the small size of the sector and the high risk and capital involved in commercialization has made it difficult for some existing entrepreneurs to experiment, and for new ones to remain in the sector.

Overview of Functional Analysis

F4 Guidance of the Search

Unlike many countries, the US sector does not have clear strategies, roadmaps, or targets set for marine energy at any government level. This means that individuals and groups have developed their own visions and expectations in terms of how and when technologies will innovate. Because of this lack of cohesive vision, the perspectives vary, and are not necessarily reflective of the actual stage of technology development. This lack of shared vision and guidance could hamper the development of the marine energy TIS in the US. On the other hand, the diversification of applications for marine energy has created new opportunities and value propositions.

F5 Resource Mobilization

Physical resources including testing and infrastructure are becoming increasingly thorough and accessible in the US. Financial resources, however, are more difficult to assess. Although there is clearly funding being applied and spent on marine energy R&D, the amounts are not transparent or consistent. Many people do cite a need for more funding to conduct research, especially to support graduate student research and training, as well as to see projects through commercialization. Human resources are insufficient to support a growing sector, with many people worried about lack of trained engineers for their workforce. This problem may, in turn, be exacerbated by the lack of programs and resources to train emerging professionals.

F6 Market Formation

Market formation is a difficult function to measure in a sector that is not yet commercialized. Markets are shifting within the marine energy sector in the US, as new, high-value applications are extending the market to provide power at sea and to remote communities. However, looking at the given indicators, the market formation for marine energy in the US is not mature. The number of US marine energy firms is low, as is installed capacity. Although there are many technologies in development, the low number of marine energy firms puts the sector in a tentative situation, and the market size could form a barrier to the development of the innovation system if it is not strengthened.

Overview of Functional Analysis

F7 Legitimation

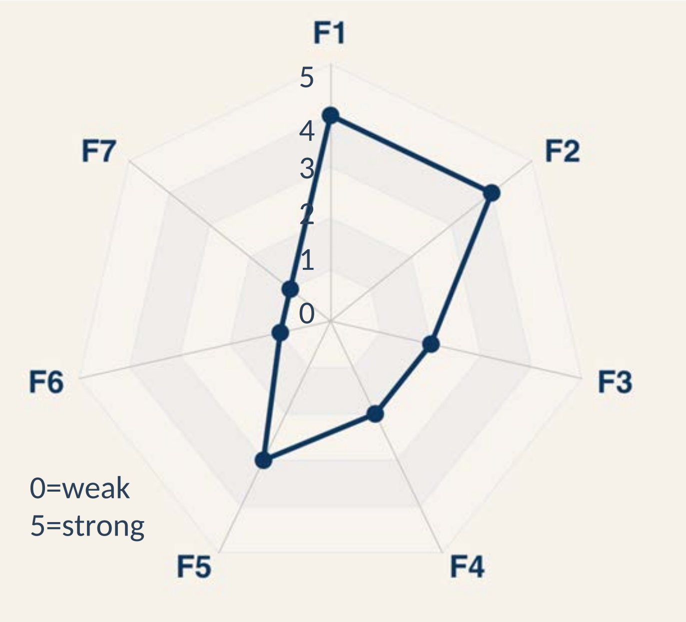
Although public support for marine energy is potentially high, legitimation of the sector is a potential barrier to innovation. This is due to the highly complex regulatory process, the small number of permitted projects, the lack of coordinated support for commercialization of the sector, and the small number of government policies and reports that explicitly incorporate marine energy into their programs and strategies. Programs such as Wave-SPARC, and IEC TC-114 which aim to provide validation and verification for technologies will help legitimize early-mid stage R&D with standards.

Figure 11: Functional Analysis of Marine Energy in the US

Functional Analysis of Marine Energy in the US

Functions of an Innovation Ecosystem

F1 Knowledge Development
F2 Knowledge Exhange
F3 Entrepreneurial Experimentation
F4 Guidance of the Search
F5 Resource Mobilization
F6 Market Formation
F7 Legitimation



F1 Knowledge Development

- **Is the amount and quality of knowledge development sufficient for the development of the innovation system?**
- **Does the type of knowledge developed align with the knowledge needs within the innovation system?**
- **Does the quality and quantity of knowledge development form a barrier for the TIS to move to the next phase?**
- **Amount of patents and publications (from structural analysis)**

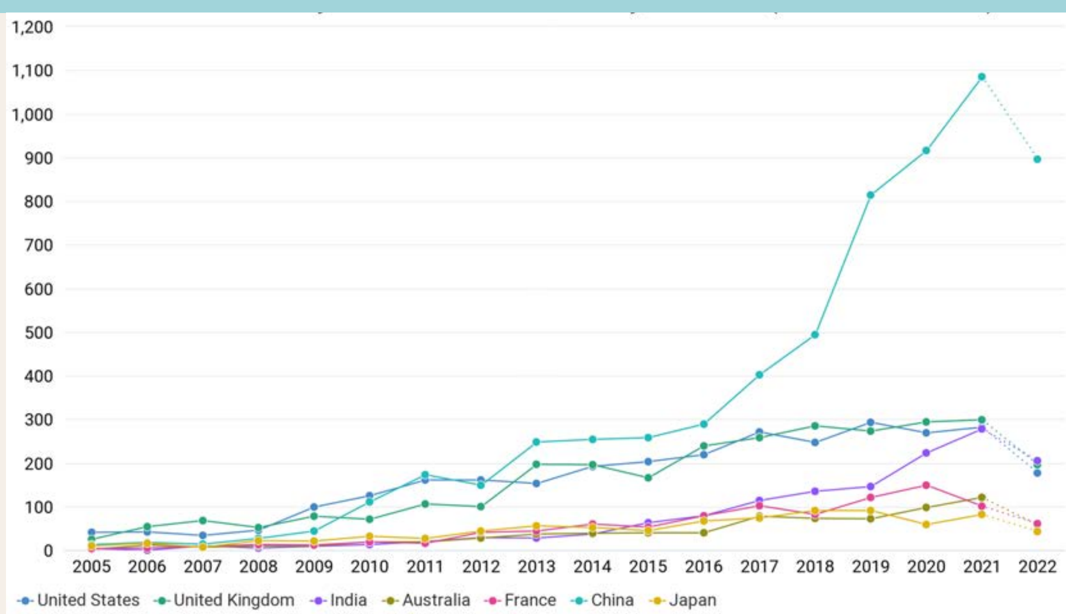
Table 6: F1: Knowledge Development Quantitative Indicators 2005–2021

Sub-theme	Indicator	Total	Latest Year	Overall Trend	Change Between 1st and 2nd Half Period	Change on Last Year versus Mean	Data Source
Early TRL	Number of US ME publications	2830	278	↗	+158%	+28%	Dimensions AI
Early TRL	US Share of Global ME publications	--	8%	↘	-11%	-18%	Dimensions AI
Early TRL	Number of US ME publication citations	55349	11132	↗	+787%	+161%	Dimensions AI
Early TRL	US Share of global ME publication citations	--	15%	↘	-11%	-18%	Dimensions AI
Mid TRL	Number of US ME patents	3313	261	↗	+90%	+2%	Dimensions AI
Mid TRL	US Share of global ME patents	--	6%	↘	-3%	-8%	Dimensions AI

F1 Knowledge Development

One of the most readily available and trackable indicators for the quantity of knowledge development in early TRL stages is the **number of scientific publications**. Although falling well below the number of publications being produced by China, the US is nevertheless a leader in quantity of publications in the sector, roughly aligning with publication amounts from the UK and India (Figure 12). While the number of publications has continued to increase, the US share in global publications is decreasing, in part due to the number of publications being released from China. The **number of citations** of US publications follows a similar pattern, although the increase in citation has been more dramatic, with +787% increase in the second half over the first half of the period (2005-2021) (Figure 13). In the same period, the overall share of global citations for US authors declined.

Figure 12: Publications Each Year for Selected Countries 2005-2022



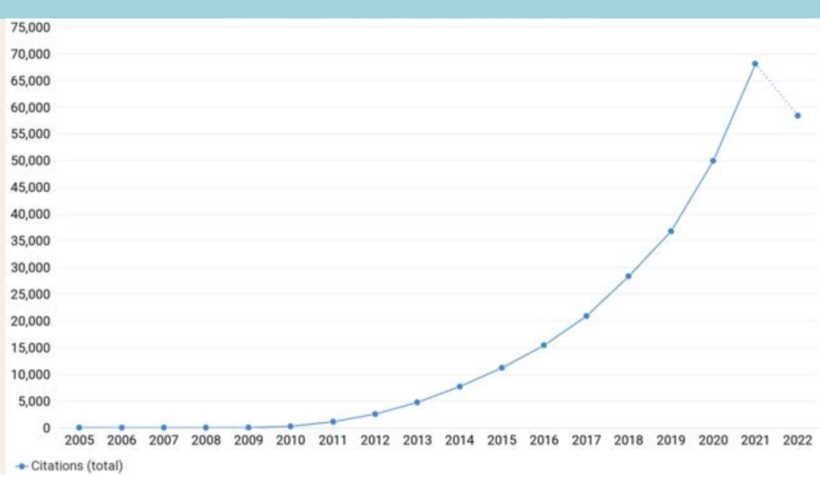
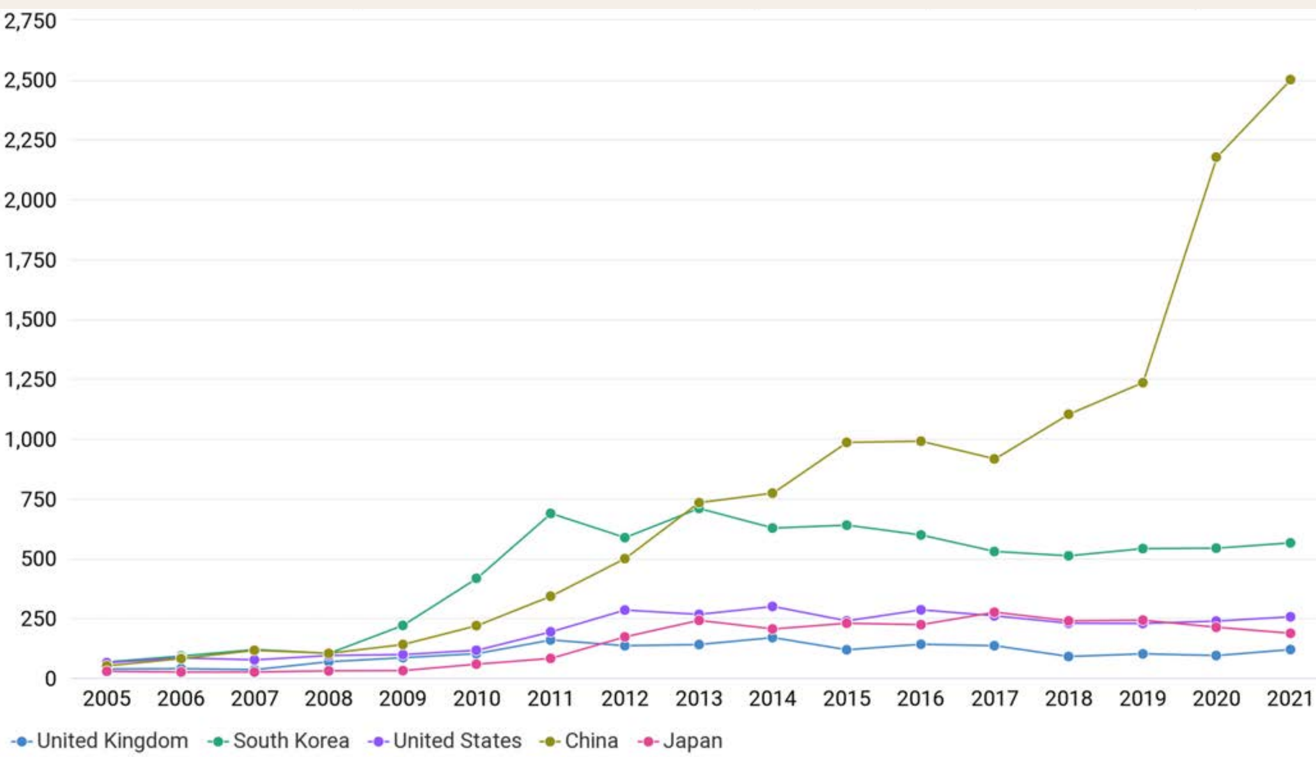


Figure 13: Citations each year for marine energy publications globally 2005-2022

F1 Knowledge Development

Mid-TRL stage knowledge development can be understood by analyzing the **quantity and quality of patents**. US patents related to marine energy technologies have remained fairly steady, with a slight increase in the second half of the period (2005-2021) (Figure 14). After a surge in patenting in China and South Korea around 2009, the US share of global patents has dropped and continues to do so. While patents can be a good proxy for mid-scale TRLs, it important to recognize that levels of patenting will change over time, especially as a technology matures. This means that increased numbers of patents do not necessarily equate with a healthier TIS (Hannon et al., 2017). With this in mind, the patenting levels do still appear to show continued, steady innovation in the marine energy sector in the US.

Figure 14: Marine energy-related Patents each year for top five countries 2005-2021



F2 Knowledge Exchange

- **Is there enough knowledge exchange between science and industry?**
- **Is there enough knowledge exchange between users and industry?**
- **Is there sufficient knowledge exchange across geographical borders?**
- **Are there problematic parts of the innovation system in terms of knowledge exchange?**
- **Is knowledge exchange forming a barrier for the TIS to move to the next phase?**
- **Type and amount of networks.**

Table 7: F2: Knowledge Exchange Quantitative Indicators: 2005–2021

Sub-theme	Indicator	Total	Latest Year	Overall Trend	Change Between 1st and 2nd Half Period	Change on Last Year versus Mean	Data Source
International	Number of US with international co-authors	1411	200	↗	+340%	+84%	Dimensions AI
International	Share of US ME publications with international co-authors	--	72%	↗	+23%	+14%	Dimensions AI
International	Number of US patents with international co-authors	1031	15	→	+56%	-11%	Dimensions AI
International	Share of US ME patents with international co-authors	--	+6%	→	-1%	5%	Dimensions AI
International	Number of non-US ME R&D project partners*	669	134	↗	+56%	-11%	Dimensions AI
International	Share of global projects with US-international collaborations*	--	48%	↗	+18%	+24%	Dimensions AI

*Using Nationality of Publication Funders as Proxy for Project Partners

F2: Knowledge Exchange

While knowledge exchange is difficult to measure quantitatively, metrics and data to measure international collaborations are nevertheless available. For example, we find that the **number of publications with international co-authors** has risen sharply over the past two decades. When comparing the first half of the period to the second half of the period (2005-2021), international co-authorships have increased 340%. The ***share* of US marine energy publications with international co-authors** (vs. without) has also risen, although less dramatically. Meanwhile, international collaboration on patents tell a different story, with the **number and share of patents with international co-authors** holding fairly steady overall. This is unsurprising as patents are more often local to one research institution or firm in a single country, and the small numbers of international patents make this statistic fairly insignificant. The **number and share of international project partners** on a given project is more significant, however, and is steadily increasing year over year.

Table 8: F2: Knowledge Exchange Qualitative Indicators

Sub-theme	Indicator	Data Source
International	Functionality of international research networks	Dimensions AI
Cross-fertilization	Functionality of researcher networks	Dimensions AI
Cross-fertilization	Number of US ME R&D Partners from other sectors	Dimensions AI
Cross-fertilization	Frequency of Interaction across industry-university-government-non-profit divides	UMERC Survey 2022
Industry-Science	Number of joint industry-university projects	UMERC Survey 2022/PRIMRE
Industry-Science	Number of marine energy university start-ups	UMERC Survey 2022/PRIMRE
Industry-Science	Perceived access to expertise	UMERC Survey 2022/Interviews

F2: Knowledge Exchange

While the quantitative measures above are a good way to track increases or decreases in knowledge exchange, the **functionality of international research networks** can also be understood through network maps like the one below (Figure 15). This figure shows a complex web of interactions between several major nodes of research, including the US.

When examining a network map of **international networks** based only on US-authored publications (as opposed to all marine energy publications), our perspective changes, as can be seen on the following page (Figure 16). Here we can see very strong ties between authors in the US and China and the US and UK. We can also see a diversity of countries whose co-authors are often connected to other, regional, co-authors. Again, while quantitatively analyzing this kind of network map is not possible, the networks both below and on the previous page express qualities of a complex and robust international collaboration network, with the US claiming a significant role in global research.

Figure 15: International collaboration based on number of co-authored publications 2010–2022 (top 25 countries)

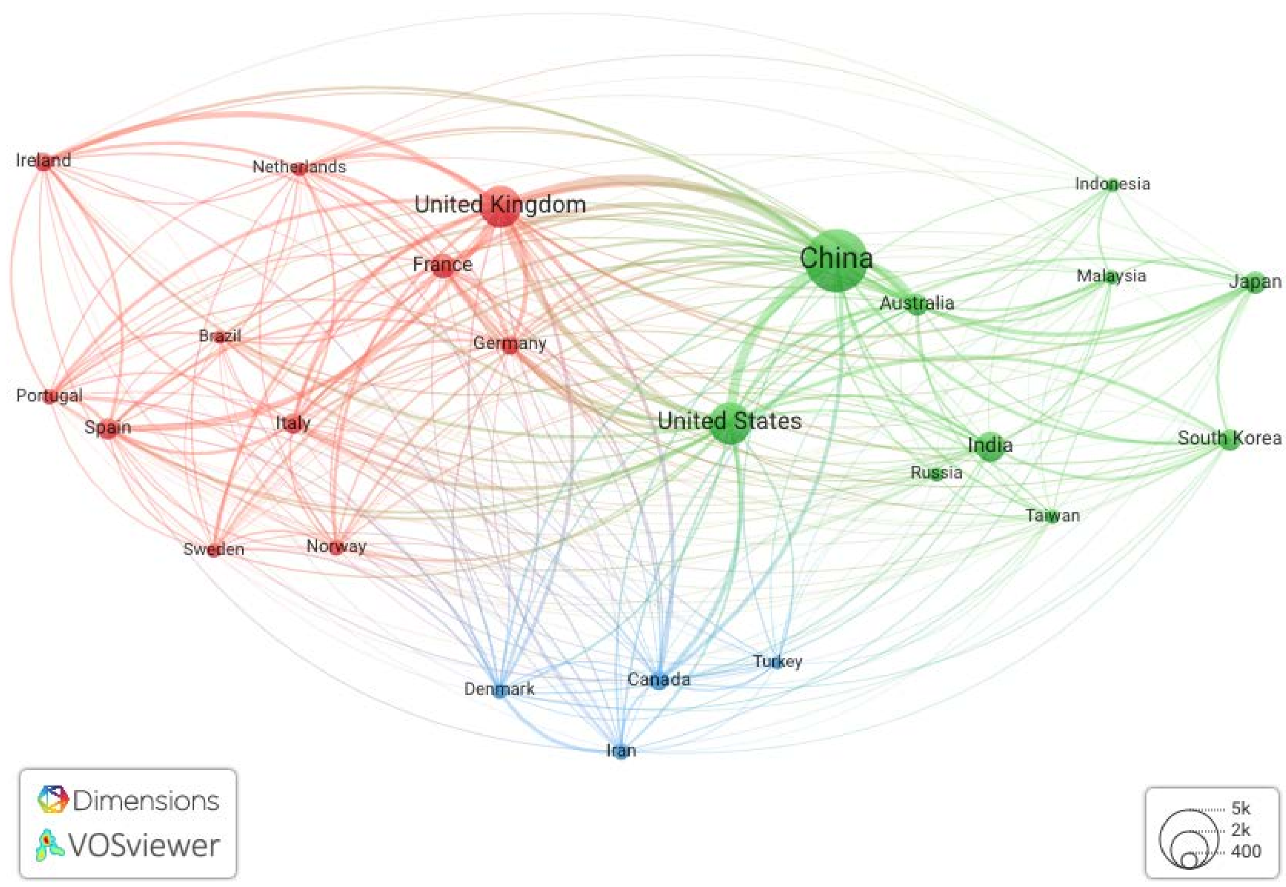
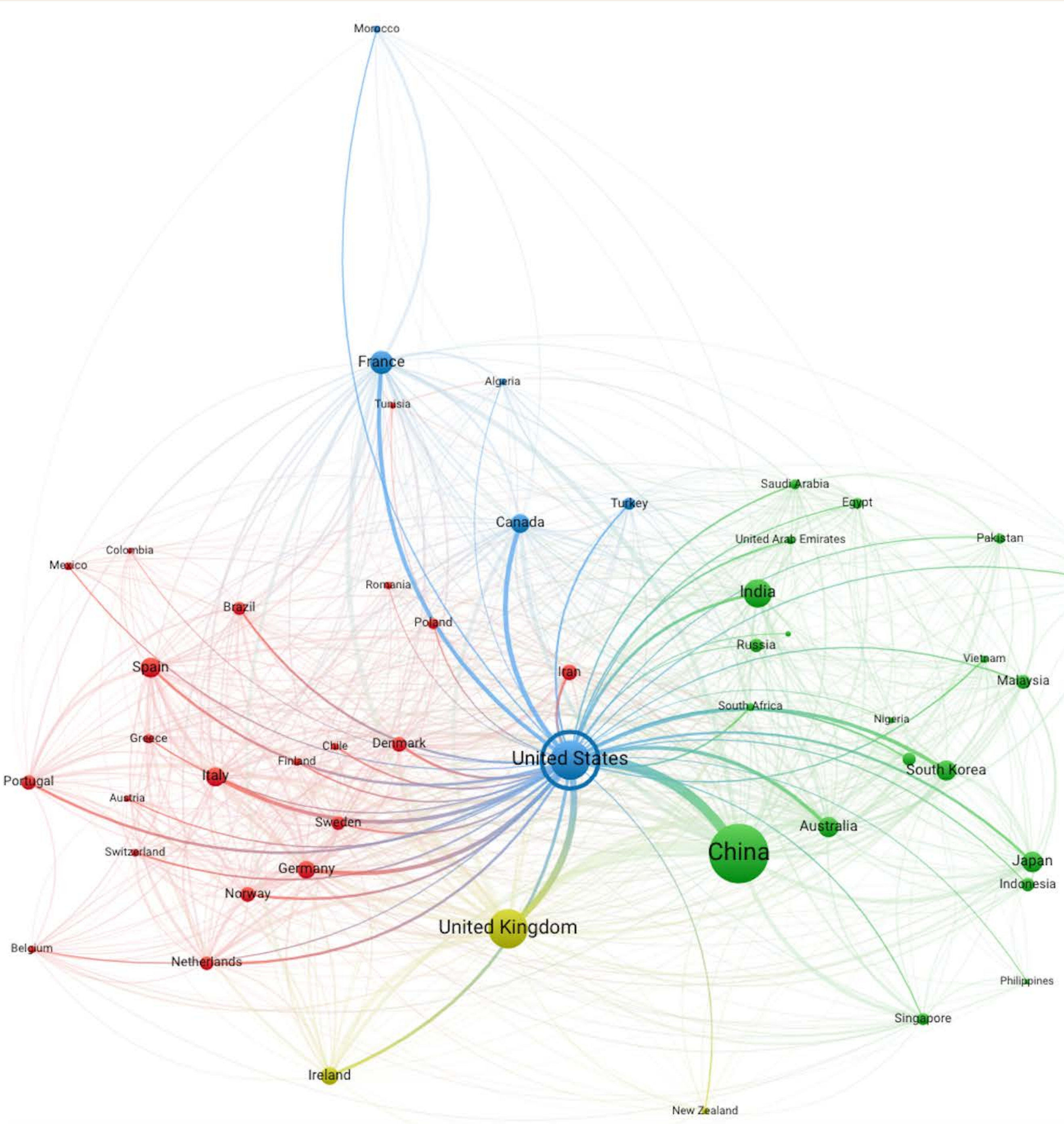


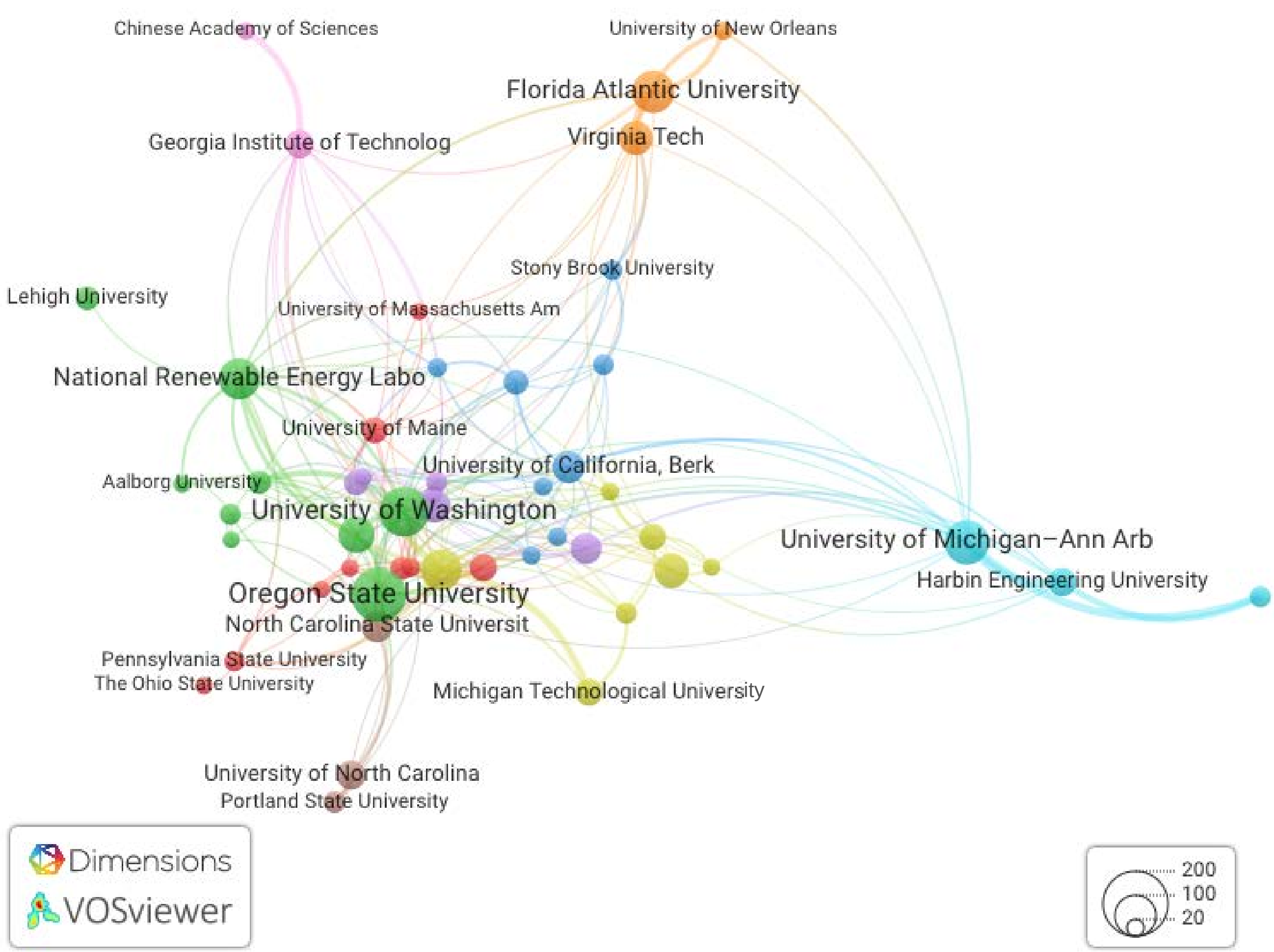
Figure 16: International collaboration based on number of US authors co-publishing with international authors 2005-2022



F2 Knowledge Exchange

The number of citations can be used as an imperfect proxy for publication quality. The number of citations continues to rise, suggesting continued quality of US knowledge production in marine energy, with the caveat that publication citation has also been increasing globally as a general trend in most fields of research. A qualitative assessment of the **co-authorship links between research institutions** shows robust linkages between key institutions in marine energy research, particularly those associated with the National Marine Energy Centers (NMECs), but also well beyond domestic research to international institutions. Although this indicator cannot be measured in quantitive terms, the figure below (Figure XX) demonstrates a complex innovation network that is indicative of a robust and complex innovation ecosystem.

Figure 17: Co-Authorship Links between top 50 Research Institutions (US Publications)



F2 Knowledge Exchange

The following two network maps (Figure 18 and 19) illustrate detailed **networks** of US researchers. Relatedness of researchers is determined based on their number of co-authored publications and is expressed by the thickness of the connecting line. The size of each circle corresponds to number of co-authored publications. This network map demonstrates a very complex, robust, and interconnected network of marine energy researchers in the US. by studying the map, we can see that there are several main research groups, with collaborating connections between them. Further, some individuals serve as "boundary crossers" that integrate different fields of knowledge. The second of the two maps overlays general topics, and further illustrates these "boundary crossing" dynamics.

Figure 18: US Marine Energy Researcher Networks

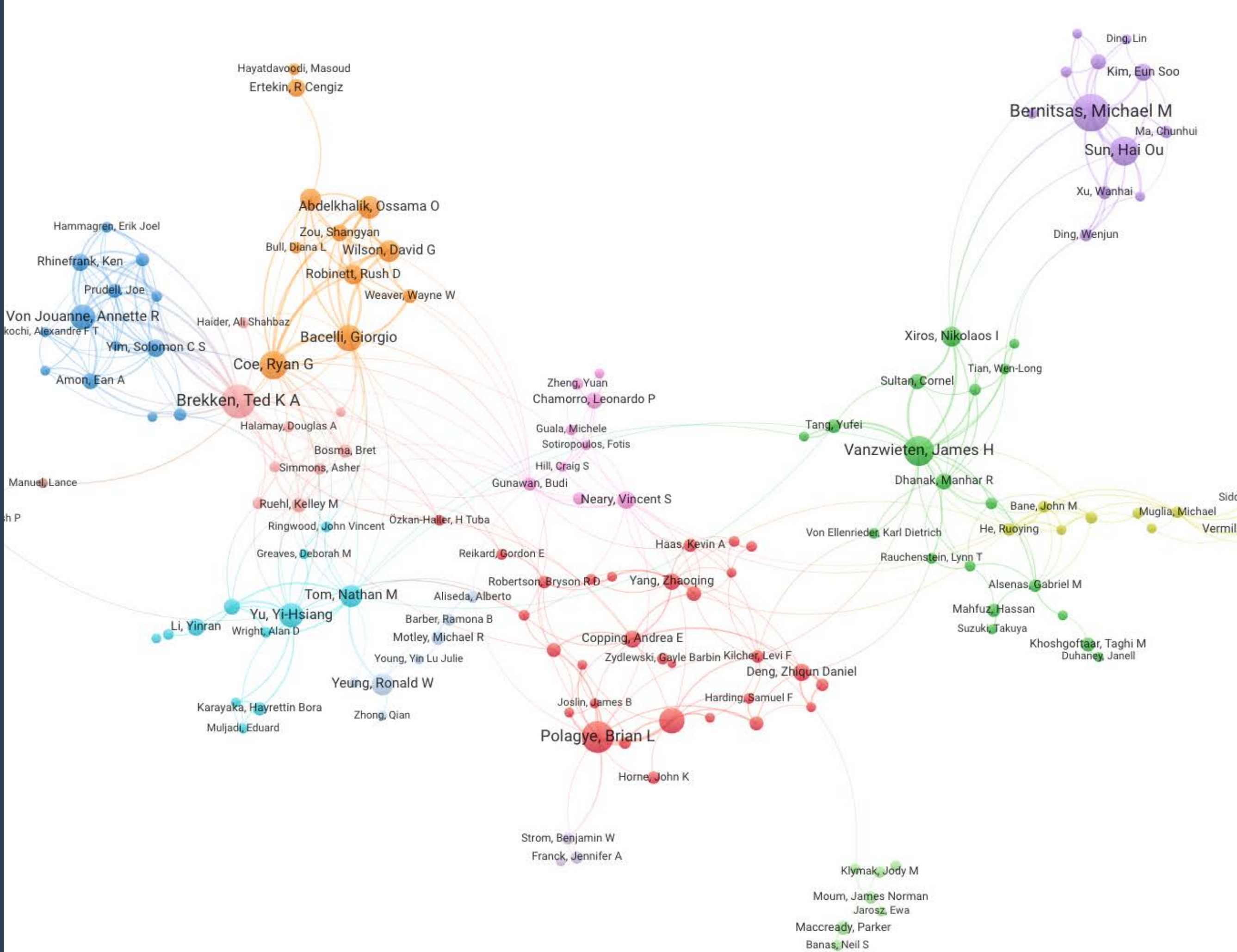
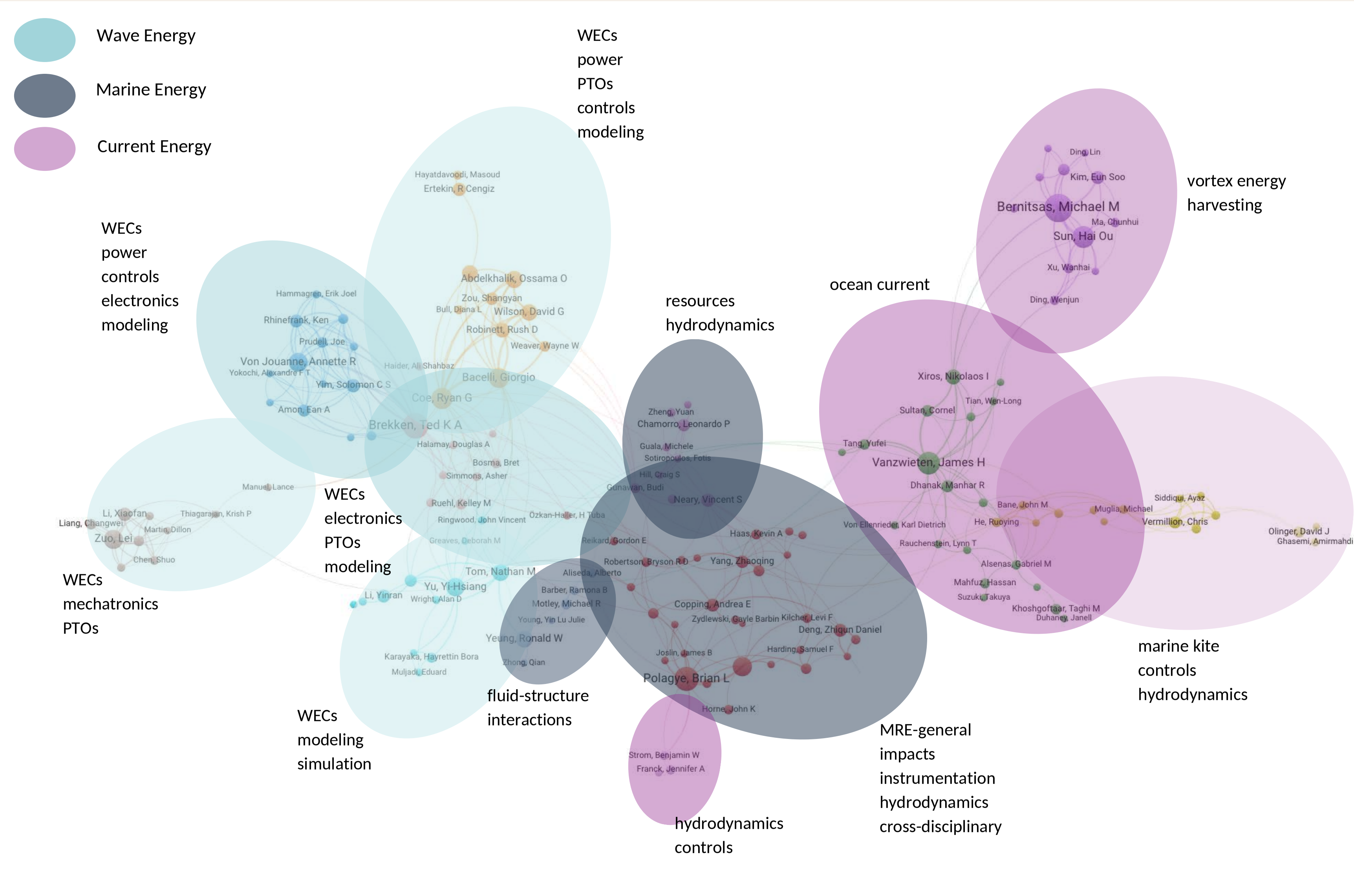


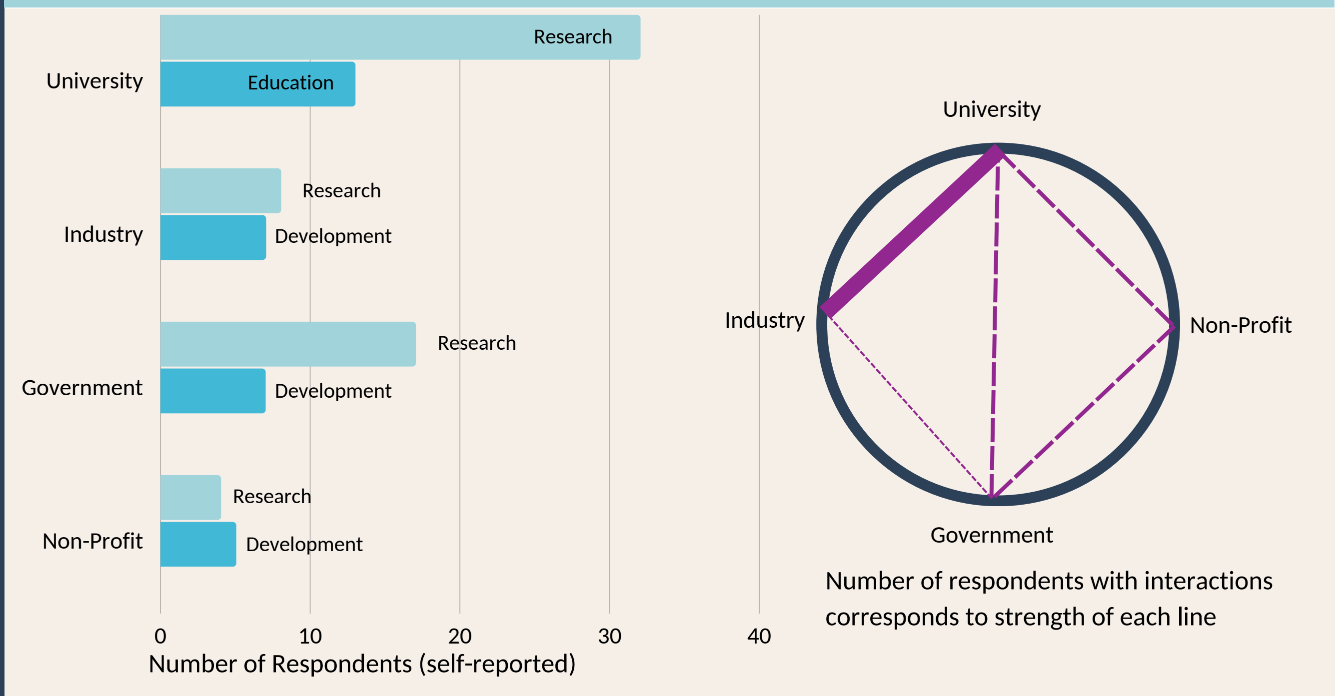
Figure 19: Map of general research topics on network. Colors correspond to general topics.



F2 Knowledge Exchange

We can analyze the **cross-fertilization between researcher networks, sectors, and interaction across industry-university-government-nonprofit divides,** also known as the "quadruple helix" mode of innovation. While the sample size below (Figure 20) is small (n=50), it represents a snap-shot of the knowledge exchange activities in the marine energy sector. When combined with the other measures, this snap-shot aligns with a more general picture whereby university and industry actors often partner on grants and projects.

Figure 20: Number of Actors and Interactions Across Quadruple Helix (based on survey)



During interviews, many people emphasized the important connections between industry and academia, but also highlighted several problems. Many academic researchers felt that it was often difficult to collaborate because of the need to fund student research over the course of 2-4 year projects, which was often too long for industry timeframes. However, the research community was generally excited about collaborations with industry, and welcomed the experience it provided for students. Most academic researchers stated that they were often approached by industry to collaborate on funding opportunities, which they welcomed. Both developers and academics also enjoyed the long-term partnerships they had developed, often through working closely with a particular institution. From a developer perspective, academic researchers were a useful source of expertise and laboratory facilities, as well as workforce training.

F2 Knowledge Exchange

Interaction across sectors and projects can also be interpolated by examining data on research categories, including data on grants and publications. The figures below (21 and 22) illustrate a significant increase in both publications and grants coming from engineering fields. This is in contrast to other research fields, such as earth and environmental sciences. This could indicate a maturing TIS, as fundamental science around resource characterization shifts to fundamental and applied engineering challenges, but it could also be interpreted as a symptom of a low-TRL sector without mature technologies. Thus, it is difficult to draw positive or negative interpretations from this data.

Figure 21: Publications each year for top 5 research categories (US publications) (2005-2022)

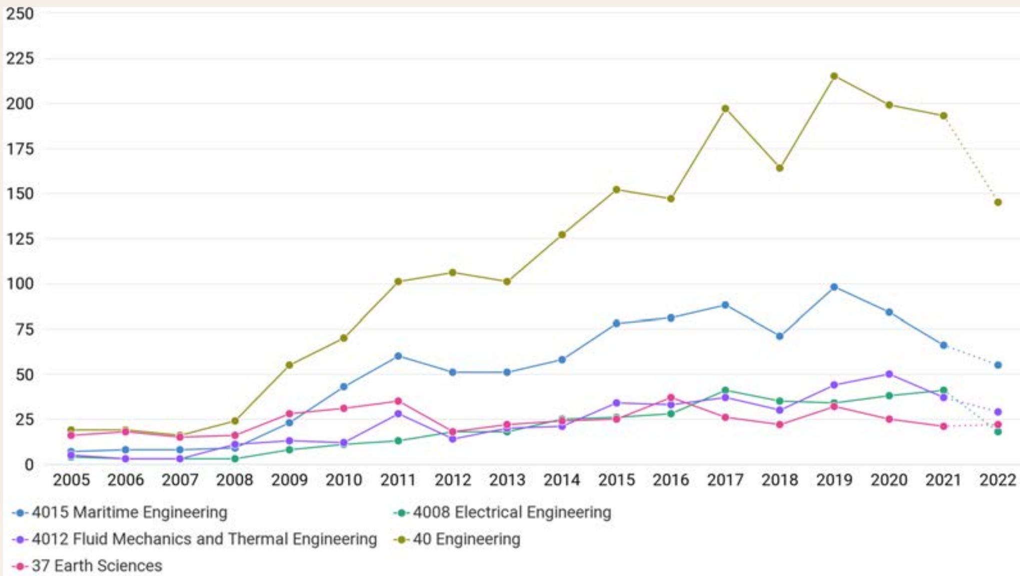
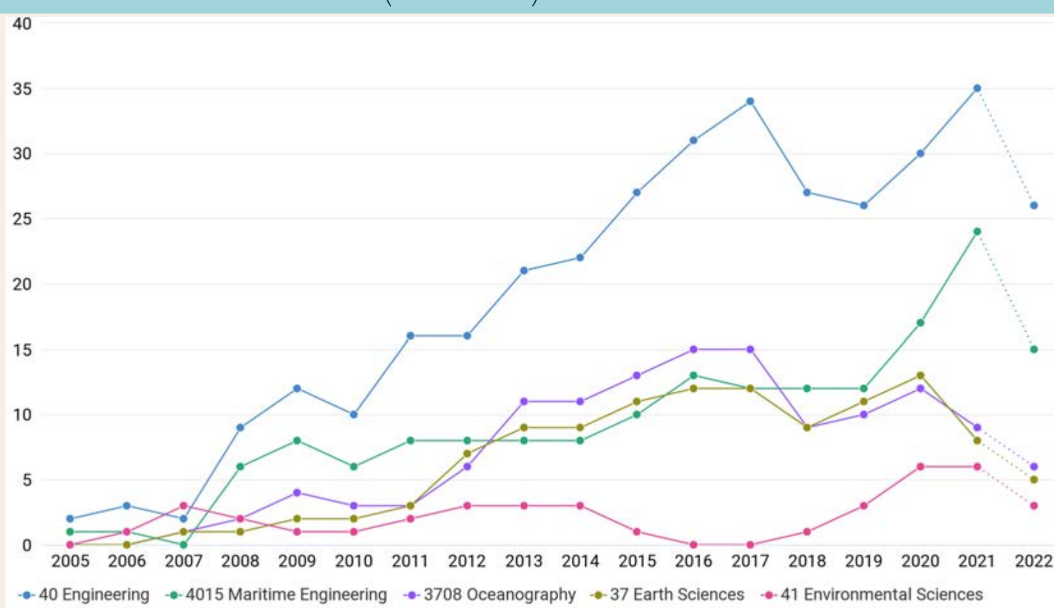


Figure 22: Active marine energy grants each year according to top 5 research categories (US funders) 2005-2022



F2 Knowledge Exchange

Cross-sectoral fertilization and interaction across the university-industry divide can also be qualified by looking at the **number and success of spin-off companies**. The table below (Table 9) highlights some of the companies created through university spin-offs, or who continue to maintain strong ties to the university research community. While not comprehensive, this list includes some of the most visible marine energy development companies in the US (and globally), representing strong and direct ties between industry and university R&D in the marine energy sector. During interviews, many people cited university spin-off companies as an inspiration for their work, and were encouraged by new spin-offs who are emerging.

Table 9: Marine energy-related University Spin-Off Companies

Name	Estab-lished	Status	University	Area
MarineSitu	2019	Active	University of Washington	Environmental Monitoring
CalWave	2014	Active	University of California-Berkeley	Wave Energy Converter
C-Power	2005	Active	Oregon State University	Wave Energy Converter
Ocean Motion	2018	Active	University of California-SanDiego	Wave Energy Observation Buoy
Water Bros Desal	2019	Active	University of North Carolina-Charlotte	Wave Energy Desalination
Oscilla	2009	Active	University of Edinburgh	Wave Energy Converter
Aquaharmonics	2015	Active	Oregon State University	Wave Energy Converter

F3 Entrepreneurial Experimentation

- **Are these the most relevant actors?**
- **Are there sufficient industrial actors in the innovation system?**
- **Do the industrial actors innovate sufficiently?**
- **Do the industrial actors focus on large scale production?**
- **Does the experimentation and production by entrepreneurs form a barrier for the TIS to move to the next phase?**
- **Actors present in industry (from structural analysis).**

Levels of Entrepreneurial Experimentation are difficult to assess in an emerging sector. For example, some aspects of innovation can be stifled by premature convergence around a single technology design, yet technological convergence is often used as a measure for a maturing technology. Despite this, we can measure the level to which developers are supported to take on risks in experimentation to move the technology forward by looking at technological and sectoral maturity as a proxy for the health of F3: Entrepreneurial Experimentation. This comes with the caveat that some common metrics of success that have been used in other technology and energy sectors may not be helpful when used in a marine energy context. This can be true for metrics like Levelized Cost of Energy (LCOE) or rated capacity, which are premised on the idea that marine energy's main impact will be grid-scale energy supply, in which case "bigger is better." However, many marine energy technologies are being developed for applications that are not aimed at supplying energy to the grid, but instead to niches that may not have access to a grid at all and are not striving to be competitive within an energy market. This makes comparisons of LCOE and capacity less useful when measuring the health of this sector. Nevertheless, these metrics are still provided here because they are commonly used in energy technology systems analysis.

Table 10: F3: Entrepreneurial Experimentation Indicators

Sub-theme	Indicator	Data Source
Sector Maturity	Length of time individuals involved in ME sector	UMERC Survey 2022
Sector Maturity	Average size of firm	PRIMRE
Technological Maturity	Rated Capacity of Technologies in Development	PRIMRE/Desk Research
Technological Maturity	Marine energy levelized cost of electricity	IRENA/Desk Research

F3 Entrepreneurial Experimentation

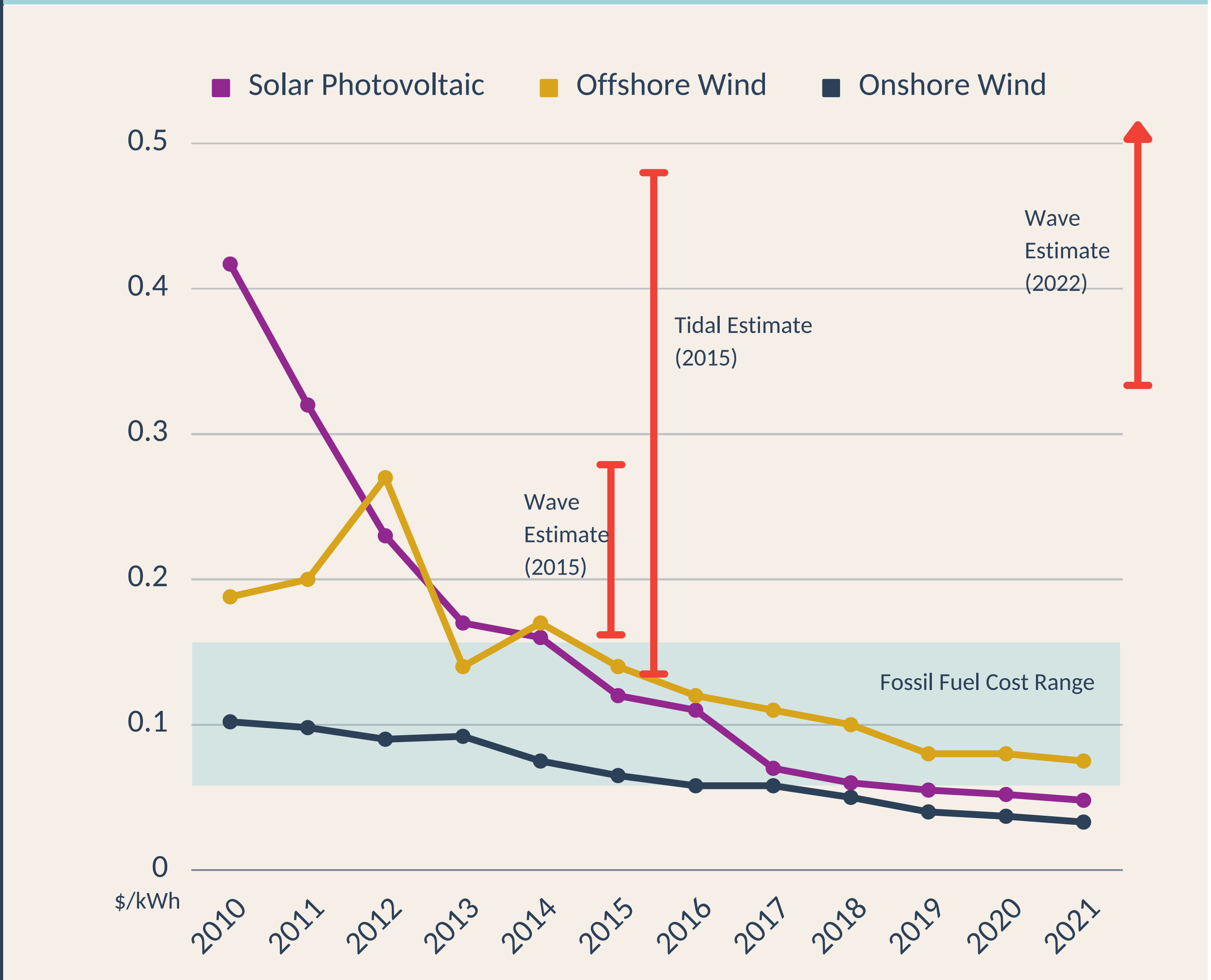
In order to understand the maturity of the sector, we can look at the **length of time that individuals have been involved** in the marine energy sector and the **average size of a firm.** These are both difficult metrics to assess as data is not readily available. Data from the survey (n=50) puts the average time of involvement at 6.7 yrs. This is a relatively short time, when considering the length of a typical career, but it is not unusual given the short-term of growth in the sector. Meanwhile, the average size of a firm in the US (according to the PRIMRE Marine Energy Projects Database) was 2-10 employees, with 10 firms having 11-50 employees. The small firm size is indicative of a technology that has not reached commercial scale, but the fact that there are larger size companies demonstrates that firms are capable of supporting broader experimentation in entrepreneurial development and that there is capacity to grow in size and remain viable. It should be noted that some of these larger firms work in areas beyond marine energy, such as offshore wind. It should also be noted that overall there are very few firms operating within the marine energy sector, and many of the early companies are no longer active. The limited number of firms and volatility within the sector--especially in terms of wave and tidal energy device developers--is concerning, as it demonstrates a lack of sectoral maturity.

In terms of *technological* maturity, there are several data points to look at. The **rated capacity of devices** and **LCOE (Levelized Cost of Electricity)** have been common ways to understand the commercial viability of an energy technology. However, it is problematic to use these metrics in a field where the applications of the technology are broad, and go well beyond grid energy. This is because there are multiple uses for power at sea, and many of these applications do not require large rated capacity to make a large impact. Further, rated capacity is not always an accurate metric, as larger numbers do not necessarily mean more efficient systems. A common perspective of interviewees was that this diversity of application and impact was a positive attribute, and that common metrics of progress such as LCOE or rated capacity were not necessarily helpful. Many entrepreneurs and researchers were more motivated to develop technologies for smaller-scale applications than larger-scale ones, and felt that their technology could have outsized impacts in fields such as ocean observing, desalination, and subsea robotics. Nevertheless, increasing rated capacity is still frequently discussed, and remains an important driver for developers working on scaling-up their technologies for either microgrid, grid, or array-based development.

F3 Entrepreneurial Experimentation

As discussed above, there are problems with using **LCOE** as a metric within the marine energy sector. Nevertheless the available data is as follows. In a consultation with marine energy experts, Baca et al. (2022) found that estimates of wave energy LCOE for 2020 (current estimates based on real-world costs assuming presently available technology) varied greatly, between \$0.35/kWh and \$0.85/kWh, with a mean of \$0.57/kWh. Opinion on when LCOE would reach \$0.30kWh varied from 2021 to 2045, with an average conservative estimate of 2033 and an average optimistic scenario as 2029. They also responded with estimates of ranges of between \$0.06/kWh and \$0.25/kWh for 2050. Another study by IRENA OES in 2015 forecasted LCOE for the first commercial-scale project was in the range of \$0.12–0.47/KWh for wave energy and \$0.13–0.28 \$/KWh for tidal energy.

Figure 23: Levelized Cost of Electricity (LCOE)



https://www.irena.org/publications/2022/Jul/Renewable-Power-Generation-Costs-in-2021

*Baca, E.; Philip, R.; Greene, D.; Battey, H. (2022). Expert Elicitation for Wave Energy LCOE Futures (Report No. NREL/TP-5700-82375). Report by National Renewable Energy Laboratory (NREL). Report for US Department of Energy (DOE).

F4 Guidance of the Search

- **Regulations, visions, expectations of government and key actors.**
- **Is there a clear vision on how the industry and market should develop in terms of growth? In terms of technological design?**
- **What are the expectations regarding the technological field?**
- **Are there clear policy goals regarding the field? Are these goals regarded as reliable?**
- **Are the visions and expectations of actors involved sufficiently aligned to reduce uncertainties?**
- **Does this (lack of) shared vision block or support the development of the TIS?**

Table 11: F4: Guidance of the Search Indicators 2005–2021

Sub-theme	Indicator	Data Source
Path Forward	Marine Energy Foresight Exercises	Desk Review
Path Forward	Number and ambition of ME deployment/capacity targets	Desk Review
Path Forward	Inspiration to conduct R & D	UMERC 2022 Survey/Interviews
Path Forward	Perceived clarity of path	UMERC 2022 Survey/Interviews
Pace of Development	Perceived stage of development	UMERC 2022 Survey
Pace of Development	Perceived pace of development	UMERC 2022 Survey/Interviews

F4 Guidance of the Search

The **number of marine energy foresight exercises and reports** provides a data point to understand the nature of the guidance given to marine energy developers and researchers. These include policy strategies, roadmaps, and memos that are publicly available and outlined in the table below.

In addition, the **number and ambition of marine energy deployment targets** provides insight into the vision, expectation, and confidence within the sector. Compared to other countries, the US has been slow to develop targets, either in terms of capacity or cost, for the sector. Thus far, no targets have been set at the federal level in the US, but a recent white paper by an industry group has set graduated targets (NHA-MEC, 2021). Many people in the US sector also look to the DOE WPTO "Powering the Blue Economy" report, and cite it as providing a useful vision for the sector. Nevertheless, the lack of a clear target or roadmap presented at the US federal level is a gap in guidance of the search, and is in contrast to many European countries and the EU Commission, which has set clear targets and goals.

Table 12: Major Marine Energy Foresight Reports

Date	Report	Organization	Level	Time horizon/Target
2011	US Marine and Hydrokinetic Renewable Energy Roadmap	MHK Trade Association	US	15 GW by 2030
2017	An International Vision for Ocean Energy	IEA OES	Global	300 GW by 2050
2019	Powering the Blue Economy	DOE WPTO	US	none
2020	Fostering a Blue Economy	IRENA	Global	none
2020	Innovation Outlook: Ocean energy Technologies	IRENA	Global	20 GW by early to mid 2030 and .11/kWH LCOE
2020	Strategic Research and Innovation Agenda for Ocean Energy	ETIP	Europe	100 GW by 2050
2020	Offshore Renewable Energy Strategy	European Commission	Europe	100 MW by 2025; 1 GW by 2030; 40 GW by 2050
2021	Commercialization Strategy for Marine Energy	NHA-MEC	US	50 MW by 2025; 500 MW by 2030; 1GW by 2035
2022	WPTO Multi-Year Program Plan	DOE WPTO	US	"up to 50 GW of marine energy capacity could be added in the United States by 2050"

F4 Guidance of the Search

When asked in the survey, both industry developers and researchers were found to have a very high **level of inspiration to conduct R&D i**n the field (Figure 24) . Respondents were also asked about their motivations and anxieties in terms of research in the field, which are shown in Figure 25.

Figure 24: Inspiration to Conduct R & D

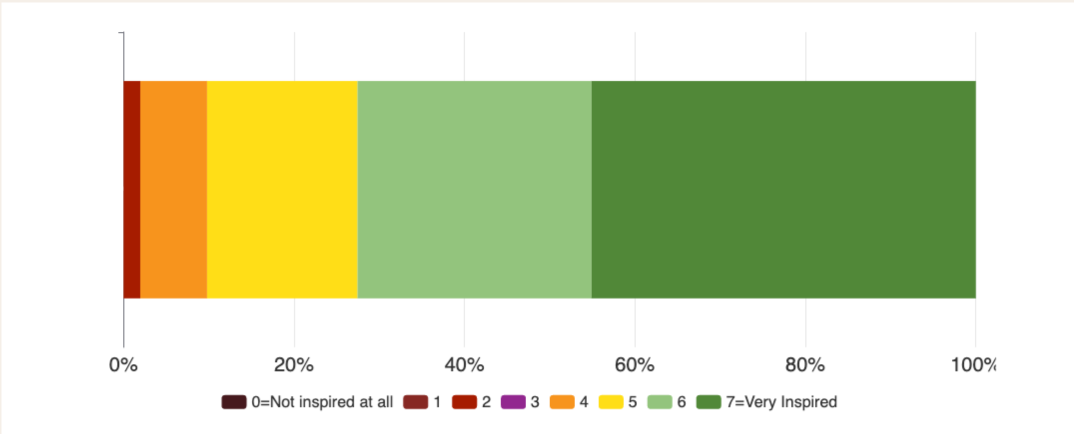
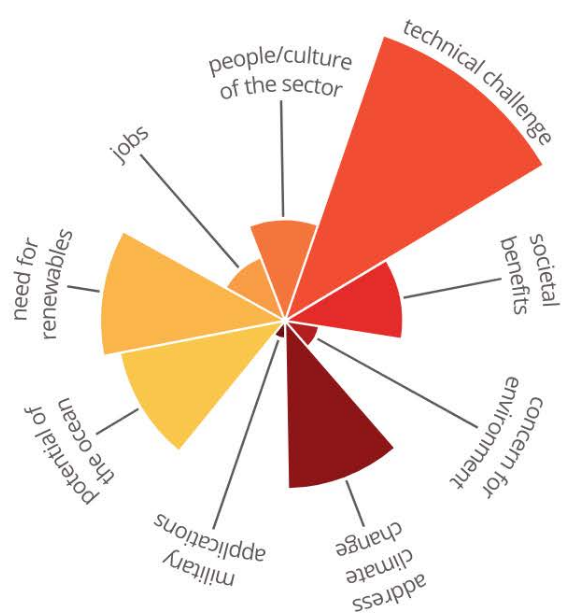
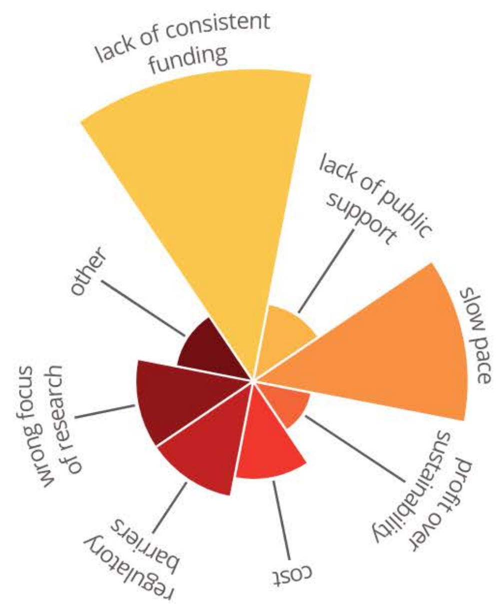


Figure 25: Motivations and Anxieties: Open-Ended Survey Questions

What makes you **inspired** or interested in conducting research activities in the marine energy sector?

Is there anything that makes you less interested, **anxious**, or just uninspired when it comes to conducting research in or for the marine energy sector?





F4 Guidance of the Search

When asked about the **perceived clarity of the path** forward for development for different technologies, there was a very low level clarity around marine energy. This was in contrast to offshore wind, which had a higher level of clarity. In terms of **perceived stage of development,** most respondents rated TRL levels on the low to middle spectrum of the scale, although riverine tidal and tidal stream were rated more often on the higher end. The perception of TRL matches fairly closely with what would be expected, with OTEC being an outlier in that it is actually at a much more advanced TRL (7) than perceived (Grech et al., 2022).

Figure 26: Perceived Clarity of Path Forward for Different ME Technologies

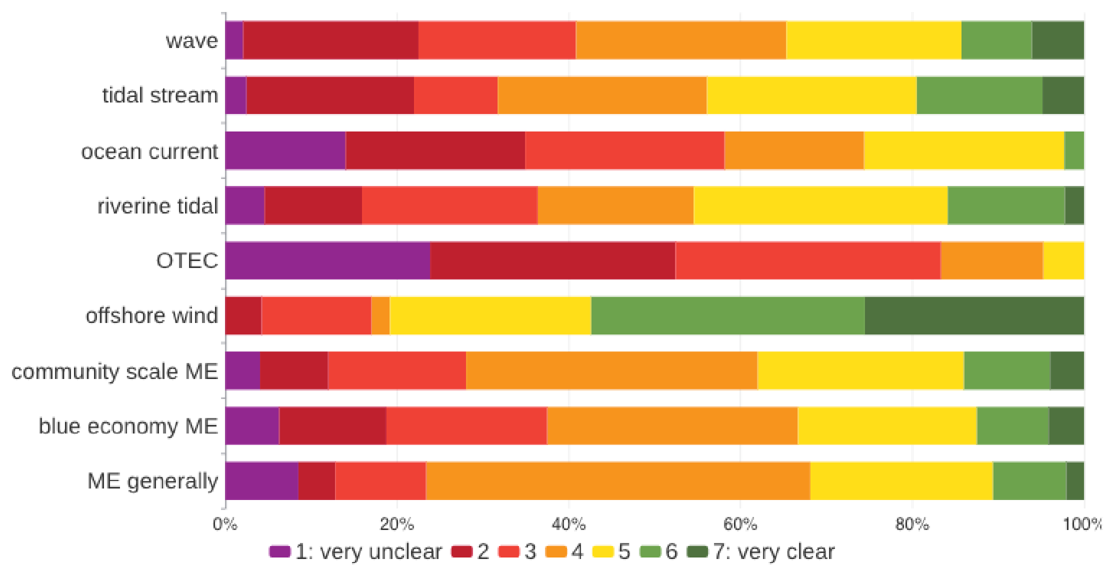
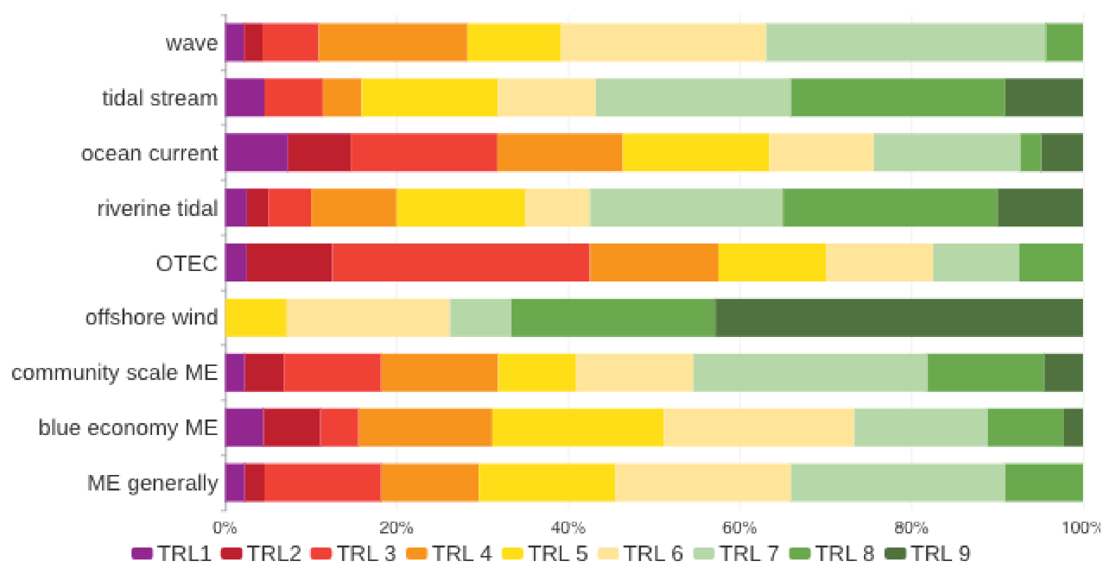


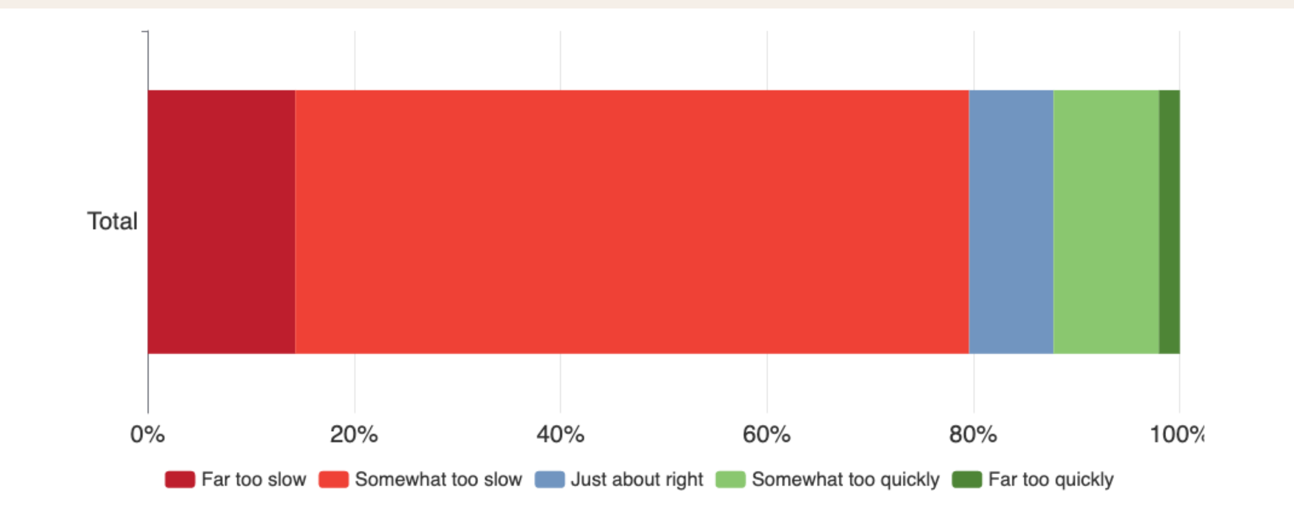
Figure 27: Perception of TRL for Different ME Technologies



F4 Guidance of the Search

When asked in surveys about their **perception of pace of development** in the sector in the US, 80% off respondents thought that it was "far" or "somewhat" too slow. When asked in interviews, however, a more nuanced picture arose. Often, people differentiated between technologies, for example citing wave energy as being "too slow" and tidal as more aligned with a good pace of development. For many people, the perception and desire for marine energy development did not align with the real pace of development. For some people, this means that the pace of development is too slow because it is not meeting the needs of society to adapt to less carbon intensive energy supply. But, for others, this mis-match of pace was a mis-placed expectation on the pace of technological development in general. From this perspective, people compared wind energy to marine energy and citing that wind energy took decades to develop to the current commercial stage, and that marine energy was being pushed too quickly forward to commercialization and needed to be given time to mature through foundational research. Meanwhile, others were concerned that the pace of development and funding would be too long for many entrepreneurs to "sit out." These opinions highlight the diversity of perspectives within the marine energy sector, and could also point to the need for more "guidance of the search."

Figure 28: Perception of Pace of Development



F5 Resource Mobilization

- **Physical resources, infrastructure, human resources, financial resources--from structural analysis**
- **Are there sufficient human resources? if not, does that form a barrier?**
- **Are there sufficient financial resources? If not, does that form a barrier?**
- **Are there expected physical resource constraints that may hamper technology diffusion?**
- **Is the physical infrastructure developed well enough to support the diffusion of technology?**

Resources that need mobilization to support innovation include financial, human, and physical resources that support the innovation process. It is difficult to find reliable metrics to understand levels of funding for specific technologies and programs in the US. This is because many of the funding programs contain multiple collaborators whose identities and affiliations are not readily apparent. In addition, some of the funding sources for marine energy research are defense-related, making them very difficult to track. Because of gaps in funding data, they are not presented here as comprehensive, but are intended to provide a snapshot at what resources are being used by researchers in the sector. The data sources for funding are listed below, and should each be taken as an incomplete perspective. **Level of US funding** for marine energy in the US, according to Dimensions AI, shows that funding levels for marine energy have increased over the past two decades, with the exception of a significant reduction in funding between 2014 and 2018. Using the same data, and comparing them to the rest of the world, the US is one of the top countries in terms of funding marine energy.

Table 13: F5: Resource Mobilization Quantitative Indicators

Sub-theme	Indicator	Data Source
Financial	Level of US Funding	Dimensions AI
Financial	Funding by US Funding Agency	Dimensions AI
Financial	DOE Funding by Program Purpose	Document Analysis of FOAs (2008-2021)
Financial	DOE Funding by Technology	Document Analysis of FOAs (2008-2021)
Financial	Publications by Funder	Dimensions AI
Financial	Perception of Sector Needs	UMERC Survey 2022
Human	Number of degree and certification programs	PRIMRE STEM Resources
Human	Perception of Training Support	UMERC Survey 2022

Figure 29: Aggregated funding amount of marine energy research per country/territory 2010-2022

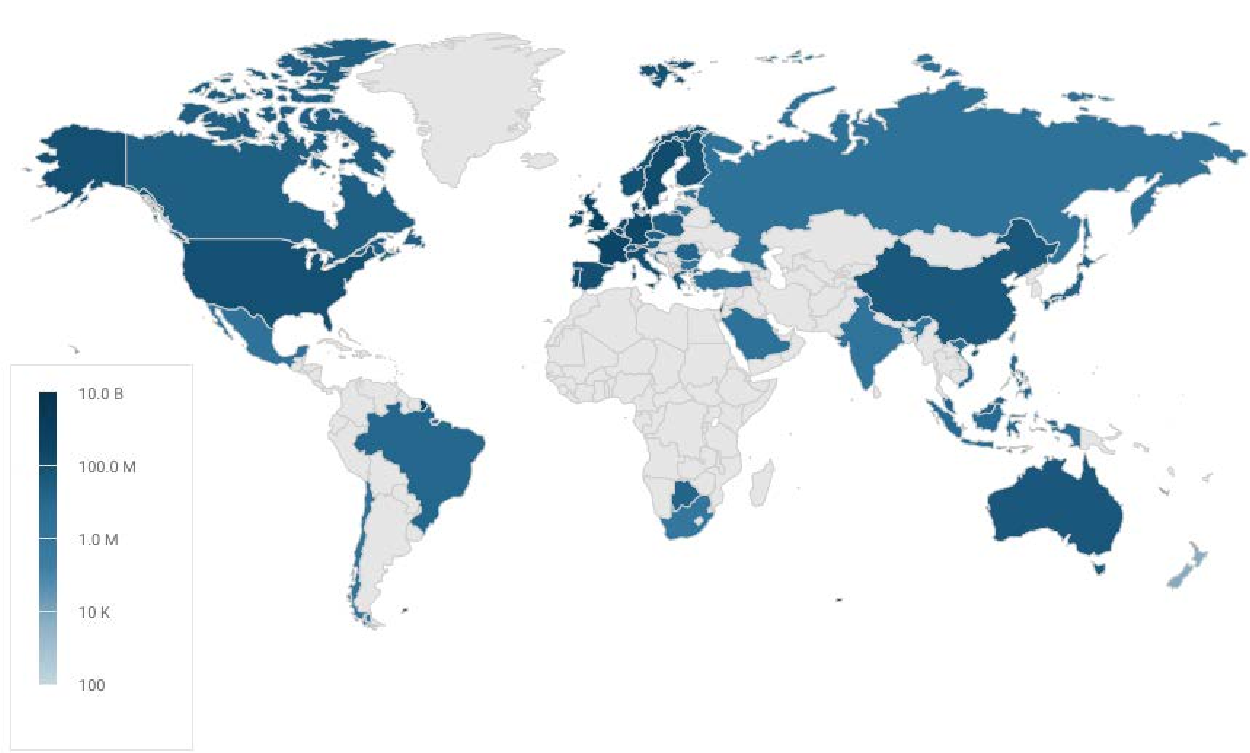
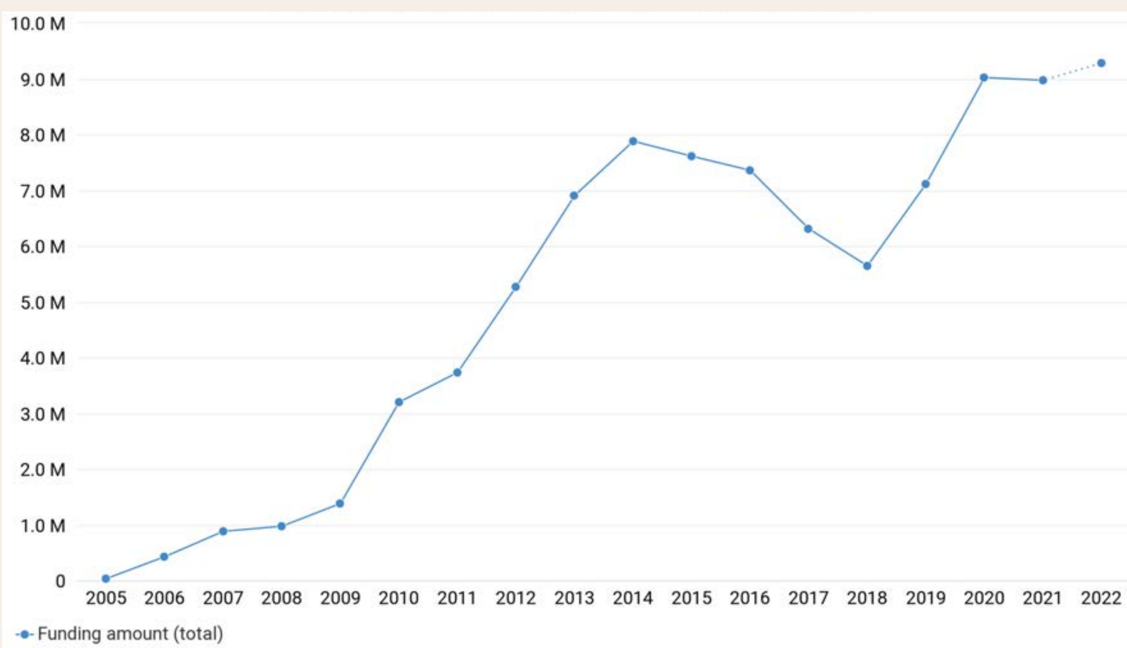


Figure 30: Research funding amount each year in US* 2005-2022



* The visualization shows the aggregated funding amount in each year. The funding amount of each grant is allocated equally to the months of the respective funding period - the funding amount is converted for each year's exchange rate.

Please be cautious when using this graph for detailed trend analysis. Funding amount trends may be skewed due to grants in the database without funding amounts, historical currency exchange rates to your currency of choice and/or small numbers of large grants, giving a misleading picture in some cases.

F5 Resource Mobilization

Funding by US Funding Agency is tracked in the Dimensions AI database, and can be seen in the chart below. Figure 31 shows that there is a diverse set of funders for research in marine energy. It is important to recognize that much of the data in the Dimensions AI database is focused on research, and so some testing or infrastructure funding will be missed. In an attempt to delve more deeply into this issue, funding opportunity announcements from the US Department of Energy were reviewed and categorized based on program purpose. These categories can be seen in Figure 32, demonstrating a diversity of funding programs in addition to research, some of which are missed in the Dimensions AI data.

Figure 31: Total Amount funding per US funding agency 2005-2022

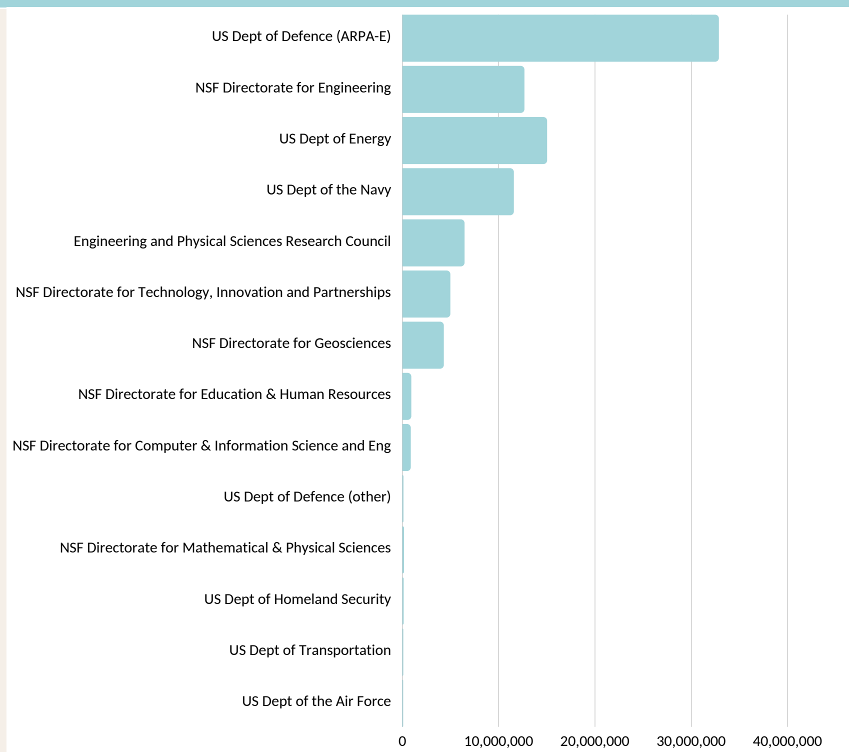
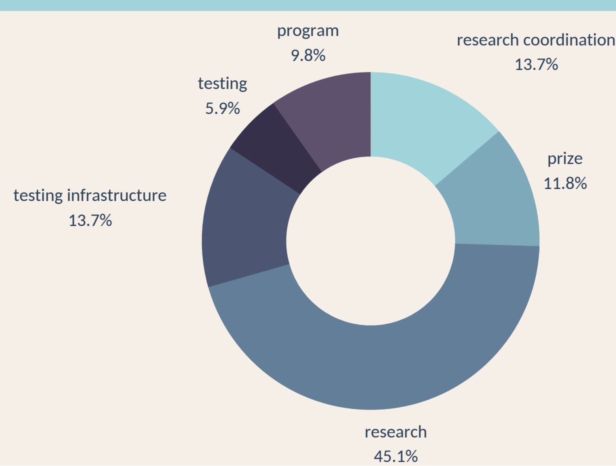


Figure 32: DOE Funding by Program Purpose (2008-2021)



F5 Resource Mobilization

Research funding by technology is categorized in Figure 33, but only by DOE Funding Opportunity Announcement, as not all funding sources could be analyzed in this way. **Publication by funder** is also broken down in Figure 34, with fewer publications resulting from DOD research, as can be expected due to the nature of the research.

Figure 33: DOE FOAs: specified technologies in Millions USD (2008-2021)

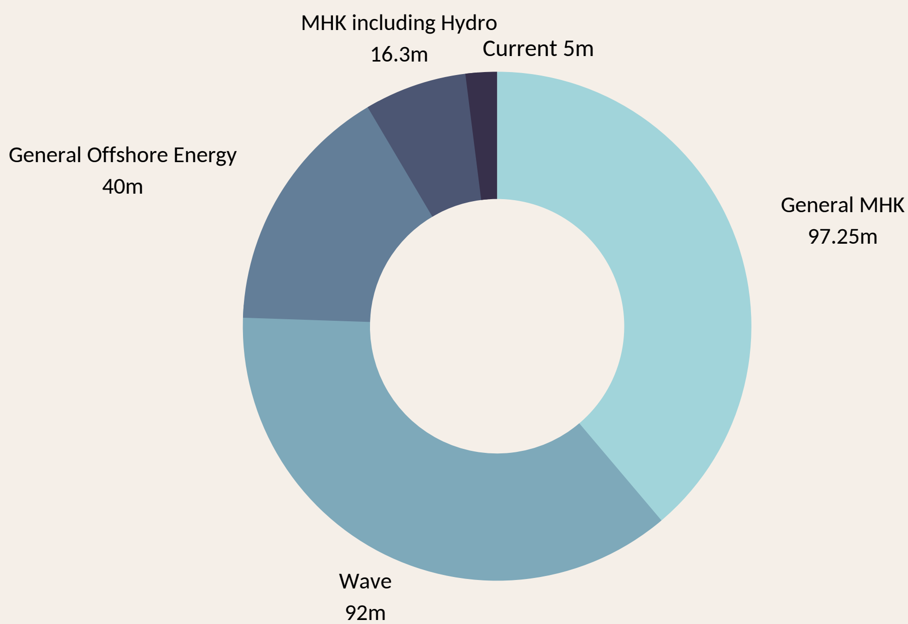
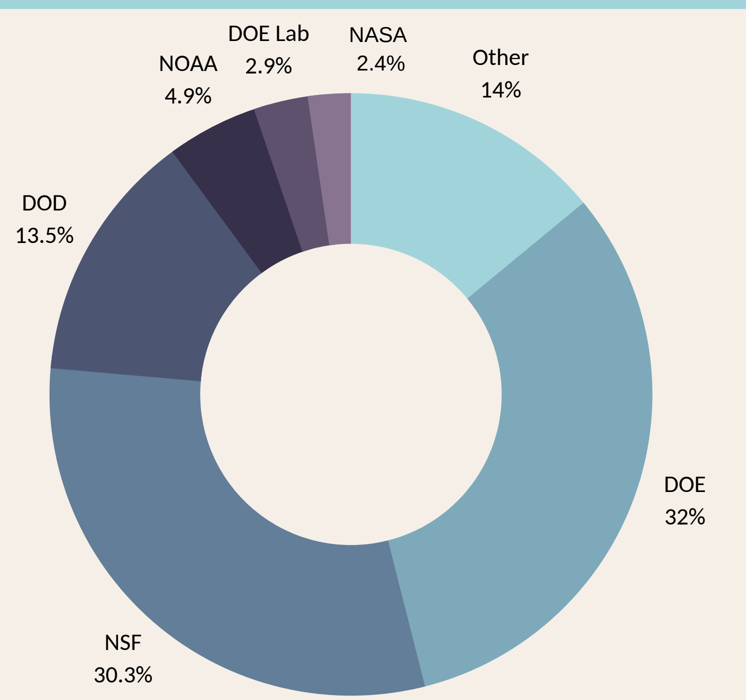


Figure 34: Percent Publications by Funder in US 2005-2022



F5 Resource Mobilization

In terms of **perception of sector needs,** many people surveyed thought that funding for research was the most impactful. In terms of **perception of training support** available, answers ranged about how available training is in the sector. When asked about workforce needs in interviews, however, many people were concerned about a severe lack of trained engineers and worried about their ability to find and retain a workforce. This highlights a tension, whereby there are many training programs in marine engineering and related fields, but employers do not feel that there are adequate numbers of these engineers deciding to make careers in the marine energy sector specifically.

Figure 35: Perception of Sector Needs

Please rate the following kinds of support mechanisms in terms of how they would help you make progress in your research or development:

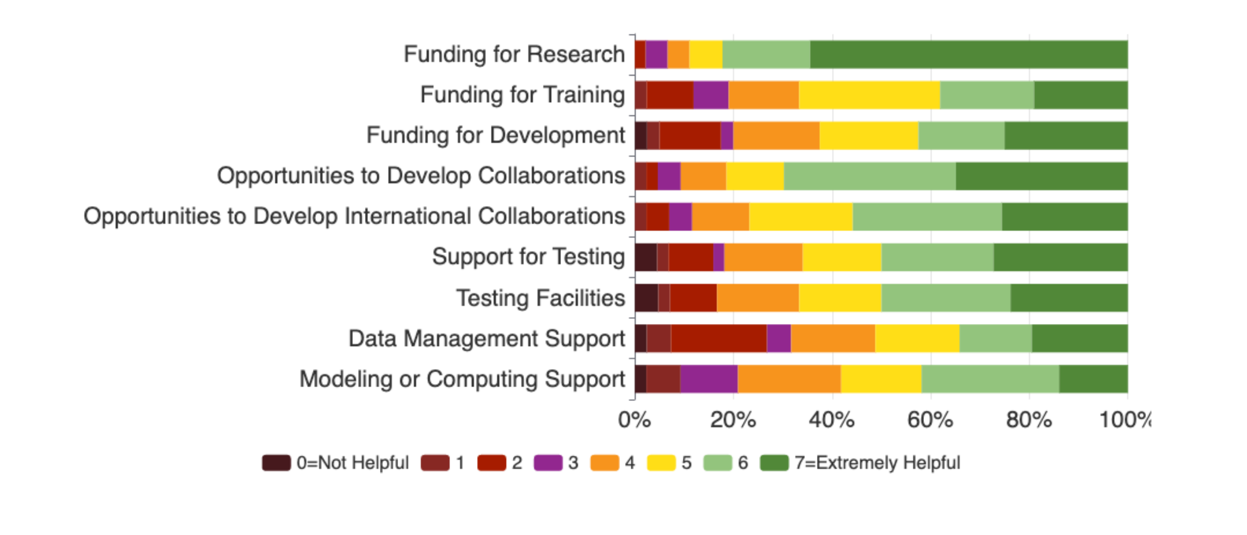
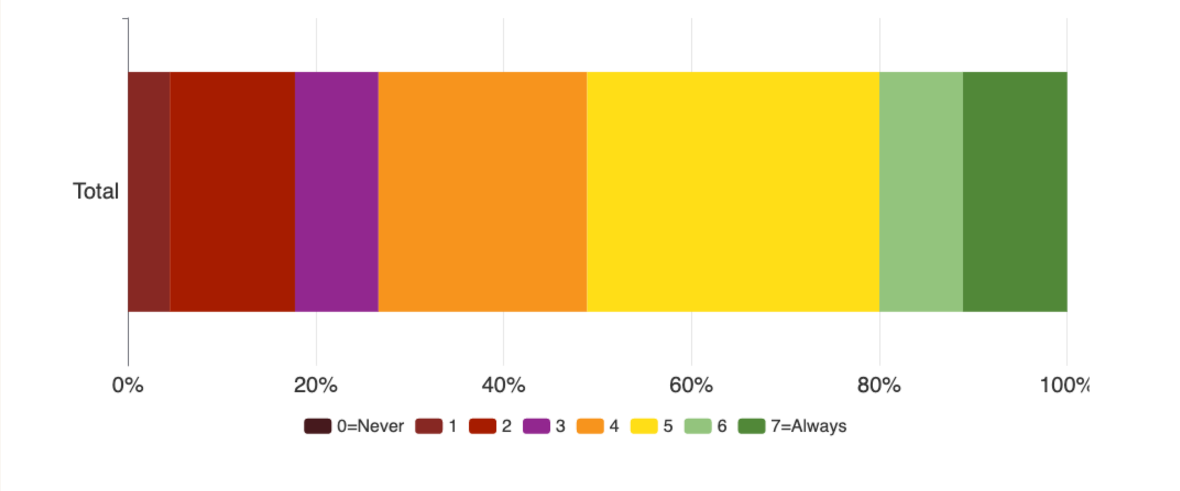


Figure 36: Perception of Training Support

How often have you been able to find the technical or professional training that you need in order to progress in the marine energy sector?



F5 Resource Mobilization

Below is a list of US **engineering degree programs** related to marine energy. This list covers a broad range of institutions and regions, but it should be noted that there is no degree offered in marine energy, specifically. During interviews, some people cited a need for more dedicated training in marine energy, although for some, this did not necessarily mean a dedicated degree program, but a course or training program in marine energy. Overall, there was a diversity of perspectives in this regard.

Table 14: Degree and Certification Programs

Institution	Program Type
University of Alaska Fairbanks	Engineering
University of California-Berkeley	Mechanical and Ocean Engineering
College of the Florida Keys	Engineering Technology/Renewable Energy
Florida Atlantic University	Ocean Engineering
Florida Tech	Ocean Engineering/Ocean Science
Florida Atlantic University	Ocean and Mechanical Engineering
Georgia Institute of Technology	Water Resources Engineering
University of Hawai'i at Mānoa	Ocean and Resources Engineering
University of New Orleans	Naval Architecture/Marine Engineering
Massachusetts Institute of Technology	Mechanical Engineering/Ocean Engineering
University of Massachusetts--Dartmouth	Marine Science and Technology/Innovation Program
Massachusetts Maritime Academy	Energy Systems Engineering/Marine Engineering
US Naval Academy	Naval Architecture/Marine and Ocean Engineering
University of Maine	Mechanical Engineering
University of Michigan	Naval Architecture and Marine Engineering
Coastal Studies Institute of North Carolina	Engineering
Duke University	Civil and Environmental Engineering
University of New Hampshire	Ocean Engineering/Mechanical Engineering
Stevens Institute of Technology	Naval Engineering/Ocean Engineering
Wright State University	Renewable and Clean Energy
Oregon State University	Mechanical and Civil Engineering/Marine Resource Management
Willamette University	Utility Management
Lehigh University	Water Resources Engineering
University of Rhode Island	Ocean Engineering
University of Tennessee--Knoxville	Energy Science and Engineering
Texas A&M	Ocean Engineering
University of Texas at Austin	Mechanical Engineering
Virginia Tech	Aerospace and Ocean Engineering
Old Dominion University	Coastal Engineering
University of Washington	Ocean Engineering/Mechanical Engineering/Energy Infrastructure
Seattle Colleges	Marine Engineering Technology
Skagit Valley College	Marine Maintenance

*Information Courtesy Jennifer Daw, NREL Marine Energy Curricula Assessment

F6 Market Formation

- **Projects installed, planned, constructed**
- **Is the current and expected future market size sufficient?**
- **Does market size form a barrier for the development of the innovation system?**

Table 15: F6: Market Formation Indicators 2005–2021

Sub-theme	Indicator	Data Source
Market Formation	Number of US marine energy firms	PRIMRE/Survey/Desk Research
Market Formation	Marine energy installed capacity	PRIMRE/Survey/Desk Research
Market Formation	Marine energy capacity in developent	PRIMRE/Survey/Desk Research

Market formation is a difficult function to assess in an innovation system that is in an early stage TRL. The **number of US marine energy firms** is small. Depending on sources and status of the firm (active/inactive), the number of active firms in the US is somewhere around one dozen, yet there are other firms that work internationally, and although they may not be based in the US, they remain part of the innovation ecosystem by exchanging and competing for knowledge, workforce, and development opportunities. Further, it is difficult to assess market formation because of the recent shift to community-scale and blue-economy applications for marine energy. This broadens the market for marine energy well beyond the electrical grid, into sectors such as ocean observation and robotics that are not yet well bounded. Market formation can also be assessed by metrics such as **installed capacity and capacity in development.** But, again, these numbers may not be as useful if the value of the application is not based on the metric of generation capacity.

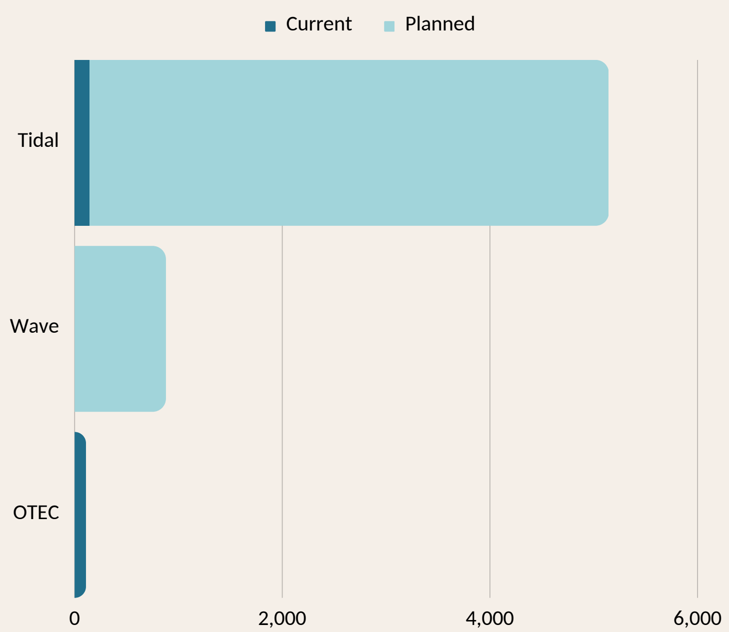


Figure 37: kW of Current and Planned Capacity in the US

F7 Legitimation

- **Is there a lot of resistance towards the new form of technology, the set up of projects, and permit procedures?**
- **Do these create barriers to progress?**

Legitimacy is granted to an emerging technology when it is strengthened with in the current institutional regime. For example, actors within the TIS work to gain support for the new technology through lobbying and public engagement, but also through granting of regulatory support. **Regulatory support** can include both support to gain permitting approval or incentives to develop technologies through taxing or energy pricing and subsidy. These can occur at the state or federal level. The WPTO is currently supporting the creation of a Marine Energy Regulatory Toolkit, which facilitates access to permitting requirements and clarifies the process for developers. This is an important step in reducing resistance to legitimizing the technology. Anticipating and retiring environmental risks has also been a major thrust of the marine energy program in the US. This effort to characterize impacts and establish baselines has significantly reduced anticipated barriers in the environmental regulatory area. Despite these supportive measures, there have been very few permitted projects in the US to date, as can be seen in Table 17, on the following page.

Table 16: F7: Legitimation Indicators 2005–2021

Sub-theme	Indicator	Data Source
Government	Regulatory support	UMERC Annual Survey
Government	Number of Policy Documents	Dimensions AI
Public	Public support for marine energy	Desk/Literature Review

Table 17: Sites with Environmental Permitting for Marine Energy in the US

Name	Status	Permit Status	Resource
Igiugig	Active	Permit 2019	Riverine
Admiralty Inlet	Inactive	Permit 2014	Tidal
Cobscook Bay	Active	Permit 2012	Tidal
RITE	Active but Decommissioned	Permit 2012 Re-license 2019	Tidal
OPT Reedsport	Inactive	Permit 2012	Wave
PacWave North	Active	Environmental Assessment 2012	Wave
PacWave South	Active	Permit 2021	Wave
WETS	Active	Environmental Assessment 2014	Wave

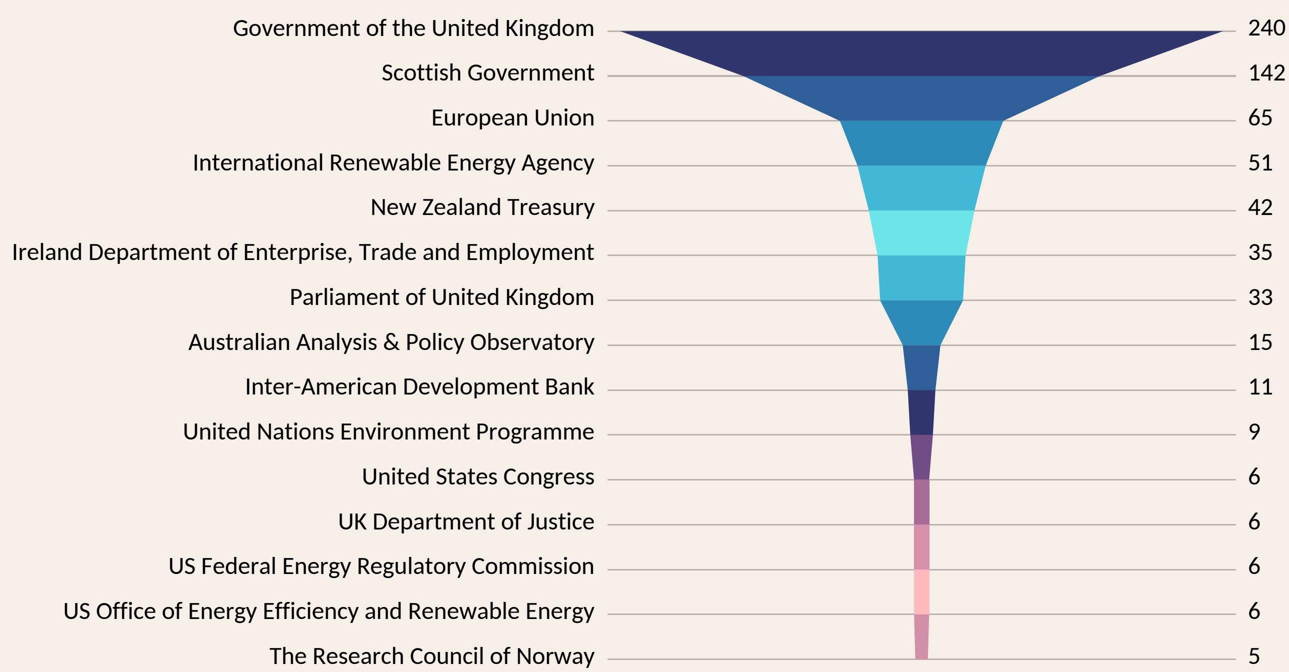
From: Marine Energy Reporting Tool (Accessed 2022: https://marineenergy.app/)

F7 Legitimation

The number of government policy documents with a significant focus on marine energy that have been released in the US is small, at only 18 from 2010-2020. In contrast, countries such as the UK have had 240 (and Scotland 142). This indicates a low level of legitimacy for marine energy in government agencies in the US. Thus, legitimacy for the sector is relying heavily on policy being discussed and developed in other countries and at the international level.

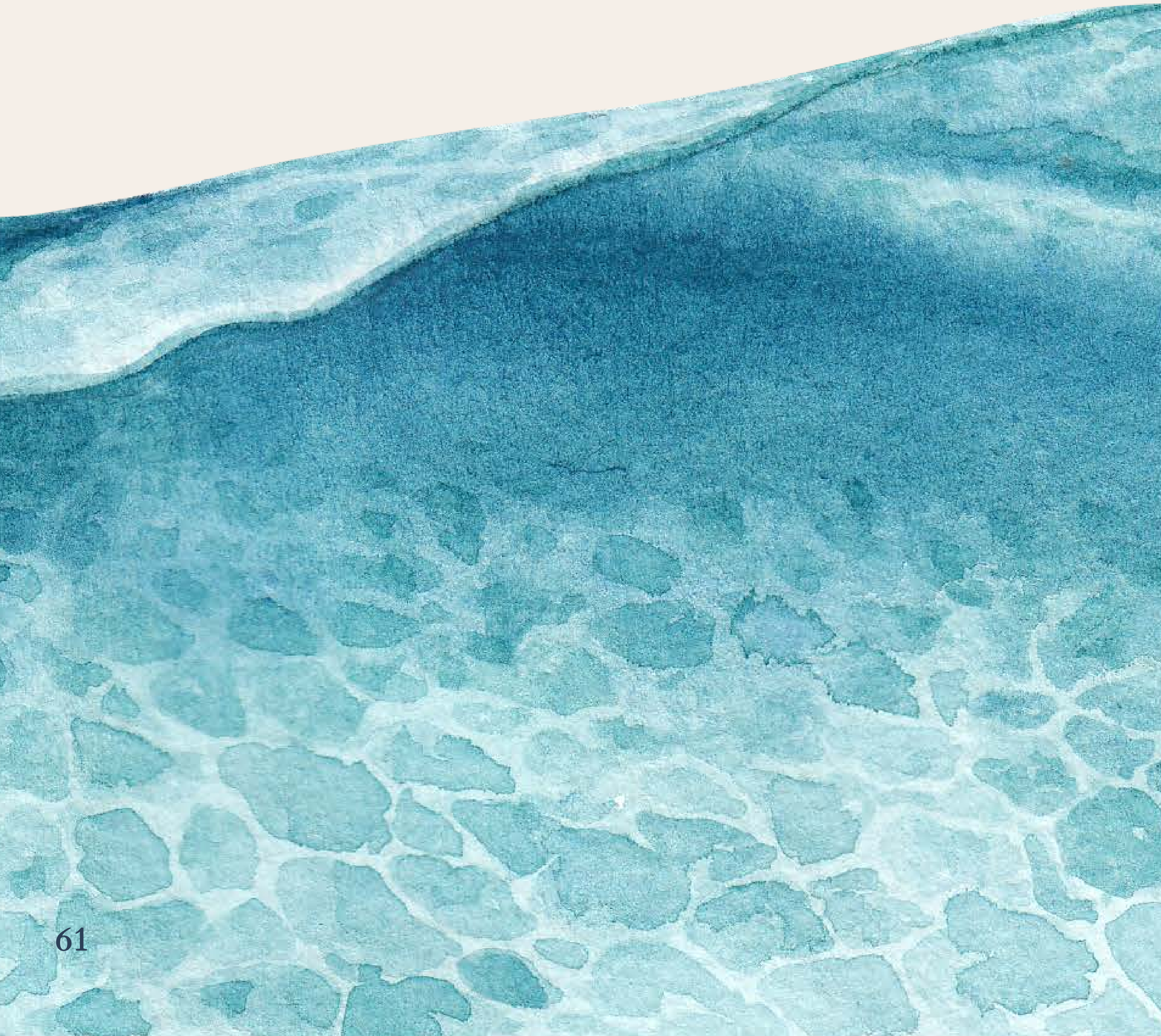
Public support for marine energy has not been extensively tracked in the US. One of the only data points is a YouGov Survey (n=2000) from 2022 of the US Pacific Coast on public perceptions of wave energy (Boudet et al., 2022). More than half of the respondents had not heard of wave energy and most people had little knowledge about it. Despite this, most people had a positive attitude towards it (Boudet et al., 2022). In terms of tidal energy, a study from 2017 found that public perception toward tidal energy is positive in Washington State, with high levels of acceptability and support (Dreyer et al., 2017).

Figure 38: Number of policy documents per agency in corpus 2010-2020



06

Conclusions and Recommendations

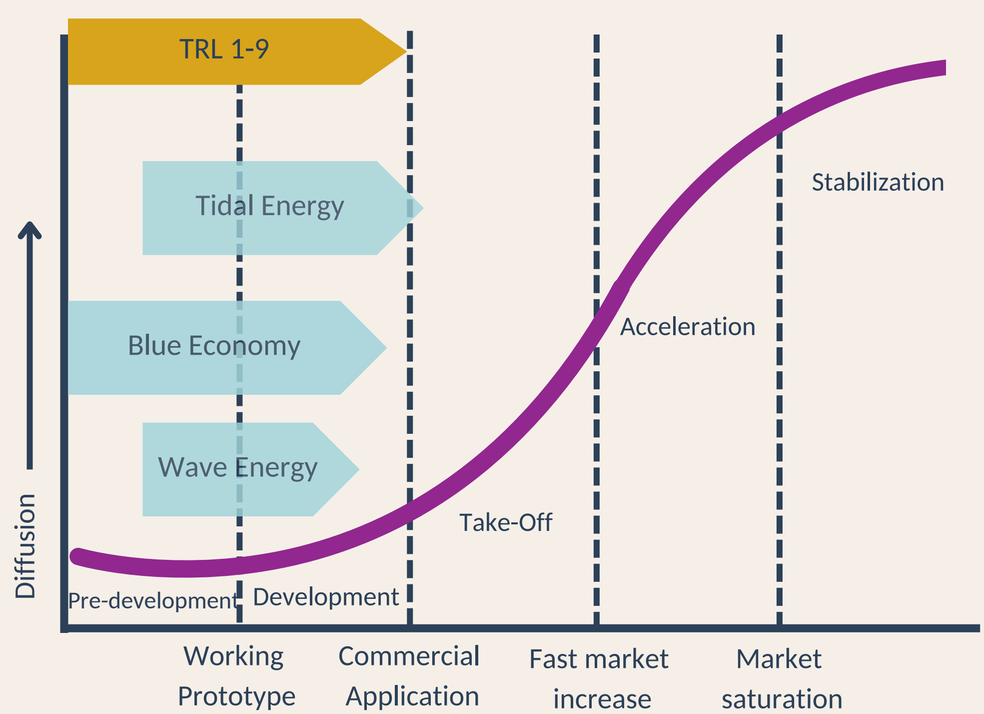


06 Conclusions and Recommendations

TISs change over time, and it is important to consider how structures use system functions differently as the TIS builds up over time (Hekkert et al., 2011). The goal for innovation policy is to fulfill the appropriate system functions at the right time, so that the TIS can build and move to the next phase. Therefore, the stage of development of the technology is important to consider. In the figure below (Figure 39), we can see the diffusion curve of a technology. The curve represents the process of development, application, and diffusion of the technology.

One finding of this research is that marine energy technologies are diverse, and are at different stages of development depending on the application and desired final scale. For example, tidal energy technologies have just reached the "development phase" in which the first commercial applications are entering the market. Whereas wave energy technologies are in the "pre-development phase" whereby they are being proven. "Blue economy" applications are at various phases, with some very early in the pre-development phase and others beginning to enter the market. Regardless, what the TIS Analysis framework encourages is to look ahead to the next phase and use policy and other mechanisms to push the technology into that next phase. For marine energy, this next phase is "take-off" phase, where the technology is diffused and the market grows.

Figure 39: Phase of Development

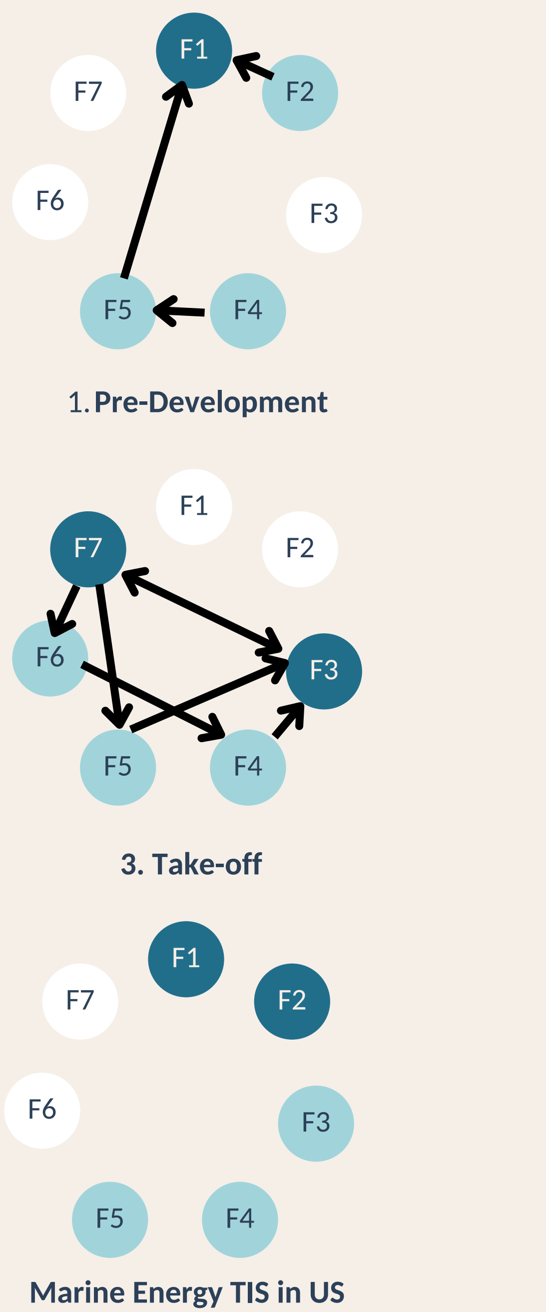


From: (Hekkert et al., 2011)

What does the sector need at this phase of development?

The importance of each function varies according to the stage of development of the technology (Hekkert et al., 2011). Since most marine energy technologies are in Stages 1 & 2, the functions should reflect a healthy pattern, as described in Figure 40, below. Further, the functional pattern in Phase 3 should also be supported, as the technologies move from Phase 2 to Phase 3. These functional patterns are discussed in depth on the following page as recommendations.

Figure 40: Functional Patterns Per Phase



Functions

F1 Knowledge Development

F2 Knowledge Exhange

F3 Entrepreneurial Experimentation

F4 Guidance of the Search

F5 Resource Mobilization

F6 Market Formation

F7 Legitimation

From: (Hekkert et al., 2011)

What does the sector need at this phase of development?

1. Pre-Development Phase

In this phase knowledge development is critical. In the US, this function scored high due to the robust and high quality research. At this stage, guidance of the search should be supporting resource mobilization. In the US TIS, both of these function need to be strengthened and require more cohesive strategies that target needs for financial resources and trained workforce. Knowledge exchange should also be supporting knowledge development at this stage. In the US, this is functioning well, with strong networks of researchers. The other functions are less influential at this phase of development.

2. Development Phase

This is the most important phase for entrepreneurial experimentation. In the US, this function lacks strength due to high risk of entry due to unstable support to commercialization and difficult and slow regulatory processes. This has resulted in a small size and number of firms. In order to function well during this phase, entrepreneurial experimentation needs to be supported so that pilots in each technology can be demonstrated. At this stage, all other system functions will positively or negatively affect the system function, and they all must be functioning. Therefore, market formation and legitimation also need to be strengthened.

3. Take-off Phase

During this phase, entrepreneurial experimentation is also critical, and the entrepreneurs should drive the system, building legitimacy. If the TIS of marine energy is to reach this phase, mobilization and market formation will also need to be strengthened, possibly through niche or high-value markets. Public support will be needed by providing regulatory pathways, and high-skilled workforce will need to be available.

Recommendations

The following recommendations for strengthening the US marine energy TIS are drawn from the previous structural and functional analyses and previous TIS Analyses including: Hannon et al., (2017) and Hekkert et al., (2011). Many of the recommendations span multiple organizations and scales, and so each actor will have different capacities for implementing the changes. Therefore, all actors within the innovation ecosystem will need to address them in different ways, whether through innovation policy or other structural means.

1 Create cohesive, realistic, and focused strategy that provides a roadmap for innovation in the sector.

The US marine energy TIS is entering a new phase of innovation: a development phase that requires support from all functions in order to succeed. This phase must be supported by cohesive, technology-specific and cross-cutting innovation strategy. This strategy also needs to be realistic in terms of the time that it takes for technology to innovate. Putting too much pressure on fast-tracking innovation has been problematic in the context of early UK wave energy development (Hannon et al., 2017). Further, each scale and niche of marine energy application will require different (if sometimes overlapping) pathways and strategies. One speed and one size will not fit all.

2 Provide predictable support to reduce risk and build entrepreneurial experimentation.

Entrepreneurial experimentation was one of the least robust functions of the US marine energy TIS. This is especially concerning because this is the most important function for the development phase and must be strong in order for the TIS to move into the take-off phase. Although funding is inevitably constrained due to the nature of public funding, it should be acknowledged that marine energy has not garnered the level of regular funding and support for R&D as other renewable sectors such as solar or wind. This fact has, in turn, hampered the ability for entrepreneurs to move to commercialization, and has led to a small number of viable US firms. The loss of firms, in turn, leads to loss of tacit knowledge and skilled workforce, as individuals leave the sector. Support will be needed to reduce risk and allow entrepreneurs to move through development phases at a reasonable pace, especially because private sector funding (such as match funding) will not necessarily be available to entrepreneurs at this stage of development. Support for early stage commercial deployments in terms of production tax-credits or energy pricing policies have been successful in other contexts and countries.

Recommendations

3 Align with adjacent sectors to draw in relevant knowledge and talented workforce.

At this stage of development, collaboration and competition must be balanced (Hannon et al., 2017), yet relevant knowledge from other fields can be drawn into the sector without hampering competition within it. The siloed nature of marine energy R&D in the US is stifling the ability to innovate, and most importantly, to draw on previous knowledge from adjacent sectors such as oceanographic sensing, offshore wind, oil and gas, marine operations, and others. With an increasing focus on "blue economy," "ocean internet of things," and offshore renewable energy, the marine energy sector has an opportunity to seize on an important narrative which can draw in knowledge, research funding and support, and talented workforce from adjacent sectors and programs. The time to do this is now.

4 Continue to support knowledge production and exchange.

Knowledge production and knowledge exchange are currently robust in the US. However, both of these functions are leveling off, and becoming less competitive when compared to other countries. These functions must continue to be supported by strong networks including already-existing networks that are shown to have high levels of interaction and knowledge production, such as the National Marine Energy Centers. Not only will this support the development of knowledge, it will also provide a skilled workforce, a lack of which could create a blocking mechanism to moving to the next phase of development.

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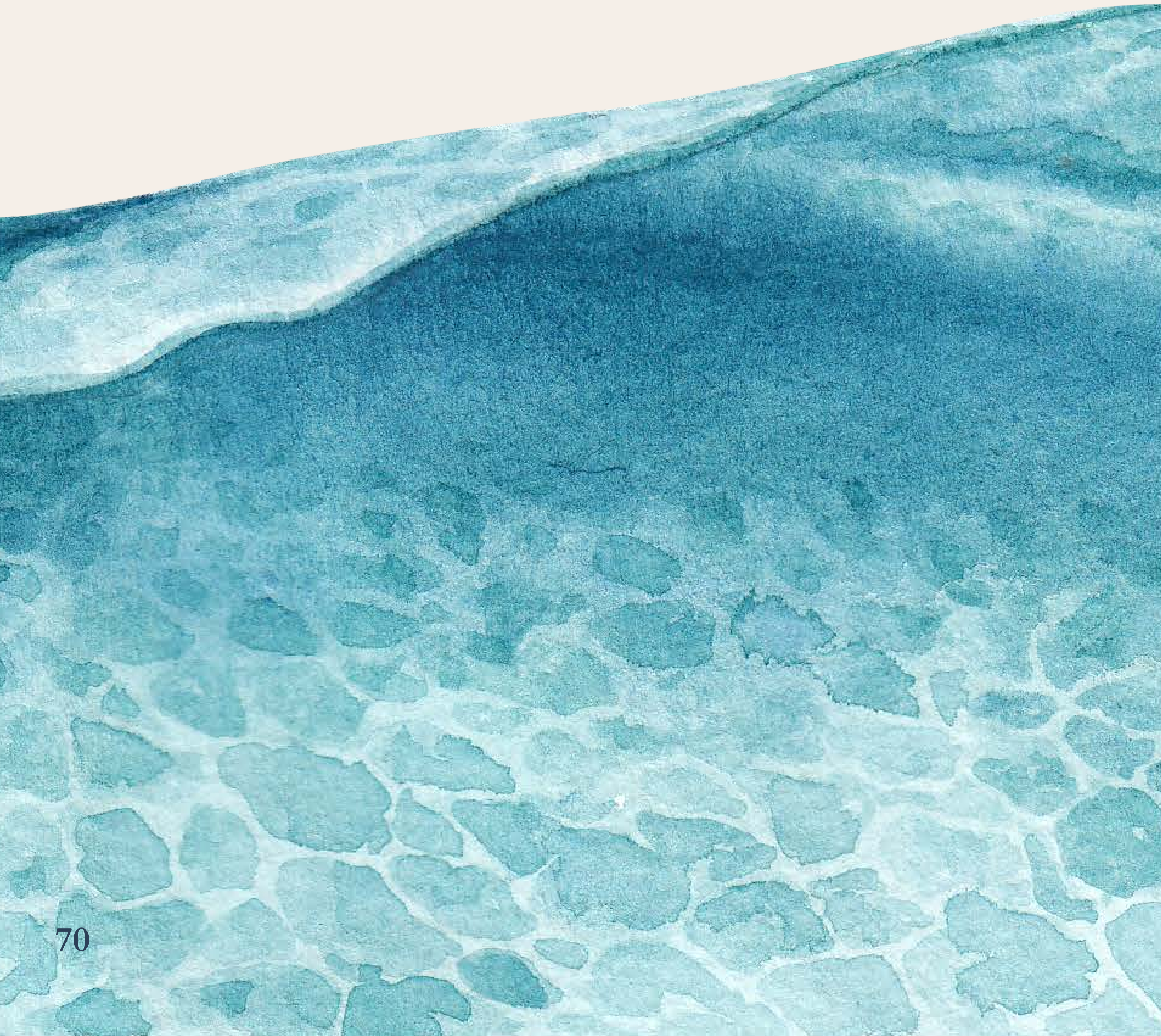
07

Appendices



Appendix A
Search Terms

Search in Dimensions AI Database
Exported on Aug 23, 2022 Results: 3015 publications

Criteria:

(“marine energy”) OR (“marine power”) OR (“ocean power”) OR (“tidal energy”) OR (“tidal power”) OR (“marine hydrokinetic energy”) OR ("ocean wave power") OR ("ocean hydrokinetic energy") OR ("ocean thermal energy conversion") OR ("marine renewable energy") OR ("cross-flow hydrokinetic turbine")

NOT ("paleoclimate") NOT ("sea ice") NOT ("air quality") NOT ("glaciation") NOT ("epidemiology") NOT ("astronomy") NOT ("audiology") NOT ("paleontology") NOT ("methane") NOT ("morphodynamics") NOT ("marsh") NOT ("cyclone") NOT ("game theory") NOT ("chuchki") NOT ("whale song") NOT ("Beaufort") NOT ("tidal internal waves") NOT ("atmospheric winds") NOT ("Drake Passage") NOT ("offshore pipeline") NOT ("icy satellites") NOT ("flyway") NOT ("Sikuliaq") NOT ("cetacean density") NOT ("UNOLS") NOT ("inertial oscillation") NOT ("seismic survey") NOT ("Cuvier's") NOT ("sea otters") NOT ("kogia") NOT ("oil and gas platforms") NOT ("black scoter") NOT ("shipwreck") NOT ("isotope") NOT ("disease") NOT ("turtle") NOT ("anesthesia") NOT ("endocrine") NOT ("internal gravity wave") NOT ("groundwater") NOT ("paralytic shellfish") NOT ("larvae") NOT ("M2 internal tides") NOT ("oceanic circulation") NOT ("tidal winds") NOT ("nearshore waves") NOT ("gas turbine") NOT ("rogue waves")'

in full data;

Publication Year is 2022 or 2021 or 2020 or 2019 or 2018 or 2017 or 2016 or 2015 or 2014 or 2013 or 2012 or 2011 or 2010 or 2009 or 2008 or 2007 or 2006 or 2005;

Country/Territory is United States;

Fields of Research is not 0404 Geophysics and not 0201 Astronomical and Space Sciences and not 0402 Geochemistry and not 0503 Soil Sciences and not 0603 Evolutionary Biology and not 0608 Zoology and not 0699 Other Biological Sciences and not 0799 Other Agricultural and Veterinary Sciences and not 0105 Mathematical Physics and not 1002 Environmental Biotechnology.

Appendix B
Annual Survey Questions

Information about your role in the sector: The aim of this section is to help us understand the work currently taking place within the marine energy sector.

1. What is the name and location of your organization?
2. How many people work on marine energy-related projects in your organization?
3. If you have more than one person in your organization, are you completing this survey for your organization as a whole?
4. *Mark only one oval.*
5. Yes, my answers to this survey consider my entire organization. No, my answers to this survey consider only myself.
6. What is your title and/or rank?
7. How long have you been involved in the marine energy sector?
8. What kind of work do you do? (check all that apply)
9. What kinds of marine energy technology do you research or develop? (check all that apply)
10. If you conduct research, how would you characterize your research expertise in your own words?
11. In terms of TRL (Technology Readiness Level), what stage(s) of development are the focus of your work? (check all that apply)

Taking the Pulse of the Innovation System: The aim of this section is to help us understand individual perspectives on the health of the marine energy innovation system.

1. What national or international educational or training programs related to marine energy have you participated in or been involved with (taken a training, given a talk at, etc)?
2. When compared to other countries, how strong do you think support for marine energy research is in the United States?
3. When compared to other fields, how strong do you think support for **foundational** marine energy research is in the United States?
4. Generally, how inspired are you about conducting research in or for the marine energy sector?
5. What makes you inspired or interested in conducting research activities in the marine energy sector?
6. Is there anything that makes you less interested, anxious, or just uninspired when it comes to conducting research in or for the marine energy sector?
7. In your opinion, how clear is the path forward for research and development in the following marine energy areas? In other words: how clear are the next steps in progressing knowledge for the field?
8. Generally, what stage of development do you think the marine energy sector is at right now? TRL=Technology Readiness Level (choose the closest one)
9. In terms of the pace of marine energy research and development in the US sector, do you think it is moving:

Understanding University-Industry Interaction: The aim of this section is to understand how universities and the marine energy industry interact.

1. How often do you interact across the university-industry divide? In other words, if you work for industry, how often do you interact with university researchers and visa versa?
2. How do you interact with the National Marine Energy Research Centers (NMRECs)? (choose all that apply)
3. Please list any marine energy-related start-ups that you are aware of that have emerged from universities.

Appendix B
Annual Survey Questions (cont.)

Understanding Engagement with the Innovation System: The aim of this section is to understand how researchers and developers in the marine energy sector engage with or are supported by the innovation system.

1. What testing resources have you used in your research and development of marine energy?
2. What online resources do you use? *Mark only one oval per row.*
3. Are there any other marine energy-related online resources that you use?
4. What granting agencies have you applied to for funding for research or development? (check all that apply)
5. Which marine energy-related organizations do you commonly interact with (attend workshops, seek advice, follow closely)? (check all that apply)
6. Which conferences do you regularly attend? (they DO NOT have to be marine energy-related)

Understanding Innovation System Needs: The aim of this section is to understand gaps in the innovation system for marine energy in the US.

1. Please rate the following kinds of support mechanisms in terms of how they would help you make progress in your research or development:
2. What data or information would help you make progress in your marine energy research and/or development? (your answer does not need to be practical)
3. How often have you been able to access the expertise/professional help that you need in order to conduct your work?
4. How often have you been able to find the technical or professional training that you need in order to progress in the marine energy sector?
5. What kinds of technical or professional training courses or programs would be helpful for the marine energy industry? (university or otherwise)
6. Right now, what do you think the marine energy sector needs in terms of support to be able to innovate? (this could be capacity, funding, knowledge, infrastructure, etc.)
7. Right now, what topics do you think should be priorities for marine energy research?

UMERC Membership: The aim of this section is to gather data on the knowledge created by UMERC members. If you are not a UMERC member, please continue to the next section.

1. Are you a UMERC member?
2. To help us comprehensively track research in marine energy, please list any publications or products you have produced within the last year that may not be available on a common scholarly search engine: (links are fine)
3. Please list any collaborations you have been involved in that have been facilitated by UMERC within the last year:
4. What marine energy-related research are you engaged in right now?
5. Do you have any additional comments for UMERC?

The purpose of this section is to understand the overall diversity of our respondents and to understand whose voice we are hearing.

1. OPTIONAL: What is your age?
2. OPTIONAL: What is your gender? *Mark only one oval.*
3. OPTIONAL: What is your race and/or ethnicity?
4. Optional: Contact Information

Appendix C
Interview Protocol (Researchers)

Sample Questions for Researchers: (keep guiding discussion and questions related to foundational research in marine energy in the US)

- Could you please describe your research and expertise in relation to marine energy?
- Do you feel like you have the resources to conduct your research? What resources would you like to see to further your research?
  - knowledge and human resources
  - physical research infrastructure
- Are you being asked by industry to research things? Do you feel like your research is relevant to the marine energy industry? Do you feel like it is being used? How often do you interact with marine energy technology developers? Who do you interact with? What kinds of knowledge are they seeking?
- Are students asking to gain particular skills? Do you have the resources to teach them or lead them into marine energy careers?
- Where do you see your research in terms of marine energy going in the future? Is there a clear path for where your research is going to be used? If so, where?
- What do you think the marine energy industry needs right now in terms of foundational knowledge? How could this knowledge be strengthened?
- Do you think the sector has a shared vision? (if not, is this a problem?)
-

Moving to UMERC-specific

- How could UMERC support you? How is UMERC supporting you?
- What is the value of university-industry collaboration and how can UMERC strengthen that?
- What foundational knowledge should UMERC focus on?
- If you have one message for UMERC, and this research, what would it be?

Appendix C
Interview Protocol (Developers)

Sample Questions for Technology Developers: (keep guiding discussion and questions related to foundational research in marine energy in the US)

- Could you please describe your technology development and expertise in relation to marine energy?
- Is there a clear path for you to develop your technology? A clear path to market?
- When thinking of the marine energy sector both in the US and globally, would you describe it as competitive or collaborative? Why? Do you think that designs are competing for prominence right now? In what ways?
- Do you think the sector has a shared vision? (if not, is this a problem?)
- How easy is it for you to find the foundational research or expertise that you need to develop your technology? Who do you reach out to? Why?
- Do you feel like you can find the knowledge and human resources that you need to develop your technology? the physical research infrastructure sufficiently supporting your development?
- What is preventing you from developing the technologies that you want?
- Do you think that foundational research is meeting the needs of the marine energy industry? How so/how not? What do you think needs to be researched to meet your needs for knowledge?
- Do you have examples of foundational research that have been helpful to your industrial development? Do you have examples of foundational research that you see as irrelevant to your industrial development? (If knowledge, what? If infrastructure, what? If funding, what?)

Moving to UMERC-specific

- How could UMERC support you? How is UMERC supporting you?
- What is the value of university-industry collaboration and how can UMERC strengthen that?
- What foundational knowledge should UMERC focus on?
- If you have on message for UMERC, and this research, what would it be?

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poet

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