Chapter

Knowledge Management for the Marine Energy Industry: PRIMRE

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Abstract

Marine energy involves capturing power from ocean currents and waves, and natural gradients of temperature and salinity. In nearly 20 years of modern development, the industry has generated considerable knowledge around resource assessment, site selection, technology design, manufacturing, testing, environmental effects, and standardization. The Portal and Repository for Information on Marine Renewable Energy integrates and connects marine energy knowledge hubs into a comprehensive and connected knowledge ecosystem with the goal of progressing the industry. The seven knowledge hubs include the Marine and Hydrokinetic Data Repository for datasets, Tethys and Tethys Engineering for environmental and technical documents, Marine Energy Projects Database for deployment activities, Marine Energy Software for software, Marine Energy Atlas for geospatial data, and Telesto for development guidance. At an early tumultuous time in the industry, these knowledge management systems organize vocabularies, retain important early lessons from developers, guide research activities internationally, inform permitting decisions for regulators, and provide authoritative sources of information for the public.

Keywords: marine energy, wave energy, tidal energy, knowledge hub, data, environmental effects, engineering, software, projects, geospatial, guidance

1. Introduction

The marine environment contains vast amounts of energy in the movement of waves and currents, and in natural gradients in temperature and salinity, which can be harnessed to provide power. Marine energy (also known as ocean energy, marine renewable energy, and marine and hydrokinetic energy) has significant potential to contribute predictable renewable energy to meet rising energy demands, enhance grid resiliency, and meet climate change goals [1]. Each marine energy resource is harvested by a different type of device that optimizes the type of energy, its periodicity, and the scale of the resource.

Waves are generated by wind passing over the ocean surface and friction causing wave crests to form. The wave climate is determined by local wind waves and swells caused by distant storms that can propagate great distances. The global wave power potential is estimated at around 29,500 TWh per year [2], mainly centralized in two westerly zones along the 40–60° latitude bands in both hemispheres [3]. This amount of power is approximate to present global power consumption, though realistic energy extraction is quite variable and is constrained by cost, conversion efficiencies, energy diffusion, and conflicting ocean use. Wave energy is being extracted using a variety of wave energy converters (WECs): point absorber, oscillating water column, attenuator, pressure differential, oscillating wave surge converter, or overtopping device (**Figure 1**). The wave energy industry is in the early stages of development and has few large or long-term deployments on record, though there is substantial research focused on unlocking wave energy developments.

Currents consist of movement of water in the oceans and exist as tidal currents and persistent ocean currents, which can be harvested for energy. In addition, the open flow of large rivers can also be harnessed for energy generation. Tides are driven by the gravitational pull of the moon and sun, as well as the rotation of the Earth and achieve fast speeds through flow concentration at land constrictions. Large-scale persistent ocean currents, such as the Gulf Stream, are driven by winds, the Coriolis effect, density gradients, and interactions with the continental shelves. Rivers are a byproduct of the water cycle and gravity, as runoff from precipitation moves from higher elevations towards oceans or basins. Approaches that completely restrict flow, such as dams and tidal barrages, are not considered as marine energy. The global tidal power potential is estimated at around 1200 TWh per year [4], concentrated at inlets and channels where the landmass constricts flow, though realistic energy extraction is significantly less. Current energy is being extracted in a variety of forms: axial flow turbine, cross flow turbine, tidal kite, Archimedes screw, or oscillating hydrofoil (**Figure 2**). The global tidal energy industry is more developed than that of wave energy, with more technology convergence on axial and cross flow turbines, some longer-term deployments, and the first commercial arrays coming online [5]. The high energy and often murky waters in tidal areas challenge the survivability and lead to high costs of deployment and operations [6].

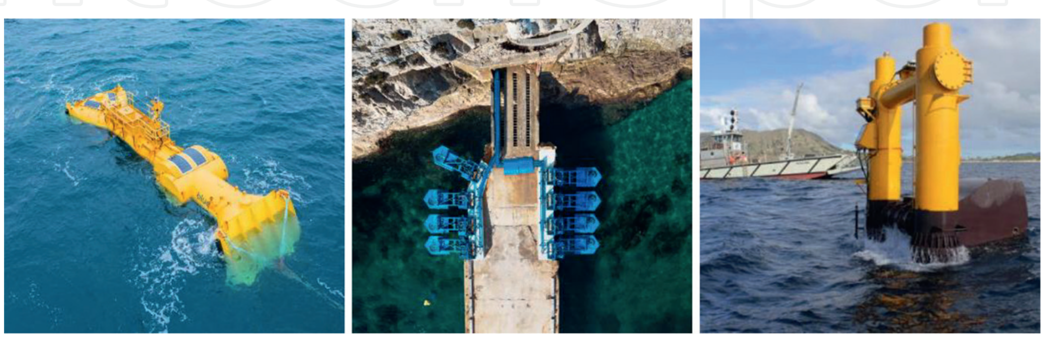

Figure 1.
Examples of wave energy converters tested around the world. Pictured from left to right are Mocean Energy's Blue X attenuator deployed in the United Kingdom, Eco Wave Power's point absorbers deployed in Israel, and Azura Wave Energy's point absorber deployed in the United States.

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Figure 2.
Examples of tidal energy turbines tested around the world. Pictured from left to right are Andritz Hydro's HS1500 in the United Kingdom, Orbital Marine Power's O_2 in the United Kingdom, and Verdant Power's Gen5 KHPS in the United States.

Ocean thermal energy conversion (OTEC) involves harnessing energy from the difference in temperatures between warm upper layers and cold deep layers at about 800–1000 m depth [7]. Heat is accumulated in the ocean's surface by solar irradiance, warming the surface waters in the tropics. The global thermal power potential is estimated at 34,500 TWh per year [8], concentrated between 30° north and south latitudes where the differential between the surface water and deep-water temperatures are at least 20°C. All the existing OTEC technologies use heat exchanges in conjunction with systems that use seawater or a working fluid for power conversion. Several OTEC demonstration projects have been deployed around the world (**Figure 3**) and the technology is emerging as a viable means of baseload power production, as well as providing ancillary services for freshwater desalination, fertilizing seaweed production, and seawater air conditioning. High capital costs have prevented commercial scale deployment of OTEC to date, reflecting the large size of the piping and plant systems.

Figure 3.
Examples of OTEC demonstration projects around the world. Pictured from left to right are the Makai Ocean Engineering plant in Hawaii, United States, and the Okinawa Prefecture OTEC Demonstration Facility in Okinawa, Japan. Facility in Okinawa, Japan. Photo provided by Okinawa Prefectural Government, Industrial Policy Division.

Salinity gradient generation involves extracting energy from the chemical potential between saltwater and freshwater, using pressure across semi-permeable membranes or ion-exchange membranes [9]. There is an estimated 1650 TWh per year [10] of technical potential power generation, concentrated at locations where large rivers flow into seawater. This technology has limited deployments [5] and is still the subject of considerable research and development before widespread commercial deployments will become feasible.

Internationally, the development of marine energy technologies has taken place largely over the past two decades. As an emerging field, information on marine energy has been distributed in many formats and locations, and critical lessons learned from early deployments may have been lost as early pioneering companies were liquidated or merged [11]. The natural progression of the industry has led to the development of several knowledge management systems around the world.

The value proposition for these knowledge management systems is to support the efficient advancement of the industry. Knowledge ultimately creates the foundation on which new advancements are rooted. Learning from existing efforts yields better efficiency by preventing the duplication of activities. Knowledge must be well archived to assess knowledge gaps that inform future targeted research, and widely accessible for multiple audiences. Dissemination of knowledge may also generate important financial investments as investors gain a clearer picture of activities. Creating authoritative sources of knowledge may also prevent the spread of misinformation among the public. Finally, knowledge management systems and the networks they support encourage partnerships and collaboration.

Within the United States, early knowledge management systems funded by the U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO) included Tethys and the Marine and Hydrokinetic Data Repository (MHKDR). Tethys was developed in 2009 and collects documents on the environmental effects of marine energy, while MHKDR was developed in 2015 and stores marine energy datasets generated from WPTO-funded research and development activities. Many smaller resources and online tools were also created at that time but were scattered among various websites. In 2018, WPTO funded three national laboratories – Pacific Northwest National Laboratory (PNNL), National Renewable Energy Laboratory (NREL), and Sandia National Laboratories (SNL) – to develop a system that would coordinate these databases and future databases into a single system known as the Portal and Repository for Information on Marine Renewable Energy (PRIMRE). This chapter will describe this effort to coordinate databases and knowledge across the developing marine energy industry.

2. Portal and repository for information on marine renewable energy

As the concept for PRIMRE (https://primre.org) was developed, the team considered that knowledge hubs like Tethys and MHKDR hosted very different types of data and information and had intentionally unique designs. These differences precluded combining the existing as well as future knowledge hubs into a single database. Rather, PRIMRE was envisioned to aggregate and combine different knowledge hubs under a single banner with strong internal connections, while allowing each to retain a unique identity, thereby valuing flexibility over conformity. A gap analysis was conducted to design and determine the content for five additional knowledge hubs: Tethys Engineering, Marine Energy Projects Database, Marine Energy Software,

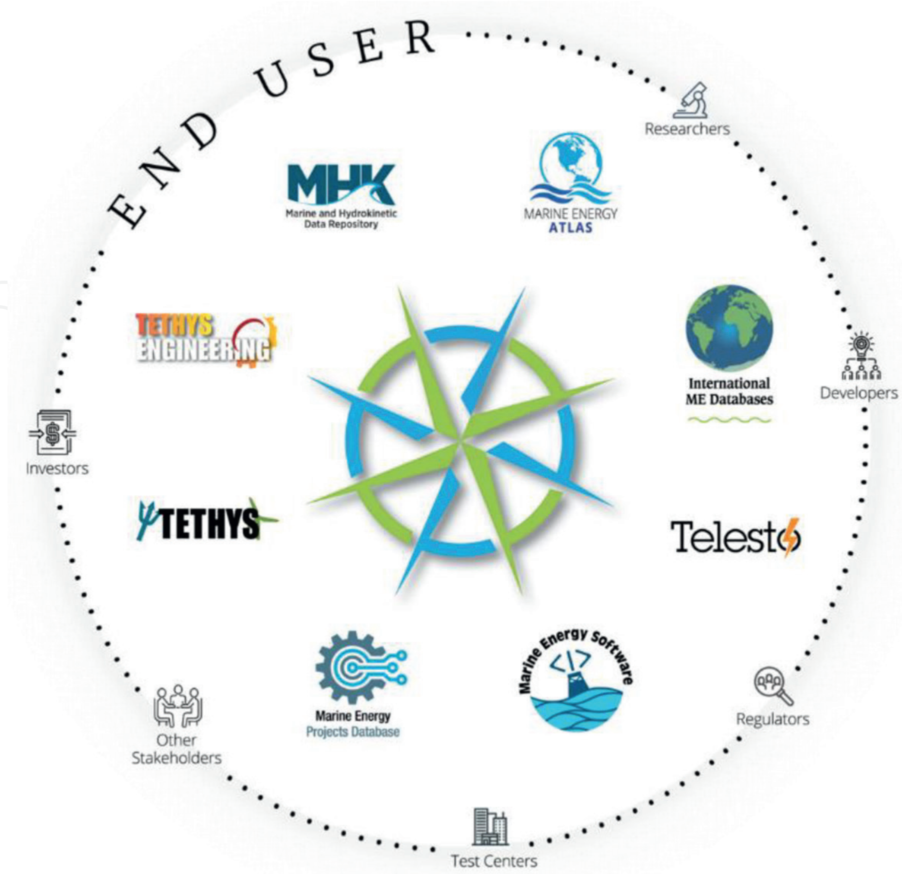

Figure 4.
Diagram of the PRIMRE system, indicating the seven knowledge hubs and the end users that are targeted by the information.

Marine Energy Atlas, and Telesto. These seven knowledge hubs form the ecosystem of PRIMRE (**Figure 4**) and will be described in more detail below. Interconnectivity between the databases was designed as a single aggregate search in PRIMRE, powered by a published metadata standard [12] and uniform Application Programming Interface (API) exchanges.

2.1 Design theory

The grand vision for PRIMRE was to create a coordinated ecosystem of industry-specific knowledge to overcome information barriers for research, development, and testing to progress the marine energy industry. Each knowledge hub houses a different format of information including data, documents, deployment activities, software, resource mapping, and testing guidance. PRIMRE acts as an umbrella that aggregates the knowledge hubs through a centralized search, while also including high-level information such as an events calendar, webinars, tutorials on marine energy, and educational resources. PRIMRE's goal is to house all relevant types of information in an appropriate location within the knowledge ecosystem. PRIMRE addresses challenges that exist around the difficulty in obtaining information that supports an emerging industry's existing data constructs. Information availability challenges are overcome by encouraging information to be made public, centralizing the information into a one-stop search, providing data and terminology standardization, and cataloging information to make it more discoverable and accessible.

The development of PRIMRE and its knowledge hubs is guided by regular user reviews and a steering committee. On a rotating basis, two knowledge hubs are reviewed each year with short surveys that encourage users to interact with and comment on specific aspects of the website, while their responses remain anonymous. Feedback is compiled into a report and action items are identified that guide development activities. Guidance is also provided by the steering committee that is composed of non-affiliated marine energy experts across industry, universities, test centers, and government agencies. This group meets regularly for updates on PRIMRE activities and provides guidance on critical needs for the marine energy community to the PRIMRE team.

The primary guiding principle reflected in the architecture of PRIMRE is to follow the FAIR data principles [13], making data and information findable, accessible, interoperable, and reusable. FAIR principles are common among data management practitioners, but it has also been applied to general knowledge management. Specifically, PRIMRE is designed to support the FAIR principles:

- **Findable**: PRIMRE follows a semantic structure with descriptive metadata that supports queries and machine readability. Significant focus is placed on search engine optimization and direct outreach to stakeholders. An example of structural enhancements to support findability was the creation of "signature projects", which collate information related to complex projects where information is decentralized. Signature projects are organizational constructs that aggregate information across all the knowledge hubs.

- **Accessible**: All PRIMRE content is free and available to the public, except for some proprietary data that are subject to moratoriums for a period. For all aspects of PRIMRE other than content editing, account login walls are intentionally avoided to reduce barriers that lead to information siloing and limit search engine archival.

- **Interoperable**: PRIMRE created a simplified metadata schema based on the U.S. Project Open Data [14] which allows standardized APIs to exchange metadata between the knowledge hubs and with external databases. Several PRIMRE taxonomies are controlled for consistency, drawing on international standards such as the IEC TC 114 [15].

- **Reusable**: PRIMRE content is always referenced to the appropriate source material, by either serving data with associated reports or deep-linking to authoritative source material such as a developer website. All methodologies for content collection and curation, data processing, and frameworks are made openly available through documentation.

2.2 In practice

While PRIMRE was originally envisioned to tie together existing knowledge hubs, it became apparent that the formats for many data and information sources pertinent to marine energy did not fit into existing knowledge hubs, requiring the creation of new ones. This led the PRIMRE team to create Tethys Engineering, Marine Energy Software, Telesto, Marine Energy Projects Database, and Marine Energy Atlas. Some knowledge hubs effectively live as subdomains under PRIMRE, but each holds a unique identity, structure, and purpose. This structure recognizes the value of content-specific design and branding to create a better user experience. For example, Marine Energy Software can create unique integrations with GitHub that show live statistics on recent code releases, and the Marine Energy Projects Database can generate live graphics that describe marine energy deployments. The user experience is tailored to the information within each knowledge hub, but users do not need to distinguish between knowledge hubs to find the information and can access all information through the PRIMRE aggregated search. By branding each knowledge hubs as PRIMRE, the system connectivity is underscored.

Collating large amounts of marine energy-specific knowledge in one location allows for the creation of products that analyze and leverage the information. PRIMRE is working towards developing "value-added products" that capitalize upon PRIMRE's centralized access to standardized, interoperable data sets to provide insights into industry trends, promote multi-sector analyses, and further advance marine energy research.

In the spirit of accessibility and discoverability, the PRIMRE team actively engages with the community including the marine energy industry, researchers, and other stakeholders. Activities such as search engine optimization, social media engagement, email newsletters, and introductory videos are used to raise general awareness of PRIMRE and marine energy at large. PRIMRE also practices targeted outreach including presentations at marine energy conferences, meetings with marine energy research and industry organizations, webinars, workshops, and more. These outreach activities are directed at enhancing the impact of knowledge management under PRIMRE. While many users may stumble across content in PRIMRE from search engines and are not aware of the broader framework, communicating the integrity of the system builds trust within the marine energy community, prevents duplication of effort with other knowledge management systems, and serves as a model for knowledge sharing around the world.

The knowledge contained in PRIMRE is generally technical in nature, but PRIMRE distills the information for audiences who may be less familiar with the industry. A "marine energy basics" section was created with introductory information about marine energy, including animations that demonstrate common technology types, always linked to more technical resources on knowledge hubs. Educational audiences have also been considered through directed educational resources, ranging from coloring books for children to job postings and educational programs for university and graduate students. Content is often simplified into one-page handouts for better accessibility.

PRIMRE is a platform and resource connecting the marine energy community. PRIMRE maintains an events calendar that tracks marine energy conferences, workshops, and webinars around the world. A bi-weekly newsletter called the PRIMRE Blast highlights funding opportunities, job opportunities, industry news highlights, and new content from the knowledge hubs. PRIMRE also frequently engages with other marine energy knowledge management systems around the world, including through an annual international workshop on data sharing [16].

2.3 Next steps

The PRIMRE knowledge hubs are continuously being updated and may undergo redesigns to improve information organization. The current foci are on reorganizing Telesto around a simulated marine energy development pathway; merging two separate components of Marine Energy Software; enhancing marine energy data pipelines and data lake architectures within MHKDR; and incorporating international GIS data into the Marine Energy Atlas. Each of these improvements are detailed in the later sections of this chapter. Future improvements will be driven by PRIMRE's DOE sponsors and the needs of the marine energy community.

The PRIMRE team is continuously pursuing API exchanges between knowledge hubs and advocates for API development within related marine energy knowledge repositories around the world. PRIMRE is exploring the integration of large language models (LLMs) based on recent commercial artificial intelligence releases, to develop a reliable and accurate chatbot around marine energy information, further encouraging accessibility for the public.

3. MHK data repository

MHKDR (https://mhkdr.openei.org/) was developed using a data management and dissemination platform designed by NREL to make data generated from DOE-funded marine energy research and development efforts available to the public. MHKDR protects DOE's investment in research and development by preserving and providing access to data, disseminating its data catalog to a network of data sharing partners (**Figure 5**), supplying context and metadata to search engines, and by disseminating the findings from DOE marine energy projects to relevant communities so they may build upon the knowledge and experience gained, avoid duplication of effort, reduce costs and risks associated with marine energy development, and accelerate the rate of innovation in renewable energy. MHKDR was built upon lessons learned from other data repositories and the technologies used to implement them, however, it was the first repository of its kind to be hosted in the cloud. The move to cloud hosting aligned with the primary goal of MHKDR, which is to make DOE-funded marine energy data universally accessible. In addition to a cloud-based

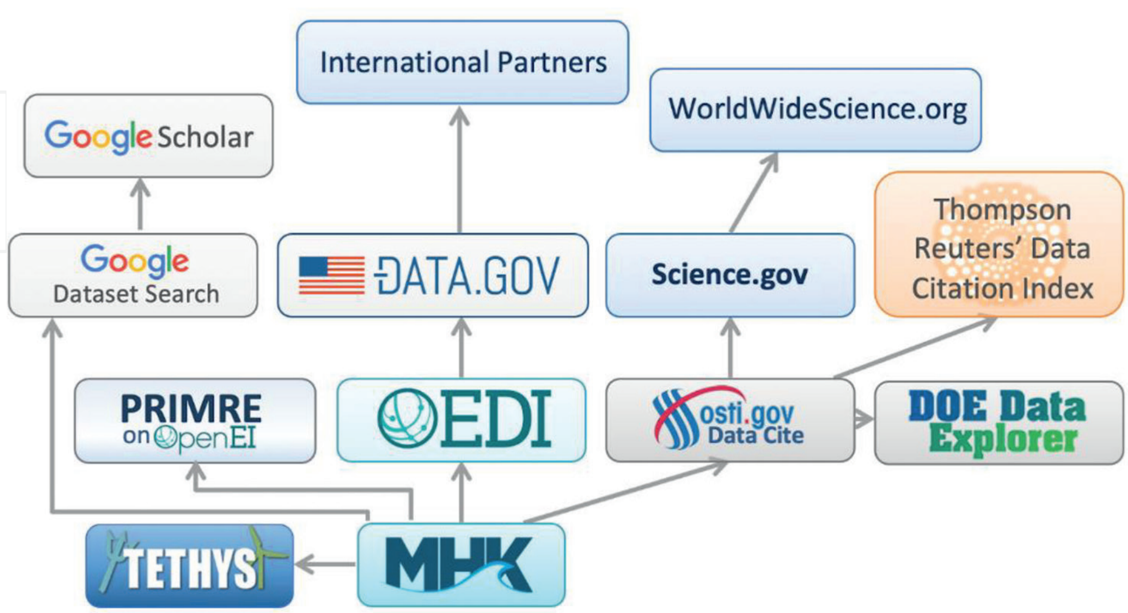

Figure 5.
Diagram of MHKDR's network of data sharing partners. Metadata from the MHKDR data catalog is automatically shared with each of the sites above, allowing users of those sites to access data from MHKDR and PRIMRE systems.

architecture, data standardization was also critical to laying the foundation for the development of marine energy data lakes. However, the practice of standardizing marine energy research data deviated significantly from initial concepts.

3.1 Design theory

The ultimate goal of PRIMRE's cloud-accessible marine energy data lake is to provide universal access to marine energy data. The PRIMRE team realized early on that high-impact, big data sets like DOE's U.S. Wave high resolution hindcast data [17] were inaccessible to many. Despite being publicly accessible, the 28 TB dataset (as of June 2023) simply could not be downloaded, stored, or utilized effectively by organizations that did not possess the high-performance computing and big data storage capabilities required to do so. The sheer size of the data inadvertently limited its availability to only those institutions endowed with the means to utilize it, typically: national laboratories, larger universities, and big corporations. By allowing free data processing directly on the cloud, DOE and the PRIMRE team could open access to big data like the U.S. Wave dataset to anyone, opening the doors for collaboration with smaller universities, high schools, start-up companies, local communities, and other sources of innovation.

MHKDR contains hundreds of datasets from many different research and development projects. To make data more interoperable and to support the development of a marine energy data lake, several data standards were developed and advertised to the marine energy community. The data models, or "content models" as they are called on MHKDR (https://mhkdr.openei.org/models/), are spreadsheet-based templates designed to create homogenous data submissions from a curated list of specific data topics. Data submitters were instructed to translate their data into these spreadsheet models prior to submission. In theory, the data submitters would accommodate the data translation exercise as part of their normal data submission workflow because of the inherent value in interoperable data and their contractual obligation as DOE funds recipients, which required them to do so. And because MHKDR was both in control of the standardization format as well as the sole recipient of that format, the data standardization process would be easy to automate. The spreadsheet-based data models were meticulously crafted and then locked down prior to being made available for download. Automated scripts were added to MHKDR that would recognize content models upon submission and process them, adding their data to a central data lake. The spreadsheet-based structure of the content models would lend itself nicely to a centralized, SQL-based data lake.

3.2 In practice

In practice, MHKDR content models had an extremely low adoption rate. Data translation is time consuming and expensive, especially for non-data scientists. Project data rarely occurs in tabular format and often requires complicated, multi-step conversions to be compatible with the content models.

The assumption that project teams would translate their own research data into standardized formats was fundamentally flawed. Even if required to do so on condition of receipt of funding, most research and development projects are focused on solving their fundamental research questions. Almost all project resources are allocated towards meeting this goal and data acquisition is no exception. Data are collected and organized within the project scope with little regard for extended use beyond the project. Little to no time or budget is allocated for data standardization, contextualization, or dissemination beyond project team members. Even if such allocations were planned, many projects lack data scientists or other supporting staff to help with lengthy or difficult data translations. Lastly, project resources are finite. Deadlines and unforeseen costs exacerbate project resources and ensure that they are only spent on critical tasks. In the end, most projects simply submit the data they have, in whatever state (organized or not) that the data exist in at the end of the project.

Complicating matters, many critical marine energy datasets are not tabular and are simply not compatible with spreadsheet-based data models. Wave data, such as the data featured in the U.S. Wave dataset, are multi-dimensional time-series data that include information on height, period, shape, direction, and more. These data are best stored and queried in high-performance computer and cloud optimized data storage formats. Other datasets on MHKDR are best served in industry standard formats such as video files, seismic data, or 3D modeling formats. Converting these formats to a tabular data standard would essentially render them useless to industry. To preserve the utility of these datasets, the PRIMRE team realized they must be made available in industry standard formats, even if data model standard formats are more efficient or more interoperable.

3.3 Next steps

To address both issues, the PRIMRE team has developed a marine energy data pipeline and integrated it with MHKDR. The Marine Energy Data Pipeline automatically recognizes select data submitted to MHKDR and translates it into standardized formats prior to making the data publicly available. This allows researchers to submit data in the format it was generated, directly from instrument or modeling software. The originally submitted data are preserved for accountability and scientific posterity and presented alongside the translated data so that users of the data have easy access to both formats. The data pipeline process shifts the burden of data translation from the project research teams to an MHKDR data curation team, this way PRIMRE has made the standardization of DOE-funded research data more efficient. Data scientists working for MHKDR, trained in data translation and cloud optimization, can do the heavy lifting, while project researchers can focus on their primary tasks, reserving more funds for research and development in marine energy. As a result, MHKDR's new data standardization policy enables researchers to submit data in any format and data scientists working for PRIMRE will optimize its utility. The increased burden to the PRIMRE team is more economical for DOE as the dozens of individual project teams no longer need access to a data scientist, resulting in program-wide cost savings.

The PRIMRE and MHKDR teams are working together to continue to develop marine energy data pipelines, to automate the standardization and interoperability of marine energy data, and to make those data universally accessible in the cloud.

4. Tethys and Tethys engineering

Tethys and Tethys Engineering are separate knowledge hubs, which share the same content types and design frameworks and will therefore be described together for simplicity. Tethys (https://tethys.pnnl.gov) was developed in 2010 and contains a comprehensive collection of international journal articles, technical reports, and other documents on the environmental effects of marine energy and wind energy. Tethys Engineering (https://tethys-engineering.pnnl.gov) was developed in 2019 and contains international documents on the technical, engineering, and economics aspects of marine energy development and operation. Together, these knowledge hubs cover all topical marine energy areas, providing a fundamental and trustworthy source of information in the form of technical and scientific documents.

4.1 Design theory

The goal of both Tethys knowledge hubs is to aggregate decentralized information into a marine energy-specific repository that serves as an authoritative source for information to inform research gaps analysis, supporting permitting and regulatory decision-making, note engineering advancements, and preserve the history of data and information collection in an emerging science and industry. Scientific and technical documents are the most fundamental and trusted sources of information, including peer-reviewed journal articles, technical reports, conference papers, books, theses, and more. Identification of recent scientific publications is important for building trust that the knowledge hub is comprehensive. Aggregating and organizing these documents form the basis of knowledge on which research synthesis can be developed, as well as providing an information base that can be shared with an emerging industry.

Knowledge collection provides more value when it can be reviewed and synthesized to inform future recommendations for research and development. Progressing the marine energy industry requires that devices be deployed in the ocean, under the auspices of national and regional regulatory requirements. Regulators are tasked with assessing environmental risk of new proposed developments and need a body of research or experiences to support their decisions. The Tethys knowledge bases provide comprehensive and organized information that fits those needs. Similarly, Tethys Engineering provides reliable information that supports the design, prototyping, testing, and development of marine energy devices, considering harsh ocean conditions that challenge survivability, as well as optimizing the energy capture in a cost-effective manner.

The two Tethys knowledge bases act as a platform for disseminating and engaging with the marine energy industry and research community to enable the development pathway and meet regulatory standards. Beyond standard search engine optimization practices, knowledge hubs should perform active outreach and dissemination to a wide variety of end users. This same philosophy has been adopted by PRIMRE, but many of the tactics were identified and refined by Tethys.

4.2 In practice

Both Tethys websites are developed on Drupal [18], an open-source knowledge management system. Drupal provides a robust framework with community-generated modules to allow customization, integration support with other online tools, and ongoing support for security updates. This flexibility supported Tethys as it expanded over time to include additional features such as a marine energy events calendar, bi-weekly newsletter, webinar archive, interactive tools, export APIs, and more. Development of the Tethys knowledge bases follows an agile scrum methodology, drawing on experience and specialties distributed among a team of developers under the direction of a domain-knowledgeable product owner.

Content management is an important aspect of knowledge management and becomes essential when the expectation is that content is required to be comprehensive and up to date. Tethys originally explored automated web crawling methods for content collection, but the approach was quickly abandoned as crawlers struggled to read unstructured gray literature and fell short of expectations around identification of relevant content and proper tagging. Tethys has adopted a manual approach, employing a team of early-career researchers trained in appropriate entry and tagging, with oversight including refining of tags [11]. User reviews are conducted annually, soliciting user input on the comprehensiveness of the content, the functionality of each site, and identification of missing seminal documents. The continued engagement of a core group of researchers and other stakeholders support the usefulness and comprehensive content of the Tethys knowledge hubs. The collection is kept up to date by following domain-specific distribution lists and collecting input from members of the community. The relative youth of the marine energy industry assures that nearly all content is digital and can be made available, pending copyright laws. The Tethys websites exclusively contain documents that can be accessed with a link or with an uploaded file, so there are no references to documents that cannot be found. Tethys is unique in that it supports two domain spaces: marine energy and wind energy. As such, there are filters and divisions woven throughout the knowledge hub to allow users to choose content matching their interests.

To support information synthesis, Tethys is the serving platform for several international collaborations, including a task under the International Energy Agency's Technology Collaboration Ocean Energy System's Environmental (OES-Environmental) task and the International Energy Agency Wind Committee's (WREN) task. These groups leverage existing information to generate extensive synthesis reports that characterize the state of science for the industry (e.g., [19]), while also distilling the key information into illustrated digestible summaries for a less technical audience. International working groups spear-headed the creation of tools like the management measures tool (https://tethys.pnnl.gov/management-measures). Tethys Engineering was created more recently and is not currently the platform supporting international working groups or synthesis efforts, so that the impact cannot be evaluated as well in terms of number of users, name recognition, and references. This further highlights the importance of synthesis.

Tethys pioneers many forms of outreach and has achieved international name recognition, substantial visitors, and unanimous support and trust from the marine energy community. Tethys is technical by nature but attempts to distill information with the creation of illustrated summaries that focus on specific environmental interactions (e.g., collision risk of animals with turbine blades), while providing links to supporting documents as citations. An entire suite of educational materials has been created for students from primary school through college, including coloring pages and age-specific webinars (https://tethys.pnnl.gov/marine-renewable-energy-educational-resources). The team manages a mailing list to send new publications and industry announcements to nearly 3300 subscribers, effectively providing push notifications of content rather than waiting passively for users to search for content on Tethys. Significant effort goes into search engine optimization including crafting accurate and detailed metadata descriptions, exchanging links with other authoritative websites, improving speed and accessibility metrics, submitting a sitemap, and remaining stable and authoritative over a long time.

4.3 Next steps

With separate sponsors funding the wind energy and marine energy sides of Tethys, there are positive iterative improvements made by each respective sponsor that draws on the experience of the other. An example was the creation of the management measures tool for marine energy which catalogs environmental management and mitigation techniques available to developers; wind energy sponsors requested a similar tool but geared more towards a catalog of active monitoring technologies rather than methodologies, and several innovative features were replicated on the marine energy management measures tool.

Tethys Engineering lacks some community support compared to Tethys and is more often grouped under the banner of PRIMRE, but it may benefit from engagement with international working groups that can actively perform synthesis of the content. Leveraging PRIMRE-developed API schemas, Tethys content can be searched from Tethys Engineering and vice versa to make a seamless connection between the databases. This is aided by the two sites having identical frameworks, differing only in content scope.

Both Tethys knowledge hubs are expected to continue steadily increasing in content and functionality, remaining as backbones of information to support the advancement of the marine energy industry. User reviews, direct feedback from the community, and active engagement with researchers, regulators, and marine energy device developers guide new website development activities. Requests are from external knowledge hubs wishing to ingest Tethys or Tethys Engineering content into their websites becoming increasingly common. The Tethys and Tethys Engineering project teams are keen to support these requests to reduce redundant creation of competing knowledge repositories.

5. Marine energy projects database

The Marine Energy Projects Database (https://primre.org/Projects_Database) originated in 2018 with a U.S. DOE compilation of international planned, ongoing, and completed marine energy deployments. The list was restructured, expanded, and converted to a PRIMRE knowledge hub, launching in 2022. The Marine Energy Projects Database contains international information about marine energy projects, test sites, devices, and organizations engaged in marine energy development. The intent of the knowledge base is to support a range of users through transparency of information, including investors in understanding industry trends to guide investment decisions, researchers identifying knowledge gaps, regulators finding comparable deployments and forecasting industry growth, marine energy developers in communicating progress and seeking collaborators, and the public.

5.1 Design theory

The Marine Energy Projects Database is designed with a semantic structure that clearly defines taxonomies, relationships between content, and supports efficient querying of content. For example, a device is linked to projects and test sites where the device has been deployed, as well as to the manufacturer's organization page. A semantic structure provides a natural way for users to explore the content, supporting intuitively filterable searches as well as natural page progression through content. Live graphs convey statistics to communicate industry trends.

Content curation is designed to be open to the public so that developers can add or update their own entries through simple form submissions. This creates transparency and allows users to take ownership of their content if they wish. However, with the realistic expectation that the public alone will not create comprehensive and up-to-date content, a trained team of content curators review and add content on a regular basis.

5.2 In practice

The Marine Energy Projects Database is created on Semantic Mediawiki [20], within a subdomain of PRIMRE. It was designed with two different methods of exploring the system. The landing page is a faceted search that adds results matching keywords and limits results based on facet filters. This user-friendly and familiar interface allows the user to explore the entire database but is somewhat limited by only returning views for a subset of the content, as well as creating some inconsistency between different content types. The second method of exploration includes a searchable and sortable table view for each content type, highlighting key relevant fields for specific content types. Content-specific views also support live graphs with statistics on industry trends. Providing both query options allow for the user to choose the pathway most suited for the use case of interest.

Creating a highly interconnected database required a mapping exercise to identify how content is related to each other, including directionality of relationships and inheritance of properties. For example, a project should identify related devices but should inherit a technology type from the device. Queries become complex when mapping both directions and chaining relationships, but they enable a natural experience when exploring content. For example, searching for an organization that creates a device will return a listing of marine energy projects where the device was deployed.

Collection of content is uniquely challenging in a dynamic and emerging industry like marine energy, at times resulting in poorly documented or accessible information. Content entry is primarily conducted by a team of trained entry-level researchers with top-down supervision, documented search methodologies, and internal tracking mechanisms. The content team originally focused on updating the original list of deployments to match the expanded schema of information fields. Organizations were systematically updated from company websites and other online sources such as social media, while associated devices, projects, and test sites were flagged for updates. New content is discovered by following news releases from industry distribution lists and government funding announcements and by community suggestions, often from device developers.

5.3 Next steps

Outreach efforts will continue to seek buy-in from developers and manufacturers to begin updating their own content, while the PRIMRE team will continue to update content. Information about projects and organizations are rather fundamental to the industry, and other areas of PRIMRE collect similar information from various sources. One major next step will be using APIs to exchange the data with other knowledge hubs to reduce duplication. An example is that the Marine Energy Atlas receives project information from international sources and therefore has a subset of projects listed in the Marine Energy Projects Database, so workflows are being created so that the international sources feed directly into the Marine Energy Projects Database, which can be imported into the Marine Energy Atlas.

6. Marine energy software

The Marine Energy Software knowledge hub (https://primre.org/Software) is a collection of commercial and open-access software relevant to marine energy that was launched in 2020. This knowledge hub contains a variety of software packages used by the marine energy community to aid in analyses across the scope of marine energy such as engineering and technical design, operations and maintenance, environmental assessment, economics and performance metrics, optimization, and data analytics and visualization. While the marine energy industry calls for a breadth of analyses to be performed, the members of the community often have a more focused line of expertise, and this makes it difficult to know what software tools are available to perform other aspects of the marine energy projects that fall outside of their line of expertise. This created a need for developing a collection of the software tools that are used by the marine energy community to accelerate industry development and identify gaps where the availability of software is lacking or underrepresented. This need led to the development of the Marine Energy Software knowledge hub. Currently, this knowledge hub is split between the Code Hub and Code Catalog with each developed around the familiarity and expectations of their respective target audiences.

6.1 Design theory

The main goal of the Marine Energy Software knowledge hub is to provide a space where relevant marine energy software and content about the software is aggregated and available for universal access. This goal called for the Marine Energy Software pages to be hosted on public web platforms. Moreover, an aspect of this universal access goal is to provide relevant information that will aid decision-making around adoption of individual and/or suites of software. Relevant information to display is based on target audiences, because some intended users rely on open-source software while others are more comfortable using commercial software. Users of open-source software have typically become accustomed to using version-control systems for software development such as GitHub and GitLab when it comes to searching and browsing open-source software packages that they can adopt. This is because these platforms not only allow the software development to be controlled, but they also allow the potential user to understand how well maintained the open-source software is and the depth of the adoption among users. This differs from users of commercial software in that they are more likely to use catalogs that compare software packages that were developed for specific purposes and do not necessarily rely on understanding how the software is maintained. This difference in the target audience called for two separate resources to be developed.

Another goal of the Marine Energy Software Knowledge Hub was to allow developers to easily maintain content. This is because the marine energy space is constantly evolving with new needs and software development to address these needs. Thus, Marine Energy Software was designed to allow new software or new versions of existing software to be easily incorporated into each resource. Moreover, the ability for users to also add software was incorporated to allow the community to also contribute to what is found within the knowledge hub.

6.2 In practice

Marine Energy Software is split between the Code Hub and Code Catalog. The Code Catalog was developed using Semantic MediaWiki [20] within a subdomain of PRIMRE and it is composed of results following a standard template of relevant information for open-sourced and commercially available software within the resource. The search page has facets that can filter results within the catalog by price, commercially available or open-source, license and development status, and relevant marine energy technology types. Users can register their software to be included in the Marine Energy Software knowledge hub using a standard submission form.

The Code Hub is hosted outside of PRIMRE on a site that was developed using the React framework and it is composed of a GitHub software collection. Only open-source software is currently included within the Code Hub. The Code Hub features automatic pulls from the GitHub repositories for all open-source software to feature new releases on the landing page, so users are made aware of new software releases. Users can navigate and browse the Code Hub with the search bar or filtering by facets. Like the Code Catalog, Code Hub results provide metadata on open-source license type, marine energy technology type, and the domain-specific use for the software. The Code Hub also provides metadata and metrics that are relevant to software development, such as maintenance and adoption by the user community. Users can add their open-source software to the Code Hub by using the same standard submission form that is used by the Code Catalog.

6.3 Next steps

A user review in 2021 revealed that there was confusion over whether to use the Code Hub or Code Catalog to find relevant software of interest. To streamline and unify access to the software and software content, the Code Hub and the Code Catalog will be combined into one resource. When users search through the reorganized Code Hub, the content and schema from the Code Catalog will be combined with the existing Code Hub repository content. This improvement eliminates confusion and reduces knowledge hub maintenance costs. User reviews will continue to identify development priorities and new content, so that the knowledge hub will continue to grow with the marine energy community.

7. Marine energy atlas

The Marine Energy Atlas (https://maps.nrel.gov/marine-energy-atlas/) is an interactive, open-access web application that allows users to visualize, analyze and download spatial data related to the marine energy industry. The overarching goal of the application is to make it easy for different stakeholders to access data that can help them plan for marine energy projects, whether for device design or project siting. The datasets on the Marine Energy Atlas can be queried and downloaded, and the application features an in-app processing tool that performs easy analyses within an internet browser. The back-end architecture of the Marine Energy Atlas is the Visualization Analysis Design Research (VADR) system, which has a "future-proof" structure with the potential for adding new layers, updating data, and adding in-app processing tools.

7.1 Design theory

The Marine Energy Atlas is primarily an interactive map viewer. Multiple layers can be visualized on the map at the same time. The layers are organized by dataset in the Data Library, which is easily searchable, and users can browse tags to further narrow down layers of interest. Through the legend panel, layers can be elevated, removed, and opacity can be changed so that overlapping layers are still viewable. With the layers on the map, the user can quickly query the layers using the tools on the map, either via a coordinate or shape. Querying through the application allows the user to quickly identify areas of interest without needing to download the entire datasets while also allowing them to inform their interrogation if the dataset is downloaded.

The VADR system on which the Marine Energy Atlas is built is a monolithic code repository that allows for the shared maintenance of the Marine Energy Atlas codebase. It has been designed with modularity in mind, with Docker images being the primary deployment architecture to better support updating and maintaining applications. Improvements made to other parts of the repository allow for the Marine Energy Atlas to benefit without any additional cost. VADR utilizes a Continuous Integration/Continuous Delivery pipeline to permit seamless deployments and updates to the AWS infrastructure that backs the Marine Energy Atlas and other applications. Marine Energy Atlas and all VADR applications are built with modern tools and libraries that are actively maintained to allow for ease of maintenance.

7.2 In practice

Resource assessments of U.S.-based marine and hydrokinetic resources are the featured data layers on the Marine Energy Atlas. The U.S. DOE WPTO Wave Hindcast Dataset (https://www.nrel.gov/water/wave-hindcast-dataset.html) contains the highest-resolution time-series data on wave attributes in U.S. waters. The six variables are defined by the International Electrotechnical Commission Technical Commission 114 wave resource assessment technical specification [21], are available in a spatial resolution as fine as 100 to 200 meters in shallow water and a three-hour time step, and span from 1979 to 2020. The Marine Energy Atlas also contains resource data on ocean currents, temperature, salinity, tidal and river currents, and links to buoys that collect real-time wave data.

The Marine Energy Atlas also contains non-resource spatial data that helps stakeholders approach other facets of project planning. Through a partnership with OES, international layers were added to the Marine Energy Atlas. The new data feature locations of marine energy projects at different stages, as well as the locations of marine energy test facilities. Other new layers include spatial data on ports, population density, marine protected area shapefiles, and bathymetry.

The Capacity Factor Tool is an in-app processing tool that allows users to create capacity factor maps for a specific wave energy converter. The capacity factor is a calculation that represents the ratio of the actual time-averaged power generation to the maximum possible power generation of a particular device. This quantity is key for estimating the power output of devices that utilize intermittent energy sources, such as waves, as that device will not always be operating at peak performance. In the Marine Energy Atlas's Capacity Factor Tool, users can upload a power matrix that reflects their wave energy converter. The tool uses the significant wave height from the WPTO Wave Hindcast Dataset and the uploaded power matrix to generate a capacity factor map, based on underlying calculations and previously determined joint probability distributions. The results are generated in minutes, thanks to these optimized underlying calculations.

7.3 Next steps

The Marine Energy Atlas will continue adding spatial layers beyond resource assessments to aid in project siting and planning. Additionally, development of new in-app processing tools will further the utility of these layers by allowing users to perform geospatial analyses and interact with the data, without downloading data.

8. Telesto

Telesto (https://primre.org/Telesto) is a collection of wiki-based information pages and databases that was developed using Semantic MediaWiki [20] under a subdomain of PRIMRE. Telesto was initially developed in 2020 as a collection of databases and wiki-based guidance for technical information on marine energy that would be developed, curated, and maintained by the community. Some initial pages were created for marine energy measurement and testing guidance, as well as a sensor and instrumentation database and a testing facilities database. This type of information was useful for the community, but it lacked other relevant information such as regulation and permitting, resource characterization, and industrial materials. Moreover, the community engagement with Telesto slowed after the initial development phase and much of the information contained within Telesto became outdated, resulting in a poorly integrated and maintained set of web pages that needed reorganization. In 2023, Telesto was reorganized around the theme of providing information relevant to the stages of marine energy development.

8.1 Design theory

The reorganization of Telesto required a new central theme and design. The breadth of relevant information not already captured in one of the PRIMRE Knowledge Hubs meant that the reorganization should incorporate content that was dispersed across PRIMRE while allowing for flexibility in how the content was structured (e.g., wiki or database). Review of existing information led to a reorganization under the theme of a project timeline. The reorganization creates a landing page that links to five sub-pages of content organized by the stages of marine energy development: Planning, Design and Build, Testing and Measurement, Deployment, and Decommissioning. These stages also appear on a horizontal navigation bar that links all pages within Telesto to a specific development stage. This organization allows links to content from other Knowledge Hubs and other PRIMRE organizational schemes (e.g., Signature Projects, Marine Energy Basics), integrating the entire PRIMRE site and bringing greater attention to some content, like international standards. It also provides a home for some content which have had no well-defined home but are frequently used by the marine energy community.

8.2 In practice

Telesto content were organized under the new theme and linked accordingly. Some topics were found to span the entire development life cycle and were highlighted with separate pages: Lessons Learned; Performance Metrics; Economics; and Compliance. This creates multiple levels of visibility for finding this content, either through dedicated pages or the development life cycle themes.

With respect to design, the initial reorganization effort for Telesto visualized a somewhat linear timeline. An initial review of this design from the marine energy community pointed out that technology development in any field tends to be an iterative process of design and testing, sub-scale construction and deployments, followed by additional design and testing until a full-scale deployment may be considered possible. The Telesto reorganization pivoted away from the idea of a timeline and more towards the idea of a design pathway. Pathways can be non-linear but hopefully lead to a destination (e.g., full-scale deployment).

8.3 Next steps

The Telesto reorganization is identifying new locations for content. Although requests for new Telesto content (e.g., data/information from projects, marine energy tools and applications) regularly arise, a formal process has been designed to incorporate new future requests. Unlike all the other knowledge hubs, Telesto is the only unstructured, non-semantic database, and plays an important role of aggregating information and resources under this new cohesive theme.

9. Conclusion

PRIMRE is an expansive network of knowledge hubs focused on the emerging marine energy industry. Seven unique knowledge hubs represent different content scopes and formats that are connected by a centralized search. The scope encompasses comprehensive of authoritative information and data about the marine energy industry. Content is gathered from around the world except for datasets in MHKDR and the Marine Energy Atlas because of data mortgage limitations. While the marine energy industry is still progressing towards commercialization, this framework sets the stage for organized and efficient growth of the industry through accessible information about relevant technical, environmental, and socio-economic research and development.

Design and implementation of PRIMRE was not without challenges. The following list highlights lessons learned during the knowledge management process:

1. **Branding:** Naming conventions are bound to change with emerging technical domains. A great example is that the U.S. originally referred to this industry as "marine and hydrokinetic energy" to encompass riverine technology, before shifting towards "marine renewable energy" to match international conventions while distinguishing from non-renewable offshore energy, before ending at "marine energy" for brevity. This resulted in some database name changes along the way, though MHKDR and PRIMRE were not renamed because of established branding.

2. **Documenting procedures:** Over five years, PRIMRE has lost several key staff that were vital to the project, leading to setbacks. This raises the importance of documenting procedures and building redundancy for activities and capabilities.

3. **Multidisciplinary team:** The PRIMRE team is composed of software developers, domain experts for engineering and environmental effects, and communications and outreach professionals. Domain diversity supports successful decision-making and project direction.

4. **Sponsor support:** The U.S. Department of Energy provides more than just financial support, also providing encouragement that funding recipients contribute content, connections with international groups like Ocean Energy Systems, and legitimization of the activities.

5. **Continuous funding:** Knowledge management cannot be set up and forgotten, or the initial investment is meaningless. It requires active investment to maintain online security and development, ensure that content is recent, and to engage in outreach. The expenses often lead private companies to monetize the information, but public funding supports the accessibility and stability of collected information.

6. **Active outreach:** With all the time and money that goes into knowledge management, from architecting the system to collecting and curating the content, the goal is that the target audience is aware of and using the system. This highlights the importance of performing search engine optimization, attending industry conferences, connecting with other domain-specific networks, generating educational materials, and hosting online events to drive additional impact.

Measuring the impact of knowledge management is challenging. Web analytics can provide counts of visitors and pageviews, which gives a measure of exposure that can be influenced by global awareness or interest in the topic. During the last year, all the knowledge hubs cumulatively received over 800,000 pageviews from 250,000 visitors. PRIMRE tracks usage metrics for each knowledge hub independently and reports on these metrics annually, demonstrating continued growth. Though it is difficult to know whether to attribute this growth to an increase in content, enhanced search engine optimization, or general growing interest in marine energy. A more subjective way to measure impact is through informal comments made by key members of the marine energy community at industry events. Most of the U.S. and international communities are aware of PRIMRE and provide overwhelmingly positive feedback as to the functionality and utility of the information. Anonymous feedback is also requested from the community each year through rotating user review surveys.

An emerging industry like marine energy is a fascinating setting to practice knowledge management because the knowledge hubs are built from the ground up without competing entities. This can be juxtaposed against the offshore wind energy industry, which is a comparable renewable energy industry, but one that is commercialized as a competitive grid-scale energy source. While there are some quality knowledge hubs supporting offshore wind, it is common for there to be less connectivity between efforts, paid membership requirements to access information, and significant gaps in knowledge (e.g., many countries lacking data repositories). These factors are believed to negatively contribute to public opinion of offshore wind energy. By comparison, setting up a robust and transparent network of databases at the start of commercialization may support transparency and combat misinformation. Time will tell how impactful the PRIMRE knowledge management will be as the marine energy industry progresses towards commercialization.

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Nomenclature list

API	application programming interface
DOE	department of energy
LLM	large language model
MHKDR	Marine and Hydrokinetic Data Repository
NREL	National Renewable Energy Laboratory
OES	Ocean Energy Systems
OTEC	Ocean Thermal Energy Conversion
PNNL	Pacific Northwest National Laboratory
PRIMRE	Portal and Repository for Marine Renewable Energy
SNL	Sandia National Laboratories
TWh	Terawatt-hour
VADR	Visualization analysis design research
WEC	wave energy converter
WPTO	Water Power Technologies Office
WREN	Working Together to Resolve Environmental Effects of Wind Energy

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