Tethys knowledge management system: Working to advance the marine renewable energy industry

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Abstract—**Development of the marine renewable energy (MRE) industry has been challenged by uncertainty about potential environmental effects, which has resulted in slowing of permitting/consenting processes, and ultimately to constraints on the industry. These challenges result from a lack of sufficient devices in the water from which to learn, a dearth of quality monitoring data, and a lack of accessibility to information about these effects in general. This paper describes an ongoing process to improve understanding of the environmental effects of MRE through a public, online knowledge management system funded by the U.S. Department of Energy, known as *Tethys* (https://tethys.pnnl.gov). *Tethys* collects and curates relevant documents while supporting a diverse international community through intentional outreach and synthesis activities, which occurs largely through an international collaboration under the IEA Ocean Energy System's OES-Environmental, formerly known as Annex IV. After nearly ten years of operation, *Tethys* is internationally recognized and viewed as a trusted broker of information, with over 75,000 visitors annually. *Tethys* has provided clarity around environmental effects during a critical time in the industry when deployments are increasing in size and frequency.**

Keywords—**database, environmental effects, emerging industry, knowledge management system, marine renewable energy.**

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I. Introduction

As countries seek to meet renewable energy goals and diversify their national energy portfolios, marine renewable energy (MRE) devices that capture energy from ocean tides, waves, and currents are under development. As early as the 1970s, MRE developers have created and deployed small prototype devices, yet there are few full-scale commercial arrays currently deployed around the world. The primary challenges facing this industry include designing devices that harvest energy efficiently, surviving the harsh ocean environment, and reducing potential impacts to the marine environment [1]. The industry has been largely driven by small businesses that often focus on the challenges of efficiency and survivability while neglecting the need to address permitting/consenting requirements, most of which are concerned with potential environmental effects.

Stakeholder concerns about potential environmental effects appear to be based on the novelty of the technologies, the entry of MRE as new users of the ocean space, and concerns of negative outcomes for specific animal populations, many of which are already under stress from climate change and other anthropogenic activities. Examples of environmental effects of concern include collision risk to marine mammals or fish from rotating tidal turbine blades and the effects of underwater noise on marine animals [2], which can have population-level consequences [3]. Stakeholder concerns about the potential environmental effects of MRE have contributed to the delay or abandonment of some proposed MRE projects, which has hindered overall progress of the MRE industry [4].

Understanding these environmental concerns has proved challenging as there are a lack of research and monitoring data and information around devices that can inform regulators and stakeholders. Few devices deployed at sea have collected environmental monitoring data, and some companies that sponsored early deployments are no longer in business, making their knowledge and experience difficult to access. Understanding often must be gleaned from models (e.g. [5][6]), laboratory experiments (e.g. [7][8]), and analogous industry interactions in the marine environment (e.g. [9][10]). Decision makers need access to a broad range of research, monitoring outcomes, and modeling studies to make informed decisions that protect the marine environment while allowing the industry to progress [11][12][13].

With the goal of increasing global understanding and reducing environmental monitoring costs to advance the MRE industry, the U.S. Department of Energy's Water Power Technology Office directed Pacific Northwest National Laboratory (PNNL) to create a knowledge management system focused on the environmental effects of MRE development. PNNL developed *Tethys* (https://tethys.pnnl.gov) to collect information on the environmental effects of MRE and make it accessible to the public. Development began in 2009 with *Tethys* formally launched in 2012 [14]. Information on the environmental effects of land-based and offshore wind energy development was later included on *Tethys*, but MRE continues to be the driver behind the website design.

While technical elements and power performance of MRE devices are considered proprietary, interactions between devices and the environment are more often viewed as challenges that all developers and stakeholders must address and are appropriate areas of study where the MRE community can benefit from cooperation and sharing of information. The importance and possibility of sharing information on environmental effects of MRE prompted the U.S. to propose a task under the International Energy Agency's Ocean Energy System, known as OES-Environmental, formerly known as Annex IV. Led by the U.S., currently 15 nations participate in implementing OES-Environmental by providing environmental information to facilitate efficient and effective regulatory processes for permitting/consenting deployment of MRE devices, most notably tidal turbines and wave energy converters. PNNL implements OES-Environmental on behalf of the U.S., seeking to support the development of a commercial MRE industry that provides electricity to national grids and other smaller markets. *Tethys* was chosen as the platform to host OES-Environmental activities, further elevating the usefulness of the system as a powerful conduit for outreach and engagement with the international MRE community.

II. METHODOLOGY

Tethys was originally designed after PNNL's Knowledge Encapsulation Framework (KEF), which coalesced several common web tools into a single seamless tool that allows relational data links. Using a relational database means that each entry is comprised of fields that can be queried into views such as tables, with a data structure that can easily be read by search engines through this consistent structure. In 2013, *Tethys* was moved from the Semantic MediaWiki platform to the Drupal platform as it offered similar capabilities, with improved integration, security, and community support. Tethys is currently undergoing substantial changes during a transition from Drupal 7 to Drupal 8 necessitated by the end of security support, with the transition expected at the end of 2019.

Content on *Tethys* is primarily comprised of documents including scientific journal articles, reports, conference papers and presentations, book chapters, theses, and other media. Inclusion of documents is limited to maintain scope relevance, but no judgements are made to the accuracy or realism of papers. The collection supplements peer-reviewed literature with grey literature, or documents that are not subject to the traditional academic peer review process, such as monitoring and technical reports and working papers. Grey literature compliments scientific peer-reviewed documents by providing additional context specificity, counteracting publication bias from journal selection criteria, and offering a rich set of supplementary narratives [15][16]. While lack of access was once a limitation of grey literature, digital platforms like *Tethys* allow grey literature to be disseminated widely [17]. *Tethys* currently contains over 5,200 documents associated with MRE and wind energy, with over 2,400 documents specifically relevant to MRE. Documents are primarily in English, though content in other languages is added if an English abstract is available. Additional details about how documents and other content are collected can be found in 0.

As the reach of *Tethys* has expanded to support an international community, content to support the mission of OES-Environmental and the global MRE community has been added. This includes collected metadata that describes MRE project sites and research studies throughout the world, regularly updated. Webinars and other presentations hosted by OES-Environmental and partners are archived. *Tethys* also distributes a bi-weekly online newsletter (*Tethys* Blast) that highlights new content and happenings in the MRE community, tracks a calendar of international events, and links to complementary datasets. 0 describes how OES-Environmental promotes international collaboration through synthesis and engagement activities.

A. *Organization of Tethys content*

Organization within a knowledge management system is critical to allowing users to locate content and to create a taxonomic framework that supports the MRE industry categorize environmental impacts [18]. It is common for terminology to differ internationally, so the creation of an international knowledge management system presents an opportunity to suggest consistent terminology [19][20]. The most basic division of content on *Tethys* is by technology type, which references the source of the energy harvested (waves, tides, ocean currents, etc.).

TABLE I
ORGANIZATION OF *TETHYS* CONTENT BY MAJOR TAXONOMY TAGS: TECHNOLOGY TYPES, STRESSORS, AND RECEPTORS. THE NUMBERS IN PARENTHESES ARE THE COUNT OF DOCUMENTS TAGGED FOR EACH CATEGORY.

Technology Types	Stressors	Receptors
Marine Energy General (1,837)	Noise (387)	Socio-economics (670)
Tidal Energy (668)	Energy Removal (277)	Marine Mammals (492)
Wave Energy (497)	Static Device (252)	Fish (418)
Riverine Energy (77)	Dynamic Device (193)	Nearfield Habitat (267)
Ocean Thermal Energy Conversion (45)	Electromagnetic Fields (115)	Invertebrates (251)
Ocean Current (18)	Chemicals (54)	Birds (203)
	Lighting (10)	Farfield Environment (187)
		Ecosystem (117)
		Reptiles (57)

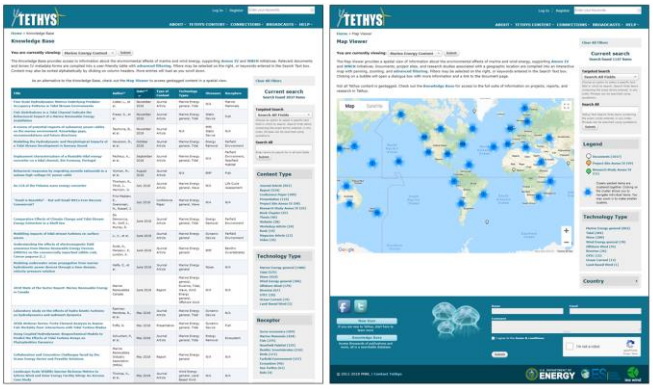

Fig 1. The primary displays for Tethys include the Knowledge Base (left) and the Map Viewer (right).

After this, the next level of fundamental organization is by environmental "stressors" and "receptors". Stressors have been defined as components of an MRE device or system that may adversely affect the environment, while receptors have been defined as animals, habitats, and ecosystems processes that may be altered [21][22]. Table I lists the technology types, stressors, and receptors that are used to organize content on *Tethys*.

B. *Display of documents in Tethys*

The relational structure on *Tethys* consists of each document being comprised of a set of fields that can be queried from anywhere on the site, as well as digested by web crawlers for indexing by search engines [23]. This structure creates flexibility to design new visualizations, while the body of content remains consistent. Fig 1 shows the primary views for exploring content on *Tethys*, the Knowledge Base and Map Viewer.

The Knowledge Base represents the most comprehensive view of available content on *Tethys* in a paginated table that provides advanced filtering, keyword searches, and column sorting. All *Tethys* content is initially loaded in the Knowledge Base, where results can be narrowed with the use of filters. Keyword searches can scan all fields or target specific fields selected by the user, such as authors or titles. Clicking on a document title will open a new page with detailed information and options to access the document.

The Map Viewer displays a subset of documents that can be geographically tagged with a location; currently about 57% of documents in the Knowledge Base are geotagged and appear in the Map Viewer. Each document is displayed as an individual bubble, but are cumulatively presented as blue clusters that will expand into individual bubbles as the user zooms in. At any point, the user may click on an individual bubble or cluster to see information about the location as well as links to the specific document pages.

Each document page provides links to all taxonomy tags, authors, and author affiliations, providing avenues for continued exploration of related documents. Clicking on any of these tags, authors, or affiliations will bring up a list of other documents with the same terms. For example, clicking on an author will bring up a list of all documents written by that author on *Tethys*. Providing various pathways for users to explore the content creates a flexible system that caters to different purposes for visiting and searching *Tethys*. The document pages also automatically create a citation in APA (American Psychological Association) format.

C. *OES-Environmental metadata forms*

While relatively few devices have been deployed and there exist few detailed environmental monitoring datasets, significant value can be gained from monitoring data collected around installed devices. Observation has shown that developers are more willing to share environmental data because it may help resolve concerns that cause permitting/consenting challenges for future projects. Since 2012, PNNL staff and contractors have sent structured questionnaires to MRE developers and researchers to collect information about environmental monitoring or research. This information is presented as OES-Environmental metadata forms, providing information that is often not accessible through formal reports or papers. The metadata forms are integrated into *Tethys* like other documents, making the information easily accessible through the Knowledge Base or Map Viewer. As the information regularly changes, *Tethys* tracks a point of contact for every metadata form and seeks updates on an annual basis.

Associated with the metadata forms, *Tethys* recently began cataloging post-installation monitoring datasets, providing a point of contact to request data access. A Data Portal view was released in 2018 to list all datasets in *Tethys*.

D. Active outreach

Tethys maintains an active outreach process to ensure that the document collection is up to date and accessible, in order to make an impact on the MRE industry [24]. *Tethys* interfaces with the public and key stakeholders through event tracking, conference and workshop engagement, online webinars and expert forums, bi-weekly newsletter (*Tethys* Blast) distributions, and search engine optimization.

Event tracking encourages awareness of key conferences and workshops, which provide valuable information exchange and networking opportunities. An interactive calendar is regularly updated with events, helping to establish *Tethys* as a one-stop-shop for information relevant to MRE and the environment. A member of the *Tethys* team or a representative from OES-Environmental showcase *Tethys* at many conferences and workshops around the world to further enhance outreach. Notable conferences include Environmental Interactions of Marine Renewables (EIMR), European Wave and Tidal Energy Conference (EWTEC), Asian Wave and Tidal Energy Conference (AWTEC), International Conference on Ocean Energy (ICOE), the Marine Energy Technology Symposium (METS), and Ocean Renewable Energy Conference (OREC). OES-Environmental hosts expert workshops in conjunction with major international conferences, capitalizing on the presence of experts to further understand key topics and challenges, with workshop reports made publicly available on *Tethys*. As not all interested parties can attend major conferences and workshops, OES-Environmental also hosts online webinars with international speakers on topics of environmental effects of MRE devices and posts webinar presentations and recordings on *Tethys* following the event. Some challenges facing the industry are very complex and technical in nature, so OES-Environmental has hosted expert forums where a dozen subject matter experts are invited to participate in a moderated discussion on a specific technical topic, which is recorded and later hosted on *Tethys* for public viewing.

Active distribution of information can further enhance outreach by bringing content to the community [25]; *Tethys* seeks to engage in active outreach and engagement regularly. *Tethys* Blast is a bi-weekly email newsletter sent to over 1,700 active subscribers that provides programmatic announcements, links to new documents on *Tethys*, notifies users of international funding opportunities, and highlights recent news and events in the MRE industry.

Tethys also enhances outreach to the MRE community through search engine optimization (SEO), which is intended to promote the ranking of webpages in public searches, allowing MRE users easier access to the site. Search engines use web crawlers to index websites, applying an algorithm to sort websites by relevance for each search. The objective of SEO is increasing the quality of webpages based on the trustworthiness of the site, accessibility of content, and the structure of webpages [26][27][28][29]. To optimize searches, quality control procedures on *Tethys* (1) ensure proper configuration of data markup, meta tags, and sitemap; (2) create clean and relevant page titles and URLs; (3) configure a secure sockets protocol (https) to encrypt communications between the website and browser; (4) fix broken links to and from *Tethys*; (5) optimize page loading speeds; (6) encourage offsite links to *Tethys*; and (7) use webmaster tools provided by Google to better identify content structure. Web analytics show that 60% of users access *Tethys* via search engines, indicating that SEO has played an important role in promoting the accessibility and visibility of *Tethys*.

III. Results

Tethys receives over 75,000 unique visitors annually from over 200 countries around the world; however, the impact to the MRE industry is difficult to quantify. The earliest commercial tidal array of full-sized devices has been deployed in Pentland Firth, north of Scotland [30]. Single devices, small-scale devices, and small arrays have been deployed or are under development in the Bay of Fundy in Nova Scotia [31][32], in the East River of New York [33], in the Shetland Islands north of Scotland [34], off the northern coast of France [35], and in coastal Maine and Alaska [36]. The industry is advancing, and *Tethys* has been a constant presence along the way. Several indirect measures can provide insights into the impact that *Tethys* may be having on the MRE industry.

Tethys has been recognized by the MRE community through referencing *Tethys* in presentations and scientific papers. Numerous presentations at MRE conferences have mentioned or promoted *Tethys* as a helpful tool for research and/or directly linked to publications on *Tethys*. This has been observed at ICOE, EIMR, EWTEC, METS, and OREC. Many scientific papers reference *Tethys* and/or OES-Environmental [37][38][39][40][41][42].

Another recognition of OES-Environmental and *Tethys* comes from an independent survey [43] that was undertaken by the International Council for the Exploration of the Sea (ICES) working groups on marine benthos and MRE to understand the degree of interconnectivity between groups across the sector, including advisory boards, expert forums, steering committees, and working groups within academic, industry, policy, and societal sectors. A total of 288 responses were collected from individuals working in over 20 countries. Preliminary results assessing connectivity among groups indicate that OES-Environmental is the largest and most central group in the sector, highlighting the important role established by OES-Environmental, supported by *Tethys*.

The *Annex IV 2016 State of the Science: Environmental Effects of Marine Renewable Energy Development around the World* [2] was written by OES-Environmental for government regulators, policy makers, resource managers, MRE developers, researchers, and stakeholders. Leveraging content available on *Tethys*, a review of all available literature on key environmental MRE interactions was conducted on topics such as collision risk, underwater noise, changes to physical systems, electromagnetic fields, and changes to habitat and reefing patterns. This report has received significant international attention with over 6,000 downloads from *Tethys* and dozens of citations over the years. The executive summary was translated into seven languages represented by OES-Environmental, while accompanying Short Science Summaries were created to address eight key environmental challenges aimed at audiences needing a quick primer on the topic, including elected officials, decision makers, and the interested public. Publicity from this document continues to drive traffic to *Tethys* and has encouraged authors to send publications for addition to *Tethys*. OES-Environmental will produce a 2020 State of the Science report that updates and builds on the 2016 report.

Following the State of the Science report, Ocean Energy Systems commissioned OES-Environmental to write a position paper on the global status of knowledge on environmental effects of MRE devices, as they drive permitting/consenting processes [13]. The paper assesses this knowledge and suggests pathways for moving the industry forward. Conclusions indicate that risks for deployment and operation of single devices and small arrays appear very low, and that larger arrays will require further investigation, paving the way for early deployments with fewer concerns over environmental effects. International sharing of information was also noted as an important component for accelerating and smoothing permitting/consenting processes. This highlights the acceptance of *Tethys* and OES-Environmental as reputable voices in the MRE community.

Lastly, the success of *Tethys* in addressing the environmental impacts of MRE has led to the creation of a new *Tethys Engineering* knowledge management system (https://tethys-engineering.pnnl.gov) to address the technical and engineering challenges of MRE deployments. The new website is also funded by the U.S. Department of Energy and developed by PNNL to emulate the functionality of *Tethys*. The website was just launched in September 2019 and already contains over 3,300 documents. Dynamic linkages will be created between *Tethys* and *Tethys Engineering* to encourage collaboration.

IV. Discussion

Building and maintaining a knowledge management system during the early stages of an emerging industry has provided important outcomes, while presenting significant challenges. Outcomes of developing and maintaining *Tethys* include providing an organized collection of information to assist the MRE industry, and the opportunity to contribute to organizing an international network of stakeholders and interest groups. The challenge of maintaining a stable and consistent system over nearly ten years has required considerable effort, international support, and significant funding. The outcome appears to have gained the respect and confidence from the MRE community.

In this digital era, information is accessible, and databases are plentiful, but the breadth and quality of databases varies greatly. *Tethys* uniquely focuses on a narrow content scope focused on environmental effects of MRE (and wind energy), and supports a broad program of outreach to a diverse international audience. Content from *Tethys* and OES-Environmental help regulators by providing evidence to support decisions [44]; aids developers by making information on environmental risks available before they design or deploy systems; informs researchers of the most pressing issues to the industry; and helps other stakeholders understand the realistic risks of MRE through transparent access to information. Additionally, *Tethys* maintains high-quality standards of information by hand-selecting relevant documents, regularly checking and correcting broken links, striving to maintain access to peer-reviewed and grey literature, and steadily enhancing website functionality to meet the needs of the community. An annual peer review process is conducted to solicit feedback from the MRE community on *Tethys* functionality and content. The results of the peer review are taken into account in updating and enhancing *Tethys*. These attributes set *Tethys* apart from other databases and result in a knowledge management system that serves the specific needs of the MRE community.

Tethys has successfully transitioned from a collection of documents to a program that is actively engaged with the international MRE community. OES-Environmental provides synthesis that supports the effectiveness of knowledge management by translating results into meaningful conclusions. Engagement through international and online events provides a means to share findings and enhance the impact of scientific research. Synthesis and engagement activities foster a core community that expands the use of *Tethys*, contributes content, and communicates the impact of research findings. *Tethys* is supporting the MRE community by increasing global understanding, allowing the MRE industry to progress in an environmentally-responsible manner.

Appendix I
Content Collection Details

A. Collection of *Tethys* documents

There are many design considerations for optimizing the collection, filtering, organization, curation, and display of database content [45]: the evolution of *Tethys* followed an iterative process of trial, testing, and improvement. Many databases that serve up content rely on collection by automated bots that crawl the internet and catalog massive amounts of content. While this methodology collects large amounts of information with little effort and uses consistent bias [46], it faces challenges including that grey literature lacks consistent formatting which hinders a bot's ability to identify vital information such as title and author [47]. We chose to use a more hands-on approach for collection.

Hand collecting and verifying documents addressed the challenge of missing seminal documents, expanded the topical scope to include important outliers relevant to the industry, improved the quality of the formatting within *Tethys*, and allowed for intuitive tagging of documents. Over a period of nearly ten years, more than a dozen staff have assisted with the collection of documents for *Tethys*. These staff go through an iterative training process to ensure a standardized collection and tagging process.

Documents on *Tethys* are collected from a variety of sources targeting both newly available peer-reviewed scientific papers and reports, as well as adding content to fill gaps in the collection. Collection methods include the following: (1) searching existing databases with key words related to MRE and environmental effects; (2) applying global search tools such as Web of Science and Google Scholar; (3) combing reference lists from seminal documents; (4) subscribing to mailing lists, academic journals, and industry newsletters; and (5) collecting contributions from the international community including representatives from each OES-Environmental member nation. The latter two methods are particularly helpful for identifying new content and have become more effective as the *Tethys* network has grown.

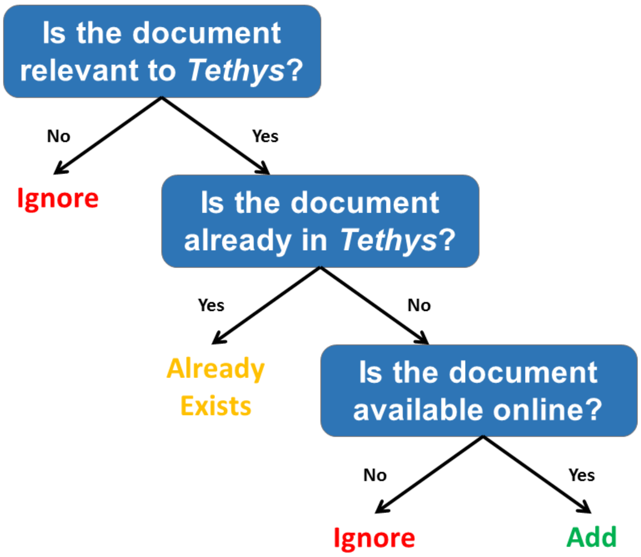

Fig 3. A decision tree used to determine which documents should be included on *Tethys*.

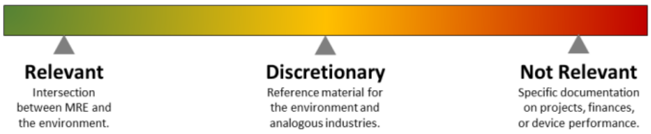

Fig 2. A spectrum of relevancy was created for *Tethys* that guides which documents should be included.

B. *Filtering content for inclusion*

When collecting and reviewing documents for inclusion, a standardized process detailed in Fig 3 is used to identify which documents should be added to *Tethys*.

The first criteria are to determine if the document is relevant to the topic of MRE and the environment, based on a spectrum of relevance that was created for the scope of topics relevant to *Tethys*, shown in Fig 2. Some documents are clearly relevant based on the intersection of MRE and the environment, while other topics have been intentionally excluded to maintain a focused collection. Examples of excluded categories includes documents about device performance (e.g., power optimization, controller calibration), economic feasibility (e.g., power potential, cost of energy, market analysis), non-environmental permitting (e.g., scoping, licensing), and basic marine environmental information. Yet some documents that fall outside this direct intersection may still be relevant to the *Tethys* audience, such as scientific analogues from related industries (e.g., oil platforms, shipping), animal behavior studies on species of interest for MRE (e.g., harbor porpoise foraging at a high-energy location), or effects of MRE on people (e.g., fisheries, navigation). Documents that fall in the middle can be added at the discretion of the responsible staff member. Clearly defining the scope of topics along the spectrum helps filter documents and creates distinct guidelines for curation that promote consistency.

Once documents are deemed appropriate for inclusion, they are checked to see if they have already been added to *Tethys*. The final criteria for inclusion are that documents must have a link to the original source, so users can download the document or purchase/subscribe to gain access. In addition to providing this link, *Tethys* uploads PDF copies of documents when copyright laws allow. This sets *Tethys* apart from databases that simply catalog the existence of documents rather than provide access to the document.

The decision to upload PDF copies of documents plays an important role in assuring the accessibility of the documents. Grey literature is typically less accessible, often being hosted on transient websites that may be removed when a project completes, when business interests shift, companies go under, or when mergers are carried out among companies [48][49]. Out of the 1,631 MRE reports currently on *Tethys*, 466 reports are no longer available at the original online source (excluding reports that were moved to a new location through acquisition or other means). In other words, 29% of the grey literature housed on *Tethys* would no longer be available to the public had it not been for *Tethys* hosting the PDF. The record created by *Tethys* maintains the history of research and development that forms foundational understanding on which the industry can progress [50].

C. *Updating metadata forms*

The metadata collection effort began in 2012, currently containing 107 project sites and 105 research studies. Leveraging the international recognition of OES-Environmental, with country representatives acting as ambassadors, metadata forms are distributed to developers and researchers around the world. The fundamental challenge is curating a growing collection while continuing to seek out new content.

In order to curate the existing content, a knowledgeable point of contact is established for each metadata form. To streamline efforts, *Tethys* sends these contacts an automated annual request for updates, and staff are notified if contacts have not responded after several attempts, signaling the need for a new point of contact. As projects and research are completed or prematurely canceled, the final details are collected and then no more updates are sought.

As automation helps curate existing metadata forms,

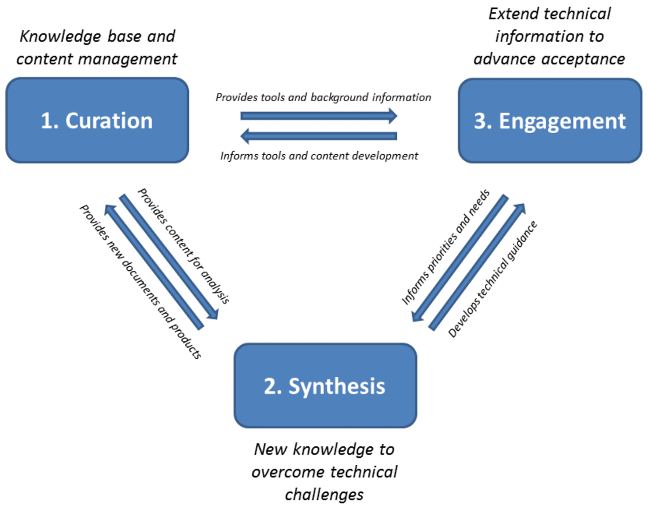

Fig 4. Aspects of the *Tethys*/OES-Environmental framework, with emphasis on the interconnectedness and feedback between the three tasks: curation, synthesis, and engagement.

staff are collecting new metadata forms to keep up with the acceleration of the industry. To limit scope, project site forms specifically focus on at-sea device deployments with environmental monitoring, omitting laboratory tests and most small-scale testing. Likewise, research studies specifically focus on large multi-year research efforts. Clearly defining these foci ensures that time and effort are being applied to collecting the more valuable information for the industry.

Appendix II
Synthesis and Engagement with OES-Environmental

Tethys and OES-Environmental are viewed collectively as a framework of curation, synthesis, and engagement tasks with activities directly and indirectly flowing from one task to another as seen in Fig 4. Performing these tasks in synergy expands the role of *Tethys* from simply collecting information to supporting active participation in the MRE community.

As the primary function of *Tethys*, the Curation task establishes the foundational knowledge that feeds analyses within the Synthesis task to produce value-added products, which form a key pillar in the engagement with key audiences. Similarly, the Curation task accumulates a searchable body of content that can be distributed to an international audience as Engagement that advances acceptance.

The value of synthesis is in distilling and interpreting the available scientific papers and reports, putting them in the context of what is known about this emerging industry, and the challenges faced by device and project developers, regulators, and other stakeholders in understanding the status of associated environmental risks. Scientific research publications typically focus on narrow topics, provide specific conclusions based on the datasets generated, and can be limited to the time and locations for which the results are directly applicable. Scientific review papers are usually prepared once a solid body of work in a field has been developed, but there is not yet a fully developed body of scientific literature on environmental effects of MRE, and planned deployments are already struggling from financial obligations associated with ill-informed regulatory requirements to protect marine life. Syntheses created by OES-Environmental and made possible by *Tethys* allow the industry and stakeholders to understand what is known, what remains to be discovered, and how far we are from retiring risks around specific environmental interactions. At the same time, researchers can view the extensively referenced syntheses to determine what challenges are most important to permitting/consenting devices and assisting the industry, allowing them to design their research studies accordingly. Funding agencies can review syntheses to determine that their support funds are most effectively directed. Thus, synthesis documents play an important role in progressing an emerging industry.

Qualified scientists and engineers from multiple nations are tapped to prepare OES-Environmental synthesis documents [2][13][51], and each document undergoes significant peer review to ensure the accuracy, utility, and accessibility of the results. Communications professionals help make the synthesis documents attractive and accessible to the reader.

The Engagement task is to ensure that key stakeholders are made aware of the state of knowledge around environmental effects of MRE development, and that there is an active channel to understand and have conversations about concerns and challenges. Key stakeholders include regulators, researchers, students, technology and project developers, consultants, and a myriad of other stakeholders in the 15 current OES-Environmental member nations and worldwide. The premise behind broad and continuous engagement is that an informed public is more likely to understand and accept proposed MRE projects [52], and to ensure that concerns are addressed before they blossom into strong opposition, misinformed regulatory and public actions, or create an atmosphere that is not conducive to promoting a low carbon energy future.

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References

[1] SuperGen, "SuperGen phase three monograph," Nov. 2016. [Online]. Available: https://tethys.pnnl.gov/publications/supergen-phase-three-monograph

[2] A. Copping, N. Sather, L. Hanna, J. Whiting, G. Zydlewski, G. Staines, A. Gill, I. Hutchison, A. O'Hagan, T. Simas, J. Bald, C. Sparling, J. Wood, E. Masden, "Annex IV 2016 state of the science report: environmental effects of marine renewable energy development around the world," Apr. 25, 2016. [Online]. Available: https://tethys.pnnl.gov/publications/state-of-the-science-2016

[3] S. King, R. Schick, C. Donovan, C. Booth, M. Burgman, L. Thomas, J. Harwood, "An interim framework for assessing the population consequences of disturbance," *Methods in Ecology and Evolution*, vol. 6, No. 10, pp. 1150-1158, 2015. DOI: 10.1111/2041-210X.12411 [Online]. Available: https://tethys.pnnl.gov/publications/interim-framework-assessing-population-consequences-disturbance

[4] I. Bailey, J. West, I. Whitehead, "Out of sight but not out of mind? Public perceptions of wave energy," *Journal of Environmental Policy & Planning*, vol. 13, no. 2, pp. 139-157, 2011. DOI: 10.1080/1523908X.2011.573632 [Online]. Available: https://tethys.pnnl.gov/publications/out-sight-not-out-mind-public-perceptions-wave-energy

[5] L. Hammar, L. Eggertsen, S. Andersson, J. Ehnberg, R. Arvidsson, M. Gullström, S. Molander, "A probabilistic model for hydrokinetic turbine collision risks: exploring impacts on fish," *Plos One*, vol. 10, no. 3, pp. 1-25, 2015. DOI: 10.1371/journal.pone.0117756 [Online]. Available: https://tethys.pnnl.gov/publications/probabilistic-model-hydrokinetic-turbine-collision-risks-exploring-impacts-fish

[6] H. Linder, J. Horne, E. Ward, "Modeling baseline conditions of ecological indicators: marine renewable energy environmental monitoring," *Ecological Indicators*, vol. 83, pp. 178-191, 2017. DOI: 10.1016/j.ecolind.2017.07.015 [Online]. Available: https://tethys.pnnl.gov/publications/modeling-baseline-conditions-ecological-indicators-marine-renewable-energy

[7] M. Bevelhimer, G. Cada, C. Scherelis, "Effects of electromagnetic fields on behavior of largemouth bass and pallid sturgeon in an experimental pond setting," Sep. 2015. [Online]. Available: https://tethys.pnnl.gov/publications/effects-electromagnetic-fields-behavior-largemouth-bass-and-pallid-sturgeon

[8] J. Zhang, D. Kitazawa, S. Taya, Y. Mizukami, "Impact assessment of marine current turbines on fish behavior using an experimental approach based on the similarity law," *Journal of Marine Science and Technology*, vol. 22, no. 2, pp. 219-230, 2017. DOI: 10.1007/s00773-016-0405-y [Online]. Available: https://tethys.pnnl.gov/publications/impact-assessment-marine-current-turbines-fish-behavior-using-experimental-approach

[9] A. Garrad, "The lessons learned from the development of the wind energy industry that might be applied to marine industry renewables," *Philosophical Transactions of the Royal Society A*, vol. 370, pp. 451-471, 2012. DOI: 0.1098/rsta.2011.0167 [Online]. Available: https://tethys.pnnl.gov/publications/lessons-learned-development-wind-energy-industry-might-be-applied-marine-industry

[10] T. Wilding, "Effects of man-made structures on sedimentary oxygenation: extent, seasonality and implications for offshore renewables," *Marine Environmental Research*, vol. 97, pp. 39-47, 2014. DOI: 10.1016/j.marenvres.2014.01.011 [Online]. Available: https://tethys.pnnl.gov/publications/effects-man-made-structures-sedimentary-oxygenation-extent-seasonality-and-implications

[11] C. Cvitanovic, A. Hobday, L. Kerkoff, S. Wilson, K. Dobbs, N. Marshall, "Improving knowledge exchange among scientists and decision-makers to facilitate the adaptive governance of marine resources: A review of knowledge and research needs," *Ocean & Coastal Management*, vol. 112, pp. 25-35, 2015. DOI: 10.1016/j.ocecoaman.2015.05.002 [Online]. Available: https://tethys.pnnl.gov/publications/improving-knowledge-exchange-among-scientists-and-decision-makers-facilitate-adaptive

[12] V. de Jonge, D. Giebels, "Handling the 'environmental knowledge paradox' in estuarine and coastal policy making," *Ocean & Coastal Management*, vol. 108, pp. 3-12, 2015. DOI: 10.1016/j.ocecoaman.2014.10.013 [Online]. Available: https://tethys.pnnl.gov/publications/handling-environmental-knowledge-paradox-estuarine-and-coastal-policy-making

[13] A. Copping, "The state of knowledge for environmental effects: driving consenting/permitting for the marine renewable energy industry," Jan. 2018. [Online]. Available: https://tethys.pnnl.gov/publications/state-knowledge-environmental-effects-driving-consentingpermitting-marine-renewable

[14] A. Copping, C. Smith, L. Hanna, H. Battey, J. Whiting, M. Reed, J. Brown-Saracino, P. Gilman, M. Massaua, "Tethys: developing a commons for understanding environmental effects of marine renewable energy," *International Journal of Marine Energy*, vol. 3-

4, pp. 41-51, 2013. DOI: 10.1016/j.ijome.2013.11.004 [Online]. Available: https://tethys.pnnl.gov/publications/tethys-developing-commons-understanding-environmental-effects-marine-renewable-energy

[15] K. Benzies, S. Premji, K. Hayden, K. Serrett, "State-of-the-evidence reviews: advantages and challenges of including grey literature," *Worldviews on Evidence-Based Nursing*, vol. 3, no. 2, pp. 55-61, 2006. DOI: 10.1111/j.1741-6787.2006.00051.x [Online].

[16] R. Adams, P. Smart, A. Huff, "Shades of grey: guidelines for working with the grey literature in systematic reviews for management and organizational studies," *International Journal of Management Reviews*, vol. 19, no. 4, pp. 432-454, 2016. DOI: 10.1111/ijmr.12102 [Online].

[17] C. Pappas, I. Williams, "Grey literature: it's emerging importance," *Journal of Hospital Librarianship*, vol. 11, no. 3, pp. 228-234, 2011. DOI: 10.1080/15323269.2011.587100 [Online].

[18] M. Costello, P. Bouchet, G. Boxshall, K. Fauchald, D. Gordon, B. Hoeksema, G. Poore, R. van Soest, S. Stöhr, T. Walter, B. Vanhoorne, W. Decock, W. Appeltans, "Global coordination and standardisation in marine biodiversity through the world register of marine species (WoRMS) and related databases," *Plos One*, vol. 8, no. 1, pp. e51629, 2013. DOI: 10.1371/journal.pone.0051629 [Online].

[19] D. Oesterwind, A. Rau, A. Zaiko, "Drivers and pressures – untangling the terms commonly used in marine science and policy," *Journal of Environmental Management*, vol. 181, pp. 8-15, 2016. DOI: 10.1016/j.jenvman.2016.05.058 [Online].

[20] H. Ojaveer, B. Galil, D. Minchin, S. Olenin, A. Amorim, J. Canning-Clode, P. Chainho, G. Copp, S. Gollasch, A. Jelmert, M. Lehiniemi, C. McKenzie, J. Mikuš, L. Miossec, A. Occhipinti-Ambrogi, J. Pederson, G. Quilez-Badia, J. Wijsman, A. Zenetos, "Ten recommendations for advancing the assessment and management of non-indigenous species in marine ecosystems," *Marine Policy*, vol. 44, pp. 160-165, 2014. DOI: 10.1016/j.marpol.2013.08.019 [Online].

[21] G. Boehlert, A. Gill, "Environmental and ecological effects of ocean renewable energy development: a current synthesis," *Oceanography*, vol. 23, no. 2, pp. 68-81, 2010. [Online]. Available: https://tethys.pnnl.gov/publications/environmental-and-ecological-effects-ocean-renewable-energy-development-current

[22] A. Copping, K. Blake, R. Anderson, L. Zdanski, G. Gill, J. Ward, "Screening analysis for the environmental risk evaluation system - environmental effects of MHK energy," PNNL-20805, Sep. 2011. [Online]. Available: https://tethys.pnnl.gov/publications/screening-analysis-environmental-risk-evaluation-system-environmental-effects-mhk

[23] T. Berners-Lee, J. Hendler, O. Lassila, "The semantic web," *Scientific American*, pp. 1-36, 2001.

[24] J. Swan, "Knowledge management in action?" in *Handbook on knowledge management 1*. Springer, 2004, ch. 14, pp. 271-296.

[25] M. Gusev, S. Ristov, G. Velkoski, P. Gushev, "Alert notification as a service," paper presented at the *37th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, Opatija, Croatia, 2014. DOI: 10.1109/MIPRO.2014.6859584 [Online].

[26] Google, "Search Engine Optimization (SEO) Starter Guide", 2018. [Online]. Available: https://support.google.com/webmasters/answer/7451184

[27] A. Halavais, *Search Engine Society, 2nd* ed. Medford, USA: Policy Press, 2018.

[28] M. Haim, A. Graefe, H. Brosius, "Burst of the filter bubble: effects of personalization on the diversity of Google News," *Digital Journalism*, vol. 6, no. 3, pp. 330-343, 2017. DOI: 10.1080/21670811.2017.1338145 [Online].

[29] J. Ledford, *Search engine optimization bible, 2nd* ed. Indianapolis, USA: Wiley Publishing, 2015.

[30] MeyGen, "Lessons learnt from MeyGen phase 1a: design phase," May 2017. [Online]. Available: https://tethys.pnnl.gov/publications/lessons-learnt-meygen-phase-1a-design-phase

[31] Cape Sharp Tidal, "Cape sharp tidal environmental effects monitoring program," Jul. 2018. [Online]. Available: https://tethys.pnnl.gov/publications/cape-sharp-tidal-environmental-effects-monitoring-program-2018

[32] Black Rock Tidal Power, "Black rock tidal power grand passage MRE permit," 2018. [Online]. Available: https://tethys.pnnl.gov/publications/black-rock-tidal-power-grand-passage-mre-permit

[33] Verdant Power, "Final pilot license application: Roosevelt Island tidal energy project," Dec. 2010. [Online]. Available: https://tethys.pnnl.gov/publications/final-pilot-license-application-roosevelt-island-tidal-energy-project

[34] G. McPherson, "Environmental monitoring and mitigation plan: Shetland Tidal Array, Bluemull Sound," Jul. 30, 2015. [Online]. Available: https://tethys.pnnl.gov/publications/environmental-monitoring-and-mitigation-plan-shetland-tidal-array-bluemull-sound

[35] A. Carlier, X. Caisey, J. Gaffet, M. Lejart, S. Derrien-Courtel, E. Catherine, E. Quimbert, O. Soubigou, "Monitoring benthic habitats and biodiversity at the tidal energy site of Paimpol-Brehat (Brittany, France)," in Environmental Impact of Marine Renewables, Stornoway, UK, 2014. [Online]. Available: https://tethys.pnnl.gov/publications/monitoring-benthic-habitats-and-biodiversity-tidal-energy-site-paimpol-brehat-brittany

[36] ORPC (Ocean Renewable Power Company) Maine, "Cobscook bay tidal energy project: 2016 environmental monitoring report," Apr. 28, 2017. [Online]. Available: https://tethys.pnnl.gov/publications/cobscook-bay-tidal-energy-project-2016-environmental-monitoring-report

[37] M. Lehman, F. Karimpour, C. Goudey, P. Jacobson, M. Alam, "Ocean wave energy in the United States: current status and future perspectives," *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 1300-1313, 2017. DOI: 10.1016/j.rser.2016.11.101 [Online]. Available: https://tethys.pnnl.gov/publications/ocean-wave-energy-united-states-current-status-and-future-perspectives

[38] N. Laws, B. Epps, "Hydrokinetic energy conversion: technology, research, and outlook," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 1245-1259, 2016. DOI: 10.1016/j.rser.2015.12.189 [Online]. Available: https://tethys.pnnl.gov/publications/hydrokinetic-energy-conversion-technology-research-and-outlook

[39] A. Copping, H. Battey, J. Brown-Saracino, M. Massaua, C. Smith, "An international assessment of the environmental effects of marine energy development," *Ocean & Coastal Management*, vol. 99, pp. 3-13, 2014. DOI: 10.1016/j.ocecoaman.2014.04.002 [Online]. Available: https://tethys.pnnl.gov/publications/international-assessment-environmental-effects-marine-energy-development

[40] G. Wright, "Strengthening the role of science in marine governance through environmental impact assessment: a case study of the marine renewable energy industry," *Ocean & Coastal Management*, vol. 99, pp. 23-30, 2014. DOI: 10.1016/j.ocecoaman.2014.07.004 [Online]. Available: https://tethys.pnnl.gov/publications/strengthening-role-science-marine-governance-through-environmental-impact-assessment

[41] J. Park, T. Kim, "Improving policies and regulations for environmental-friendly ocean renewable energy development in Korea," *Journal of Environmental Impact Assessment*, vol. 23, no. 4, pp. 237-250, 2014. [Online]. Available: https://tethys.pnnl.gov/publications/improving-policies-and-regulations-environmental-friendly-ocean-renewable-energy

[42] A. Melo, E. Sweeny, J. Villante, "Global review of recent ocean activities," *Marine Technology Society Journal*, vol. 47, no. 5, pp. 97-103, 2013. DOI: 10.4031/MTSJ.47.5.13 [Online].

[43] R. Miller, T. Wilding, "ICES pathways to impact offshore renewable energy survey: preliminary results," Nov. 2017.

[44] D. Cash, W. Clark, F. Alcock, N. Dickson, N. Eckley, D. Guston, J. Jäger, R. Mitchell, "Knowledge systems for sustainable development," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 100, no. 14, pp. 8086-8091, 2003. DOI: 10.1073/pnas.1231332100 [Online].

[45] P. Rob, C. Coronel, Database Systems: Design, Implementation, and Management, 12th ed. Boston, USA: Cengage Learning, 2016.

[46] V. Uren, P. Cimiano, J. Iria, S. Handschuh, M. Cargas-Vera, E. Motta, F. Ciravegna, "Semantic annotation for knowledge management: requirements and a survey of the state of the art," *Journal of Web Semantics*, vol. 4, no. 1, pp. 14-28, 2006. DOI: 10.1016/j.websem.2005.10.002 [Online].

[47] S. Bogdanski, B. Chang, "Collecting grey literature: an annotated bibliography, with examples from the sciences and technology," *Science & Technology Libraries*, vol. 25, no. 3, pp. 35-70, 2005. DOI: 10.1300/J122v25n03_04 [Online].

[48] A. Lawrence, "Influence seekers: the production of grey literature for policy and practice," *Information Services & Use*, vol. 37, no. 4, pp. 389-403, 2017. DOI: 10.3233/ISU-170857 [Online].

[49] A. Lawrence, J. Houghton, J. Thomas, P. Weldon, "Where is the evidence? Realising the value of grey literature for public policy and practice: a discussion paper," unpublished, Nov. 17, 2014. [Online]. Available: https://works.bepress.com/paul_weldon/24/

[50] E. Warren, "Strengthening research through data sharing," *New England Journal of Medicine*, vol. 375, pp. 401-403, 2016. DOI: 10.1056/NEJMp1607282 [Online].

[51] A. Copping, L. Hanna, J. Whiting, S. Geerlofs, M. Grear, K. Blake, A. Coffey, M. Massaua, J. Brown-Saracino, H. Battey, "Environmental effects of marine energy development around the world: Annex IV final report," Jan. 30, 2013. [Online]. Available: https://tethys.pnnl.gov/publications/environmental-effects-marine-energy-development-around-world-annex-iv-final-report

[52] N. Huijts, E. Molin, L. Steg, "Psychological factors influencing sustainable energy technology acceptance: a review-based comprehensive framework," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 525-531, 2012. DOI: 10.1016/j.rser.2011.08.018 [Online].