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Strategic roadmapping to accelerate and risk-mitigate enabling innovations: A generalizable method and a case illustration for marine renewable energy

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ABSTRACT

Understanding technological evolution and its implications is increasingly important as the public and private sectors harness next generation technologies to address society's major challenges. Current roadmapping methods for these *enabling innovations* suffer from several limitations and often shed more light on technology viability than adoptability, leading many to frame related pursuits as unpredictable high-risk, high-reward activities. However, recent research highlights that the risk associated with developing enabling innovations depends more on the approach to pursuit than the technology itself. Drawing on this perspective, we put forward a strategic roadmapping approach that overcomes historical limitations by: 1.) framing technological advance as a complex socio-technical transition and 2.) drawing upon related patterns of high-impact innovation to inform unique roadmapping analyses. The result – the Enabling Innovation Strategic Roadmapping method – examines technical, economic, and socio-cultural barriers to progress to define windows of opportunity in which viable technological capabilities can be matched to adoption-ready needs within and beyond the motivating sector, fostering advance toward a long-term vision, technology convergence, valley of death avoidance, and means to influence ecosystem evolution. To illustrate the methodology, we develop a strategic roadmap for marine hydrokinetic energy technologies that could support the advent of a marine renewable energy economy.

1. Introduction

Insight into the potential advancement and adoption of novel emerging technologies has been a sought-after goal of individual innovators, corporations, and governments for nearly a century. Following the early works of the National Resources Committee (1937), Schumpeter (1942), and Bush (1945), which made initial links between advances in science and societal prosperity, pioneers in what ultimately became known as technology future studies or technology futures analysis (TFA) (TFAM Working Group, 2004) (e.g., Gilfillan (1952), Nelson (1962), Lenz (1962), Jantsch (1967), Linstone (1969)) attempted to interpret technological progress and its implications. In the decades that followed, a host of techniques emerged to anticipate future technology and its applications and consequences, drawing on early activities of government and industry entities (e.g., NASA (Finger et al., 1964); US Air Force (Martino, 1971); US Office of Technology Assessment (Coates, 1976 & 1977); US Department of Energy (Collins and Pincock, 2010); Lockheed (Aderhold et al., 1976); Motorola (Willyard and McClees, 1987; Galvin, 2004); HRB Systems – now Raytheon (Nauda and Hall, 1991); BP (Barker and Smith, 1995); Philips Electronics (Groenveld, 1997)), as well as academics and practitioners (often in partnership with other entities) (e.g., Phaal et al., 2001; Kostoff and Schaller, 2001; Coates, 2000; Coates et al., 2001; Kostoff et al., 2004).

Among the earliest and still most broadly used approaches to technology futures analysis is technology roadmapping, which Phaal et al. (2004) described as “a flexible technique that is widely used … to support strategic and long-range planning. The approach provides a structured (and often graphical) means for exploring and communicating the relationships between evolving and developing markets, products, and technologies over time.” Applications and methodological developments of technology roadmapping have grown steadily since the late 1990's (Vatananan and Gerdsri, 2010), with a considerable surge in related activity in the last twenty-five years (Park et al., 2020). Extant roadmapping techniques can largely be grouped into exploratory,

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normative, or hybrid approaches (Linstone, 1969; Roberts, 1969; Twiss, 1992), that a) take on a technology-led or market-led perspective (Lee et al., 2009), b) adopt either continuous or discontinuous paradigms for technological change (Cho and Daim, 2013), and c) may be carried out at the organization, sector, or national level (e.g., Chakraborty et al., 2022; Phaal et al., 2001, 2004; Vishnevskiy et al., 2016).

Roadmapping has been adapted and customized for myriad purposes, spanning from highlighting priorities for R&D investment (e.g., Lee et al., 2007; Cho et al., 2016) to shaping commercialization plans for well-defined technologies (e.g., Groenveld, 1997; Albright and Kappel, 2003; Phaal et al., 2004; Lee et al., 2009) and offering insight into the general evolution and rates of improvement of technology domains (e.g., Gehani, 2007; Cho et al., 2016; Hussain et al., 2017; Lu et al., 2019), as well as more generally helping organizational leaders communicate and gain alignment on strategic issues (e.g., Kappel, 2001; Galvin, 2004), among many others. However, individual method variants tend to suffer from one or more limitations (Haleem et al., 2018), particularly in efforts to assess the potential or evolution of what are often posited as high-risk, high-return technologies. Roadmapping tends to focus on a small set of dominant technological designs (often only one) and, even if open to multiple technology development pathways (e.g., Daim et al., 2018), employs metrics of performance tied to a single motivating sector as measures of technological progress, neglecting the potential advances that could come from contributing or analogous capability development in other sectors. Even the latest efforts to embrace agile principles in roadmapping (e.g., Pearson et al., 2020) are guided by the iterative progression of prototypes/products intended to fulfill a predefined sector-specific purpose. In addition, roadmapping methods have also traditionally had limited linkage to broader economic factors beyond cost for performance, or substitute cost parity targets, and neglect critical socio-cultural influences on adoption such as technology fit with current work practices or ease of solution switching. Effectively, many of these methods anchor on an underlying assumption that technological advance will drive related demand/use if target application performance requirements are achieved – a notion reinforced by primary reliance on measures of development such as Technology Readiness Levels (TRLs). Resulting insights thus often shed more light on technology *viability* than *adoptability*, limiting their value in efforts to holistically understand the potential for financially sustainable technological progress in a given domain, a technology's broader impact on society, and the merits and/or risks of related investment.

Numerous researchers and practitioners have attempted to address these shortfalls by combining roadmapping with additional, often technology- or organization-specific, methods (e.g., scenario planning, cross-impact handling, quality function deployment, technology-affinity mapping, trend impact analysis, and system dynamics, among many others) (De Alcantara and Martens, 2019; Lee et al., 2009), facilitating context-specific insight, but limiting the generalizability of guiding methods and obtained perspectives. In addition, roadmapping can suffer from insight/data availability challenges. Roadmapping frequently relies upon the perspectives of a select set of experts, who often stem from within the sector of focus and can bring bias to the analysis (Schulz-Hardt et al., 2000; Bonaccorsi et al., 2020), or may draw upon years of data, for example from patents, to develop forward looking insights (e.g., Lee et al., 2009; Noh et al., 2021; Zhang et al., 2021). These data are generally not available for novel innovations and may become available only after considerable high-risk R&D investment has been expended. Further, in many fields, patents have given way to trade secrets and organizational know-how as means to protect intellectual advantage, further limiting applicability of these data-driven techniques (Smith and Funk, 2021). Finally, with few exceptions (e.g., Gerdsri and Vatananan, 2007; Walsh, 2004) these methods tend to be passive at the systemic level, presuming that a natural technological progression will play out, albeit under potentially varying resource constraints of those directly involved. When proactivity is considered, it tends to be at the level of the individual organization in terms of its strategic choices, or at the level of the government from a policy standpoint, without consideration of the broader proactive initiatives and influence that can be pursued across and/or between different levels of system stakeholders. Even in cases where roadmaps are updated over time, important exogenous influences are frequently deemed beyond the innovator's control (Strauss and Radnor, 2004; Pearson et al., 2020).

Collectively, it therefore remains difficult to strategically interpret the evolution of potentially transformative technologies and their implications for individual organizations or society as a whole. This gap in capability has become increasingly important as governments, research institutions, and the private sector increasingly seek tangible societal benefit from R&D through allocation of funds for what is typically framed as *applied research* – that is, efforts that seek outcomes that go beyond the advancement of the technology itself. There is thus a significant need to improve roadmapping approaches for what have been referred to as high-impact *enabling innovations*, particularly in a manner that offers insight early in the innovation process, embraces alternate pathways to advancement, leverages multiple data sources, accounts for the potential for proactive system influence, and provides a holistic perspective on impacts.

Herein, we put forward a strategic roadmapping method that overcomes these limitations by: 1.) framing advancement of high-impact enabling technology as a complex socio-technical transition, and 2.) drawing upon well-documented technical-economic-socio-cultural (TES) patterns of high-impact innovation to inform a series of unique roadmapping analyses. The result – termed Enabling Innovation Strategic Roadmapping – is a proactive approach to technology advance that is both exploratory and normative, highlighting technical, economic, and/or socio-cultural barriers that define time windows of opportunity in which the viability of specific technological capabilities provide the potential to offer adoptable solutions to specific needs within and/or beyond the motivating sector. As discussed in detail below, the capability- and time-period-specific technology advancement opportunities that result from the method, termed lily pads, provide means to 1) advance capabilities, individually or in groups, critical to achieve a long term vision, 2) avoid technological lock-in while seeking technology convergence, 3) navigate the classic technology valley of death by capturing financial returns early from capability-specific opportunities rather than delaying commercialization until full technology maturity, and 4) anticipate the evolution of business models and the stakeholder ecosystem related to the technology to understand broader technology implications and inform proactive influence strategies.

To illustrate the proposed methodology, we examine the case of marine hydrokinetic (MHK) energy technologies, technologies that harvest energy from the oceans' waves, tides, and currents, and may someday support the advent of a thriving Blue Economy based upon provision of marine renewable energy (MRE). Although pursued for decades, and despite significant potential benefits, broad-based use of MRE has remained elusive as advance of related technologies has been impeded by an array of technical, economic, and socio-cultural obstacles. The wide variety of potential technology solutions, complexity and under-developed nature of the stakeholder ecosystem, uncertainty in government and private sector support, and juxtaposition of realistic near-term opportunities with loftier long-term possibilities associated with MRE is typical of innovations with high impact potential, and thus MRE serves as a robust example to explore the perspectives developed through Enabling Innovation Strategic Roadmapping.

The following sections of this paper detail the foundational perspectives and theory that underly development of a strategic roadmap for enabling innovations (Section 2), introduce a rigorous methodology for systematic and proactive strategic roadmapping of enabling innovations (Section 3), illustrate the suggested methodology through analysis of marine hydrokinetic technologies that support renewable energy (Section 4), and discuss the implications of and future opportunities for the developed methodology (Section 5).

2. Foundational background

2.1. Technology and strategic roadmapping

Roadmapping has a long history in the technology futures space. It is not the intent here to provide a complete review of the roadmapping literature, but rather to draw out important, but currently disparate, themes from the related body of knowledge that reinforce the contributions of the novel roadmapping methodology presented herein and that when combined help overcome the limitations of extant methods outlined above. For comprehensive coverage of the literature, the reader is referred to any of numerous recent thorough reviews (see for example, Chakraborty et al., 2022; Park et al., 2020; Kerr and Phaal, 2020; De Alcantara and Martens, 2019).

As noted above, roadmapping has its roots in industry and government efforts to understand technological evolution and the opportunities and challenges it may pose. To these ends, roadmapping methods have been customized and employed to support forecasting (e.g., Kappel, 2001; Kostoff and Schaller, 2001; Cho et al., 2016) and foresight (e.g., Park et al., 2020) analyses, and have also been extensively applied as standalone approaches for more generalized technology management and decision making (e.g., product, service and strategic planning - Phaal et al., 2001; Phaal et al., 2004).

Within the forecasting space, roadmapping links potential and/or anticipated technology developments and market needs and "can provide a framework to help plan and coordinate developments both within a company or an entire industry," (Garcia and Bray, 1997) which can ultimately guide related R&D investments (Barker and Smith, 1995; Lee et al., 2007). In addition, while exploratory forecasting supported through roadmapping seeks to interpret the timing and significance of technological advances (Kappel, 2001; Roper et al., 2011; Lee, 2021), normative variants "impl[y] a certain amount of control that the decision maker has over the outcome", typically with a focus on the potential to alter resource constraints and allocations (Kappel, 2001).

In the foresight arena, roadmapping "addresses and integrates both commercial and technical issues and shows the inter-relationship between the two" and is credited with "providing a framework for communication and for the consideration of possible future scenarios" (Barker and Smith, 1995). Related roadmapping efforts also tend have a goal orientation (Kerr and Phaal, 2020), provide perspectives that have relevance to future actions (Kostoff and Schaller, 2001), especially policy formulation, and adopt "a consciously 'active' attitude towards the future, recognizing that the choices made today can shape or even create the future" (Martin, 1995) – principles strongly in alignment with the tenets of foresight as first put forward by the likes of Miles and Irvine (1979), Irvine and Martin (1984), Coates (1985), and Godet (1986) (as *la prospective*). When employed for foresight, extensive emphasis is also placed on the roadmapping *process* to expand perspectives included in analyses across stakeholder, function, discipline, or entity, depending upon the effort scope (Martin, 1995; Barker and Smith, 1995).

In more generalized technology management applications, emphasis is often placed on the communication and social alignment benefits of roadmapping, particularly in relation to the synthesis offered by the visual that is the *roadmap*. Kostoff and Schaller (2001) describe a roadmap as "… a visual aid that crystallizes the links between research programs, development programs, capability targets, and requirements." Further, Kappel (2001) highlights the potential for a roadmap to help an organization understand its strategic position, persuade its leaders or external stakeholders, and synchronize its activities. Ultimately, the creation of a technology roadmap "facilitates the process of collective learning and knowledge creation" for an organization (Cho et al., 2016).

The merits of integrating principles of roadmapping that have manifested in its various forms and applications have been the focus of considerable effort of late, and much of this integration is a byproduct of adoption of a system level lens by roadmapping scholars and practitioners. Noh et al. (2021) emphasize the complementarity of different roadmapping approaches and the importance of linking prospective market analysis with a rich understanding of technological development trends to create what they have termed an opportunity-driven roadmap. Vishnevskiy et al. (2016) also reinforce the merits of combining technology-push and market-pull perspectives, with a particular emphasis on achieving a strategic goal. Pearson et al. (2020) call attention to the need to move beyond the traditional linear model of technology-push typically associated with roadmaps for complex, capital-intensive, and thus often solely government backed, technologies, and to instead accelerate emphasis on commercialization early in the process by focusing on simple design, fast iteration, and exploration of early routes to market via minimum viable demonstrations. Sauer et al. (2017) call for modularity in roadmapping analyses to achieve an "integrated roadmap describing a broad landscape of corresponding developments in technologies, products, applications, markets and society," adopting what amounts to a system lens on roadmapping. The holistic views offered by these recent works mark considerable progress toward realization of a *strategic* roadmapping capability as perhaps first conceptualized (although not fully realized to the extent possible today) as an "S-plan" by Phaal et al. (2007) that can "support general strategic appraisal, and the identification and exploration of new strategic, innovation, and business opportunities" - a capability particularly relevant in complex technology spaces that have not yet experienced convergence of technical solution paths (Phaal et al., 2012). These recent works also collectively demonstrate increasing awareness among roadmapping scholars and practitioners that effective roadmapping, particularly in efforts to understand and help realize the transformative aspects of advanced new technologies, requires a confluence of technical, economic, and societal insights, with an eye toward mitigating the inherent risks of these pursuits.

In this article, we draw on the diverse historical foundation of roadmapping and embrace the most recent integrative, goal-oriented, system, and risk-mitigation lenses just described to put forward a strategic roadmapping *methodology* that encompasses an industry/sector focus, adopts a system level perspective that spans technical, economic, and socio-cultural dimensions, helps define and communicate a plan to risk-mitigate advanced technology development, and is proactive in consideration of the potential for system stakeholders to influence and achieve a desired future. Importantly, though, the proposed approach also draws on an additional body of knowledge – that of *Innovation Science* – to leverage well established patterns underlying high-impact innovations to shape and inform related analysis, as described below.

2.2. Innovation Science

Innovation Science offers insight into multi-faceted patterns that underlie different forms of innovation. These patterns, developed through analysis of historical and contemporary cases, are identified by descriptors like disruptive (Bower and Christensen, 1995), modular (Baldwin and Clark, 2000), or radical (Dewar and Dutton, 1986), and represent cause and effect linkages in technology-user systems associated with specific innovation characteristics such as performance attributes, adoption tendencies, financial returns, and competitive response, among others (e.g., Anderson and Tushman, 1990; Henderson and Clark, 1990; Sheth and Sinfield, 2022). Despite the rich connections between a pattern-based innovation characterization and the uptake of an innovation in society, innovation motifs have largely been absent in scholarly discourse on technology futures analysis broadly, and roadmapping more specifically. While some effort has been directed toward disruptive innovations (e.g., Rinne, 2004; Vojak and Chambers, 2004; Walsh, 2004), and considerable focus has been placed on incremental technologies (e.g., Albright and Kappel, 2003; Groenveld, 1997; Lee et al., 2009; Phaal et al., 2004), little attention has been given to a class of innovations that represent technical or conceptual advances that have notably high impact on society – as defined by their reach across users,

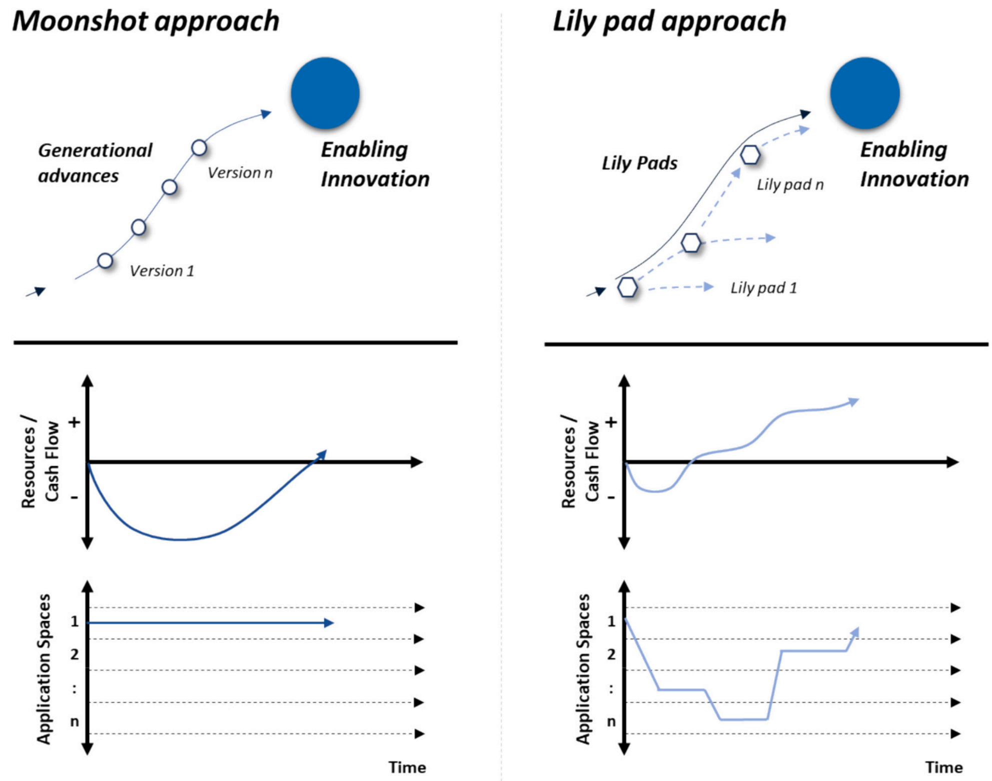

Fig. 1. Two approaches to pursue an enabling innovation (adapted from Sinfield and Solis, 2016).

alteration of prior paradigms of thought, effect on health, environment, culture, and economics, and longevity of influence (Solis and Sinfield, 2015). This form of innovation has been termed *Enabling Innovation* (Sinfield and Solis, 2016), and is well-suited to deliver on the broader societal expectations increasingly placed on applied research.

Technical enabling innovations represent agglomerations of technical, economic, and socio-cultural capabilities that manifest as major advances that fulfill multiple purposes in multiple contexts – expanding the notion of what was classically called a General Purpose Technology (GPT) (which typically fulfills just one purpose in one or more contexts) (Bresnahan and Trajtenberg, 1992). Notable examples of *enablers* include historical developments such as the laser and hydraulics, as well as more contemporary advances such as autonomous robotics. As is typical of innovation motifs, enabling innovations represent one side of a dichotomy. While enabling innovations produce significant effects on all impact dimensions, their counterparts, termed progressive innovations (Sinfield and Solis, 2016), tend to stem from an enabling innovation, are more focused in their use (narrow purpose-context applications), and have more limited albeit still beneficial effects. The culmination of a single enabling innovation is said to "enable" a whole cascade of progressive innovations. For instance, the laser enabled progressive innovations such as laser surgery, laser manufacturing, laser communication, and laser imaging (Sinfield and Solis, 2016). Emerging technologies that fit the enabling motif include the likes of artificial intelligence, advanced energy technologies, quantum computing, biotechnology, and novel materials, thus making the potential to interpret and proactively shape their advance of great interest to a broad array of entities.

While exciting for their vast impact potential, the great diversity of possible development routes and applications of enabling innovations, as well as their underlying complexity, has historically made it difficult to understand their potential future advance, and thus led many to frame enabling innovation pursuits as high-risk high-reward activities. In particular, the transition period from fundamental breakthroughs that highlight the promise of a future enabling innovation to the time at which the enabling innovation is realized and adopted at scale for its anticipated purpose can often be fraught with obstacles spanning technical, economic, and socio-cultural dimensions. This development phase has been termed the "enabling window"– a time period in which "multiple insights and capabilities coalesce" and innovators have "opportunities to make decisions about which capabilities to develop and which application contexts to pursue that will affect the significance as well as the adoption rate of the innovation" (Sinfield and Solis, 2016). Note that this is a markedly different interval than the classic technology "valley of death" which typically represents the capital sparse transition from laboratory prototype to commercial production and use (D'Amico et al., 2013), or the "chasm" often cast as a transition from early adopters to an early majority of end users (Moore, 1991). The enabling window effectively encompasses these classic periods, but starts earlier and ends later, connecting very early choices about strategic capability development and deployment to a long-term vision for the agglomerated capabilities required to achieve intended impacts.

Transiting this time period, however, need not be "high risk". Sinfield and Solis (2016) argue that the risk and time associated with developing high-impact enabling innovations depends more on the approach taken for pursuit than the nature of the technology or innovation itself (Sinfield and Solis, 2016). Two notable approaches have been prominent in the historical record to navigate the enabling window (Fig. 1). In the most conventional, a "moonshot approach" (Fig. 1, left side) is pursued, resembling what is often cast as Research, Development, Deployment and Diffusion (RDD&D), in which the enabling innovation is developed incrementally with a narrow focus on a strategic goal, and at-scale practical application and/or commercialization is delayed until full technology maturity. Interim steps – here indicated as "versions" - tend to involve prototypes (a test of a minimum viable version of a solution) and/or demonstration projects (an attempt at a scaled-down version of a solution) that combine a broad complement of in-development capabilities simultaneously, and thus suffer from

Table 1
Enabling Innovation Conditions and Supporting Roadmapping Analyses.

	Enabling innovation conditions	Supporting roadmapping analyses
1.	Vision of a desired future	Vision Analysis
2.	Understanding of TES capabilities that must be agglomerated to achieve the vision	First Principle Capability (FPC) Identification
3.	Assessment of the potential and difficulty of achieving technical advance	Technology Evaluation
4.	Awareness of the nature and likely sequence of barriers to technology advance and socio-cultural (market) adoption	Barrier Identification and Sequencing
5.	Characterization of opportunities for early application of evolving capability sets (i.e., lily pads)	Lily-pad Identification
6.	Time-ordered matching of potential/likely technological advances with ready-to-adopt applications/users (i.e., markets)	FPC and Lily Pad Sequencing
7.	Strategic perspective on proactive opportunities to create TES system conditions favorable to desired future	Ecosystem Influence Analysis

compounding risk that leads to considerable potential for failure. As depicted below the technology s-curve on the left side of Fig. 1, this moonshot approach is typically associated with a cash flow trough in which investment is repeatedly required over a long time period before positive returns can be realized. In addition, due to the narrow focus of the effort, activity, including prototyping and/or demonstration projects, tends to take place in a single application space, as indicated in the lower graphic on the left side of Fig. 1. However, a lesser known, but also historically prominent alternative exists. Termed a "lily pad approach" (Fig. 1, right side), this path emphasizes continuous deployment of one or more capabilities of the evolving solution in ready-to-adopt application spaces, or lily pads, that are tolerant of broader time-period specific market and/or societal constraints and yet can generate revenue, market learning, and/or technical advance, and thus risk-mitigate the path to maturity. In this case, as illustrated below the technology s-curve on the right side of Fig. 1, due to early in-market application, cash flow tends to become positive far in advance of what can be achieved via a moonshot approach, generating resources that may be deployed, at least in part, to support on-going R&D and/or offer returns to investors. As shown in the bottom graphic on the right side of Fig. 1, this route is made possible by recognizing capability deployment opportunities in multiple application spaces over time, as capabilities evolve.

The patterns described above are a byproduct of retrospective studies of technology development carried out by innovation scholars and characterize both the nature of enabling innovations, and the paths that have historically proven fruitful in achieving positive impacts from enabling innovations at scale. In a spirit consistent with what Park et al. (2020) framed as the "theory-oriented" Cambridge phenomenological school of roadmapping, the studies of the enabling innovation pattern have revealed a theory of technological change evident in the historical record – but importantly, one that has yet to be applied to shape forward-looking roadmapping activities. This presents an intriguing opportunity to proactively guide technology advance on advantaged, risk-mitigating pathways to accelerate progress by adopting a lily pad philosophy. With this concept in mind, this paper contributes to the literature on roadmapping by presenting a strategic roadmapping methodology specifically designed to realize a lily-pad approach to a desired future in any given technological sector.

3. Realizing enabling innovation via lily pads – a proactive strategic roadmapping methodology

In this section we introduce the key aspects of a structured methodology to realize enabling innovation by developing a strategic roadmap rooted in a risk-mitigating lily pad philosophy. Section 3.1 details the core analyses comprising the method, making extensive links to motivating theory and related disciplines. This foundation helps establish the mindsets and range of competencies required to perform the analyses and is thus followed by Section 3.2 which defines the team formation principles and implementation approach to support the method.

3.1. Method - core analyses

As detailed in Section 2.2, the lily pad path to achieve an enabling innovation and its broader benefits requires multiple conditions to be satisfied in the socio-technical system (i.e., innovation ecosystem) of focus, and it is posited here that potential means to achieve each of these conditions can be discerned through carefully designed analyses and integration of resulting insights. To this end, Table 1 outlines the key conditions underlying a lily-pad approach to enabling innovations, as well as the roadmapping analyses put forward here to help realize those conditions.

Each of the above outlined analyses contribute perspectives on important aspects of the enabling innovation pattern, and their integration represents a novel methodology that informs a proactive, risk-mitigated roadmap to the development of high-impact enabling innovations that can be tailored to any such technology. The following subsections describe the logic and theory supporting each of the proposed analyses in detail and how integration of resulting insights provides a holistic view of potential technology evolution and impacts.

3.1.1. Vision analysis

The vision establishes the overall strategic intent and desired impacts of the innovation being pursued, offering important guidance for prioritization decisions encountered in subsequent analyses. Grounded in strategy literature (e.g., Chandler, 1962) and consistent with the notion of creating a desirable future as called for in backcasting that was first introduced in the future analysis literature in the 1970's (Lovins, 1976; Robinson, 1982), the vision details long-term objectives of an innovation endeavor, defines the scale and/or scope of the challenge to be addressed, and calls attention to entity-based advantages (i.e., those of the visionary/planner) that will be employed to engage and shape the broader ecosystem (Collis and Rukstad, 2008), embracing principles of effectual logic (Sarasvathy, 2001). Ultimately, a vision may also explicitly challenge pre-existing notions or outdated assumptions that an organization, discipline, or community may hold, serving as a hallmark of the kind of change that is sought through the desired innovation.

3.1.2. First Principle Capability (FPC) identification

FPCs represent the fundamental capabilities that compose an innovation. FPCs are identified by disaggregating the envisioned innovation-driven end-state (i.e., the vision) into a comprehensive set of technical, economic, and socio-cultural capabilities that must be in-place to yield desired impacts. Related analysis is grounded in the foundational concepts of relevance trees (Churchman et al., 1957), analogical reasoning (Bono, 1975; Larkin et al., 1980), technology assessment (Arthur, 2007, 2009), and problem framing (Entman, 1993; Sinfield et al., 2020) and helps shift the priority of technology efforts from "developing one or more specific solutions" to "developing capabilities that support outcomes," offering a proactive lens to accelerate progress and prevent premature technology lock-in or solution fixation. Moreover, framing capabilities at a first principle level decontextualizes them, removing artificial ties to a presumed use, and increasing their foreseeable application scope (see discussion of lily pads below).

FPCs are not all equivalent and are herein prioritized on two major dimensions: significance and headroom for improvement. Significance refers to how important the FPC is to realization of the enabling vision. Headroom refers to the potential to realize significant gains in technological performance and/or economic or socio-cultural adoption relative to the current state that could progress the innovation toward the enabling vision (Foster, 1982; Foster et al., 1985; Sinfield and Solis, 2016). While high-significance, high-headroom FPCs are logical targets for focused investment (e.g., FPC R&D, market activity, or policy action), high-significance low-headroom FPCs could signal a need to pursue alternative solutions if their current state is unacceptable to achieve desired outcomes. Focus on a holistic and design-agnostic set of FPCs helps accelerate advancement of the industry and support optimal technology convergence.

3.1.3. Technology evaluation

Technology evaluation integrates leading perspectives on the likely upper bound of specific technological first principle capabilities, as well as the overarching capabilities of integrated technologies/platforms, all based upon an understanding of governing physical laws and system interdependencies. In this regard, effort is focused on determining if potential advances are likely to be limited more by the (uncertain) development of fundamental knowledge, or simply resource availability. Conceptually, determination of technological potential is anchored in theories of technology readiness (Mankins, 1995) prevalent in R&D management literature, with one important nuance. When developing an enabling innovation strategic roadmap, it is critical to recognize that classic Technology Readiness Levels (TRLs) are relative, not absolute metrics. TRLs are set with an envisioned performance goal in mind, and thus demarcate progress toward achievement of that goal. So, a technology that is at a low TRL for an ambitious goal, may in fact be at a higher TRL for an application that is less demanding.

With this in mind, the technology evaluation analysis informs potential lily pad linkages and helps highlight a key class of barriers to the end-state vision. Every lily pad opportunity ultimately requires a specific level of technological performance, and thus, must be linked to a technological solution that can deliver that performance. For some lily pads the technological solution can take the form of a small subset of the FPCs or components of an enabling technology that have already been developed, while for others, the solution may require nearly all of the components of an enabling technology at a level that would be considered underdeveloped as an integrated whole for the end vision, but fit-for-context for the lily pad.

Regardless of the form a technological solution takes, the process of identifying appropriate technological solutions for different lily pads can be made systematic and robust by identifying sector-specific technological performance metrics (TPMs) that create a common basis to compare different lily pads and different solutions, and to link these problem and solution spaces. Typical metrics to consider often span measures of capability, efficiency, cost-effectiveness, and competitiveness with existing/anticipated alternatives. If a more expansive analysis scope is desired (e.g., for efforts embracing principles of a circular economy), dimensions such as resource utilization, survivability, sustainability, and resilience may also be included.

3.1.4. Barrier identification and sequencing

Barrier identification recognizes that any new innovation must overcome numerous system level obstacles before achieving adoption at scale. Due to the ambitious and broad impact typically associated with enabling innovations, barriers limiting their progress are not only technical, and tend to include economic as well as socio-cultural impediments. Therefore, as a key step in roadmapping, systemic barriers, once identified, should be considered focal points for investment to realize progress. Barriers often have a natural order such that one barrier must be overcome before another can even be approached, and this interdependence drives the notion of sequencing barriers, as the sequence in which barriers are pursued and overcome determines the time, effort, and resources it takes to achieve the enabling vision. The concept of innovation barriers is rooted in literature on innovation ecosystems (Adner, 2006, 2012; Adner and Kapoor, 2010), innovation system functions (Bergek et al., 2008), and complexity (Gell-Mann, 2002; Holland, 1992).

3.1.5. Lily pad identification

Lily pads are applications that can be served by embodiments of one or more (but generally not all) established and/or developing capabilities needed to achieve the long-term vision (Sinfield and Solis, 2016). Lily pads are identified by contemplating use-cases for individual or combined first principle capabilities that may span application spaces, with an emphasis on “fit for context” logic. Focus is placed on current capabilities and where they can be immediately applied, with the rationale that use/application can accelerate learning, garner investment, and drive improvement in capability, rather than stretching capabilities for applications that are currently infeasible or forecasting the timing of performance potentially achievable in the future. Unlike full scale applications of a technology that demand high-performance, or even small-scale efforts that involve significant capability integration, lily pad applications avoid combining multiple premature capabilities that compound the risk of failure, and thus offer opportunities to test and learn about “parts of the whole” that pave lower-risk avenues to progress. Lily pad analysis is grounded in the theory of emergent strategy, (Mintzberg and Waters, 1985), as well as concepts of technology category co-evolution (Grodal et al., 2015), and technology-market matching (Freeman, 1982; Berman and Hagan, 2006; Noh et al., 2021). With these theoretical roots in mind, it becomes evident that lily pads may exist within the motivating sector, or outside it. The process of identifying lily pads can be made very systematic by framing the FPCs as solutions that solve end-use needs, or said more generally, fulfill a “purpose” in a given “context” (Sheth and Sinfield, 2021). This view fosters robust and comprehensive coverage of the lily pad landscape and reduces expert biases.

As is the case with FPCs, not all lily pad possibilities are equivalent. For an opportunity to qualify as a lily pad, it must satisfy multiple evaluative criteria focusing on the opportunity's feasibility, its success potential, and the overall benefit it can offer. Feasibility can be evaluated based on the capability readiness required for an application, noting again that this evaluation may span technical, economic, and socio-cultural capabilities. For the opportunities that are feasible for pursuit, their potential can be evaluated based on the likely competitive differentiation of the conceived solution for the lily pad application, the ecosystem barriers to entry/operation in that application area, as well as the cost and time required to pursue the opportunity. Opportunities that are feasible and have high potential, should then be evaluated for their benefits to the overall effort to achieve the long-term vision. These benefits may include opportunity to drive improvement in technical performance, manufacturability, or cost, opportunity for financial gain (that could fuel future research/development), and/or the potential to realize strategic market insight. The surviving list of opportunities – i.e., those with high feasibility, potential, and benefits – are most well suited to serve as lily pads. Importantly, the goal of the lily pad evaluation exercise is not to develop an in-depth business-case for each opportunity, but instead to efficiently filter out opportunities that may at first appear promising, but are actually undesirable or impractical.

3.1.6. FPC and lily pad sequencing

This analysis involves strategic ordering of a series of lily pads and related FPC development efforts to systematically test, demonstrate, and advance first-principle capabilities that will ultimately agglomerate into a high impact enabling innovation as called for in the vision. Optimal lily pad order is defined not only to foster technological advancement, but also to drive learning and systematically overcome identified barriers. This view of innovation draws on retrospective patterns of generic (Maine and Garnsey, 2006) and general purpose technologies (Bresnahan and Trajtenberg, 1995), but goes further to proactively agglomerate capabilities to fulfill multiple purposes in multiple contexts and thus drive new waves of subsequent innovative activity (Sinfield and Solis, 2016). Unlike the conventional moonshot approach, which tends to pursue advancements in a single envisioned context in a make-or-break effort, the lily pad approach leverages lower-risk, targeted

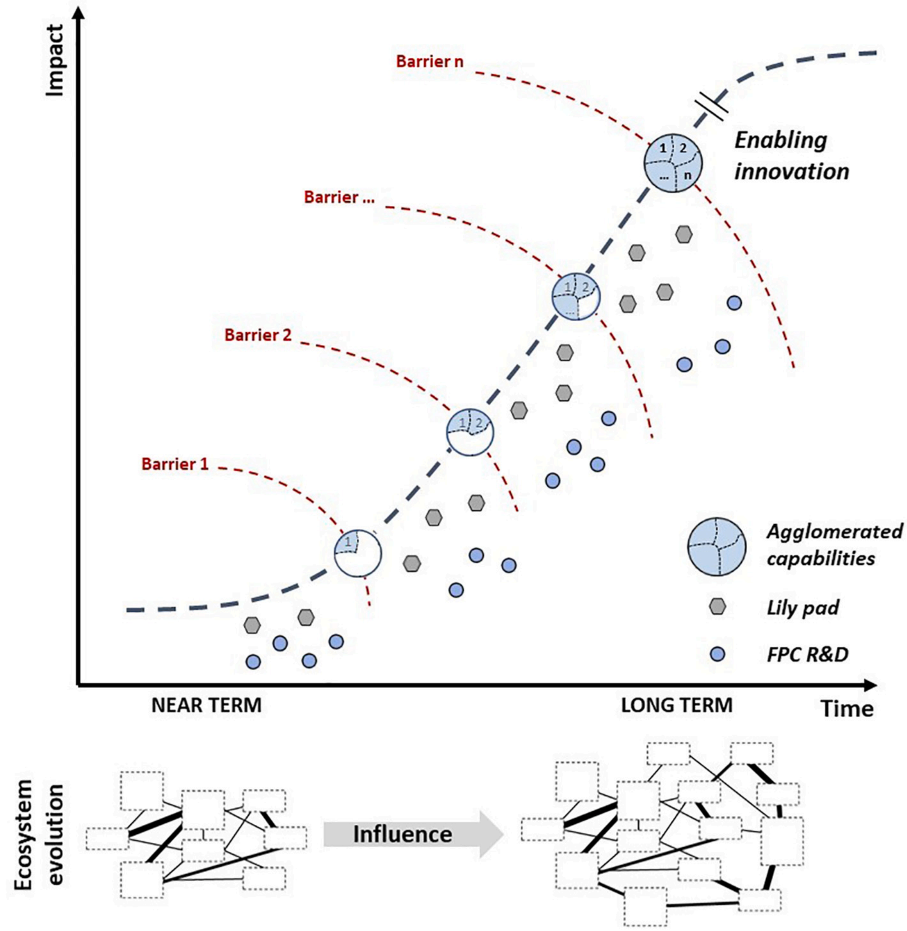

Fig. 2. Conceptual illustration of an enabling innovation strategic roadmap.

opportunities to advance different pieces of the enabling vision in different purpose-contexts that are logically sequenced to systematically align with and/or overcome barriers while delivering on interim needs. Small successes breed larger successes as acquired learning advances performance and drives realization of the enabling innovation. In-practice application and agglomeration of the needed set of technological, social, and economic FPCs over time draws attention to needs for new competencies early in the technology development process. Importantly, the specific technology typologies explored at the outset of lily pad activity need not be scalable to the full vision (albeit ideal) – it is only critical that they contribute to learning and advance. The combination of overarching learning and diverse sources of investment offers the potential to accelerate realization of the enabling innovation relative to a moonshot approach (Sinfield and Solis, 2016).

3.1.7. Ecosystem influence analysis

Once a pathway to an enabling innovation is envisioned, it is likely to become apparent that enabling innovations often spur (and require) the emergence of new value exchange systems, which may encompass numerous stakeholders and business entities that are unfamiliar to the current sector participants. This is especially true for enabling technologies that may be complex and/or multifaceted, and thus require creation of new technological value chains. Interpreting these potential changes requires systematic analysis spanning considerations of government and private sector financial support, policy, regulation, and standards, R&D needs, value chain/production system development, talent cultivation, and end-user adoption, among other factors. This analysis calls attention to the potential roles of existing members of the innovation ecosystem, highlights the likelihood that new entities will form or be needed, and helps define feasible single-entity actions as well as those that are likely to require partnerships or alliances, and typically involves at least two sub-components.

First, effort should be focused on defining the innovation ecosystem to understand the major categories of stakeholders/participants involved and to trace current and anticipated exchanges/flows of knowledge, money, information/data, capabilities, and influence among them, drawing on research derived insights into the dynamics of innovation systems (e.g., Fransman, 2018). This analysis can be deepened by building on additional research in the area of business model innovation (e.g., Gassmann et al., 2016; Zott and Amit, 2013; Liu et al., 2020), which suggests that the roles that support R&D, production, adoption/use, and long-term sustainability of an innovation are of particular interest and tend to fall into several major categories: manufacturers, designers, distributors, lenders, brokers, adders, connectors, aggregators (Liu et al., 2020; Weill et al., 2005). Further, each of these roles may leverage or effect specific assets in the ecosystem that may include physical assets, financial assets, intangible assets, talent, services, outcomes, relationships, knowledge/content/data (Liu et al., 2020). While the composition of a future ecosystem that facilitates an enabling innovation can take numerous forms, exploration of the possibilities can reveal logical gaps in key resource availability or accessibility, expose roles that are inefficient or yet to be fulfilled, and help identify potential shortfalls in workforce/talent – all factors that could be barriers or catalysts to realize the vision.

Second, with a view of the potential future ecosystem, additional analysis can be carried out to define potential avoidance or mitigative actions that leverage the unique strengths of the visionary or its allies (e.g., knowledge, convening power) to implement proactive influence tactics (e.g., awareness building, standards setting, incentives provisioning) and thereby affect the pace of change. These perspectives are grounded in systems theory (Bertalanffy, 1968; Meadows and Wright, 2008), concepts of business model innovation (Liu et al., 2020; Weill et al., 2005), and theory of influence (Bacon, 2011, 2012).

Collectively, these analyses provide perspectives that chart a potential risk-mitigated path to innovation-driven impact by proactively linking long-term strategic intent to a sequence of tangible actions that can be initiated in the present. This architecture facilitates successive small-scale applications that systematically build capabilities that aggregate in the form of an enabling innovation and drive high-impact outcomes (Fig. 2). Further, integration of the insights that result from the analyses outlined above systematically address each of the limitations of current roadmapping approaches discussed above. The development of a long-term vision and disaggregation of that vision into required first principle capabilities provide a means to foresee likely needs for technology advance and to shape and focus related research and development efforts very early in the pursuit. Exploration and evaluation of technological potential as well as identification of likely technical, economic, and socio-cultural barriers to progress provides a holistic view of the challenges likely to be encountered in the effort to achieve the vision. Barrier and lily pad sequencing then define periods of time in which technical viability and adoptability align to inform fit for context applications that provide alternate pathways to risk-mitigate technology development through strategic learning and/or revenue generation that provides means to navigate the valley of death, all while avoiding premature technology lock-in and offering application-based insight to guide technology convergence. Ecosystem influence analysis calls attention to the likely stakeholders and related business models that will be needed to fulfill the vision, again in alignment with barrier and lily pad sequencing, helping to define proactive measures that could accelerate progress and inform when to act. Finally, as described in the case study presented below, all analyses also benefit from both direct expert input and independent review of related literature to limit the potential for expert bias.

3.2. Method – implementation

Roadmapping, especially for high-impact emerging technologies, involves a high degree of uncertainty, and thus, the majority of roadmapping methods are loosely structured and open-ended. However, the strategic roadmapping methodology presented above, rooted in innovation patterns, breaks down the roadmapping activity into the seven analyses outlined in Section 3.1, fostering a structured and systematic process.

The analyses are carried out through a series of analysis-specific workshops that each entail pre-event preparation, one or more phases of in-depth expert and facilitator interaction, and post-event synthesis. While the focus of each workshop wave shifts as the locus of analysis changes throughout the process, we have found it valuable to ensure that diverse disciplinary and sector-role perspectives are present during each session, preferably spanning technology, operations, supply chain, policy, business, and social science, with representation to the extent possible from government, academia, and industry.

The effectiveness of each analysis is fully realized by conducting the roadmapping process through a collaborative effort between experts and a small team of facilitators knowledgeable in the enabling innovation patterns and analysis frameworks. The facilitators drive divergence, structuring, and convergence activities (Solis and Sinfield, 2018) for each analysis and carry out independent research to constructively support or challenge expert positions, add new perspectives, and synthesize findings. Specifically, during the pre-event preparation phase, facilitators utilize the foundational analysis frameworks and preliminary inputs from literature review to outline a contextualized structure of the workshop topic. This structure is employed to gather inputs from each of the experts through surveys and/or one-on-one interviews, always allowing for open-ended commentary to capture issues or concepts that may have initially been missed. This activity design overcomes challenges of group dynamics, ensures that all experts have a chance to provide input on all aspects of the analysis topic, and offers opportunity to bring-in external perspectives from peer-reviewed and industry literature. Perspectives gathered in the pre-event phases are then aggregated by the facilitators and discussed with the experts in a group setting, giving the experts the opportunity to debate inputs, ensure consistency in terminology, and develop a shared understanding of lines of enquiry. These early phases of activity are largely divergent, but employ structure to achieve a robust framing of the issues at hand. In the next phase, convergent efforts begin as the experts are each individually given the opportunity, again via survey and/or interview, to evaluate available inputs for each aspect of analysis (e.g., relevance of dimension of long-term vision, significance/timing of technical, economic, or socio-cultural barrier, potential for technology to address lily pad, potential for lily pad to offer risk-mitigating value to roadmap) using contextualized metrics, typically on coarse scales such as yes/no or high/medium/low to help compartmentalize uncertainty and drive consensus for decision making. The facilitators aggregate the findings of these evaluations, and the expert group is again brought together to constructively review and debate the results, with topic specific experts given final say on evaluations after rigorous consideration of all raised perspectives. Outputs resulting from this session are synthesized and employed to shape the final roadmap. The facilitators dedicate additional effort to validate or refute analysis conclusions through exploration of peer reviewed academic or industry literature/data. In the event that significant discrepancies are discovered between documented perspectives and those of the experts, which have not been justified during the working sessions, there is cause to reconvene the expert group for clarification.

Whether defining the objective, scope, and advantages of the future vision, working to identify technical, economic, and socio-cultural capabilities likely needed to achieve the vision, or mapping technological promise to likely adoption-ready applications, among the multiple analyses that comprise the strategic roadmapping method, the structure and bounded focus of each analysis accelerates the ideation and input activity and encourages consideration of diverse perspectives, helping to ensure a holistic lens is applied to the challenge. This approach helps to mitigate biases and uncover what might otherwise be unknown-unknowns. The systematic nature of each analysis also provides flexibility to the roadmapping process, accommodating both virtual and in-person expert engagement.

4. Development of an enabling innovation strategic roadmap - the case of Marine Renewable Energy

Marine Renewable Energy (MRE), harvesting energy from the oceans' waves, tides, and currents, is a predictable clean energy source that has the potential to satisfy a significant portion of the world's energy needs. This promise has occupied the imagination of innovators for centuries. Efforts to tap the power of the oceans date back to the late 1700's, with the first patent for a wave energy converter attributed to French inventor Pierre-Simon Girard in 1799 (Pecher and Kofoed, 2017; Ross, 1996, p. 19). By the mid-1800's, inventors around the world had explored multiple means to harness the power of waves. In the 1940's, Yoshio Masuda, viewed as a pioneer of modern wave energy technologies, formalized study in the field and developed several wave energy converter mechanisms (Masuda, 1986). However, it wasn't until over two decades later that possibility and technological reality converged to help realize the first large scale marine hydrokinetic power station – France's Rance Tidal Power Station (RTPS), which opened in November 1966. With a generation capacity of 0.2 GW, to this day it is the second largest tidal power station in the world (OES-Environmental, 2019).

Despite projects like RTPS, and global interest spurred by the energy crisis of the 1970's (Falcão, 2010), the full promise of the oceans' energy

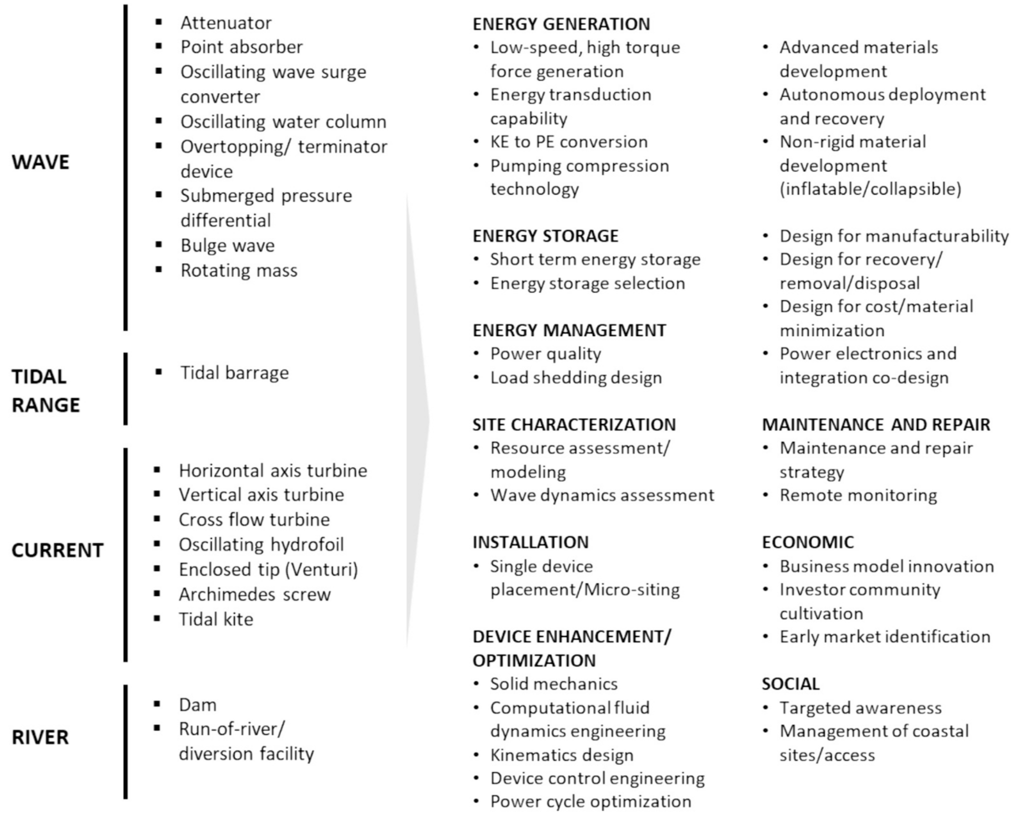

Fig. 3. High significance, high headroom first principle capabilities.

resource has yet to be realized. In fact, recently momentum in the sector has eroded (Carlson and Adams, 2020; IRENA, 2020b, 2020a; Jeffrey et al., 2013; Leete et al., 2013; Magagna and Uihlein, 2015; Masini and Menichetti, 2012; Olmos et al., 2012). Many entities initially anticipated to spur the sector have ceased operations (e.g., Seimens - 2014; Pelamis Wave Power - 2014; Aquamarine Power - 2015; OpenHydro - 2019) (Downing, 2014; Frankfurt School-UNEP and BloombergNEF, 2019; "Jobs Go …", 2014; "Jobs Lost …", 2015). Ocean Power Technologies, one of the modern forerunners in wave energy, has seen its stock dip 99 % since its public listing. As a result of a long string of challenges, MRE devices remain at a premature stage of development (Guo and Ringwood, 2021; Kerr et al., 2021; Muscio et al., 2023) and the targets anticipated in technology roadmaps not even a decade old are unfortunately far from reality (ETI and UKERC, 2014; Ocean Energy Forum, 2016; SEAI, 2015). Some researchers now suggest that the sector has failed in building investor confidence and has fallen into a "valley of death" (Muscio et al., 2023). As of 2021, the total global installed capacity across all ocean energy technologies is merely 0.5 GW, (Boshell et al., 2020) literally less than 1/1000th that of solar or wind (IRENA, 2022).

The failure of MRE to take-off is striking given the documented potential of tapping the oceans. MRE in the US alone could generate approximately 2300 terawatt-hours of green energy per year (Bhatnagar et al., 2021). This represents nearly 60 % of U.S. electricity generation in 2019 - a clear opportunity for MRE to play a significant role in the energy mix (Bhatnagar et al., 2021). Beyond power availability, MRE requires minimal land, is relatively predictable, and has low energy storage requirements. Moreover, MRE has the potential and competitive edge to power a variety of new and emerging applications in and around the ocean that lack the benefit of grid-access.

This contrast between opportunity and progress highlights that the approach taken to drive technological advance, spur adoption, and improve the risk to reward ratio for investors has been largely ineffective. With this as a backdrop, and given the prominence of lily pad phenomena in cases of significant socio-technical impact, herein we examine the potential to proactively employ the principles of lily pad-based enabling Innovation to foster the Blue Economy and realize the long-sought vision for marine renewable energy.

As any analysis is only as good as its inputs, a collaborative team was formed to carry out this exploration, involving a partnership between the Institute for Innovation Science at Purdue University, and experts from the U.S. Department of Energy (U.S. DOE) Water Power Technologies Office (WPTO), the U.S. National Renewable Energy Lab (NREL), and the U.S. Pacific Northwest National Lab (PNNL). The team included experts in marine energy technology fundamentals, at-sea/on-shore system installation and operation, financing in the renewable energy space, community engagement, related policy and incentives, as well as private sector mindsets, and included both within-industry professionals and external academics. The group worked together over a 10-month period and engaged in more than a dozen in-depth working sessions punctuated by intermittent explorations of the knowledge housed within the U.S. DOE, and that in both industry press and peer-reviewed literature. The effort employed the analyses described above to foresee obstacles and opportunities in the sector and devise means to address or capture them. The resulting strategic roadmap calls attention to several barriers that must be overcome to achieve scale in the sector, highlights multiple opportunities for lily pads that could advance related technological progress and strategic learning on MRE, and offers a detailed view of the potential evolution of the MRE ecosystem under a risk-mitigating paradigm.

4.1. Vision analysis - MRE

With an understanding of the history of the MRE sector as well as the pattern of enabling innovations, the vision exercise in this effort was intentionally pursued to objectively challenge pre-existing notions about MRE. Given the make-up of the involved team, the perspective of a government organization was adopted to guide vision development. This posture prioritizes sector wide advancement over the success of any individual entity and encompasses awareness of the organization's ability to influence policy, provide resources, and facilitate the transfer of knowledge. Through iterative dialogue and development of alternate narratives, the team defined a vision encompassing an overarching intent to develop a thriving Blue Economy and MRE ecosystem founded on a portfolio of robust, versatile, and scalable MRE technologies. The group also highlighted a desire to drive impact by supplementing power needs of the nation at an off-grid or micro-grid level in proximity to the oceans, and to maintain technical focus on energy generation capability inclusive of efforts ranging from technological ideation to technology scaling and optimization. There was also willingness to fulfill the roles of applied research supporter, research talent developer, developmental contracts provider, and energy sector job creator in the ecosystem. Finally, the vision included dedication to support grants, licensing, and open source technology know-how, with recognition that government actors can likely benefit the ecosystem most by leveraging their convening power, fostering creation of foundational knowledge and tools, and offering financial resources and technical assistance.

This vision stands out in contrast to the conventional sector vision that emphasizes levelized cost of energy (LCOE) (cost focused in contrast to value focused) considerations for grid level competitiveness, as mentioned in most literature (Bhatnagar et al., 2021; MacGillivray et al., 2013; Magagna et al., n.d., 2014; Magagna and Uihlein, 2015; Mwasilu and Jung, 2019; Parkinson et al., 2015; Uihlein and Magagna, 2016), instead focusing on employing MRE in off-grid applications where it faces lower competition and price sensitivity, in support of accelerating the achievement of a thriving U.S. marine energy sector.

4.2. First principle capability identification - MRE

Identification of FPCs in this work derived from examination of a broad range of technologies that generate marine renewable energy as outlined in Fig. 3 (LHS), review of related industry and peer-reviewed literature sources, and an analysis of the factors that have helped or hindered historical MRE initiatives (Tidal Devices, n.d.; Wave Devices, n.d.). Approximately 115 FPCs were identified that are relevant to MRE. Some FPCs, particularly in the technological area, have been in development and use in a variety of industries for decades and likely have low headroom for significant improvement. For example, while energy transmission, corrosion prevention, and hydraulics optimization are important inputs to success in this space (Lin et al., 2015; Nambiar et al., 2016; Wang et al., 2021), investment in these areas is unlikely to greatly change the likelihood of MRE technology breakthroughs or related solution adoption. Further, capabilities such as land rights management, and wildlife migration modeling, which are also important, represent well established fields (Christy, 1975; Quinn and Brodeur, 1991, p. 1). In contrast other FPCs, like device control engineering and short-term energy storage, are relatively newer capabilities that are not only critical for MRE's progress and adoption, but also have a high potential for early-market application (lily pad) (Mueller and Wallace, 2008; Ringwood et al., 2014; Wang et al., 2019; Zhou et al., 2013). Thus, from the broad FPC set, after multiple rounds of team ranking, about 30 were deemed to be of high significance and high headroom as shown in Fig. 3 (RHS).

MRE's advancement is dependent upon the development of FPCs focused on device functionality and deployment, FPCs pertaining to overall device optimization, and a handful of capabilities associated with non-technical factors such as economic feasibility and social acceptance. The prioritized FPCs are largely MRE-technology agnostic, and thus support industry advancement as a whole, while allowing convergence on the optimal technological solution(s) to play out, as opposed to fixating on a specific technology that may or may not meet the sector's immediate needs.

4.3. Technology evaluation - MRE

To date, MRE technologies have evolved in a largely uncoordinated manner across a broad array of application contexts, and hundreds of different projects, as well as over 300 context-specific device designs, have been documented (PRIMRE Marine Energy Project Databases, 2023). This complexity reflects the ocean-condition dependence of MRE technologies, and the absence of expert consensus on optimal device design - that is, a lack of technology convergence. While not an uncommon phenomenon in emerging technology domains, this problem is particularly pronounced in the MRE space due to the wide range of mechanisms that have been and can be envisioned to convert mechanical wave energy into electrical power and the lack of fundamental parametric studies to definitively inform design. However, some clarity can be brought to this situation by applying the logic underlying the enabling model which focuses on time-coordinated linkage of current and anticipated capabilities to current and anticipated needs.

At their core, MRE devices fulfill the purpose of providing power. This power can be dimensionalized in terms of average power (kW), maximum power (kW), and power quality (i.e., consistency of voltage, frequency, and waveform). For any given MRE device, additional performance metrics may include durability and service intervals, tolerable environmental conditions, location applicability (e.g., on-shore vs at-sea, depths of use, wave/current characteristics), and spatial requirements, which collectively influence feasible contexts of use, as well as installation and operating costs that translate into energy cost, relative to context-available alternatives.

With these dimensions in mind, classes of current, tidal and wave technologies were evaluated to assess their near-, mid-, and long-term capabilities, with related TRLs defined initially in reference to any given technology's potential suitability to provide traditional grid power. Generally, current and tidal technologies, although broadly pre-commercial, are more advanced than wave technologies, largely owing to their use of principles applied in wind turbines (Guo and Ringwood, 2021; Magagna, 2019; PRIMRE Marine Energy Project Databases, 2023). In this technology class, axial and cross-flow turbines offer a range of maximum power output options from ~30 to 10,000 kW at TRLs of 7 or greater (Magagna, 2019; PRIMRE Marine Energy Project Databases, 2023); however they also tend to require significant support structures as they are placed at depth in the ocean or in tidal channels, and this can drive considerable up-front expense. While the power obtained from axial turbines tends to be stable, that from cross-flow turbines can be oscillatory, leading to increased short-term storage needs. Tidal kites offer another relatively high TRL option, in the mid power range of 100–1000 kW. These devices are tethered to the sea floor, and have a very dynamic (and thus potentially maintenance intensive) mode of operation, and also require substantial spatial clearance. Among wave technologies, point absorbers stand out with a modest power generation capacity of 3 to 1000 kW at TRLs above 8, with far greater capacity expected from devices currently at lower TRLs (PRIMRE Marine Energy Project Databases, 2023). Wave driven attenuators offer similar performance at only slightly lower TRLs, and both point absorbers and attenuators offer small form-factor options for power generation in less demanding applications if desired. Both of these devices also offer simplicity in design that supports in-situ durability and reduced maintenance, and make use of tethered designs that offer siting flexibility. Other wave technologies (e.g., pressure differential devices, oscillating water columns, and overtopping systems) tend to be earlier in development and/or applicable only at significant scale, but offer the promise of delivering 10,000–100,000 kW per installation (Magagna, 2019; Malali and Marchand, 2020; PRIMRE Marine Energy Project Databases, 2023).

Collectively, all of these technologies, if deployed, offer opportunities to advance knowledge on hydrokinetic energy capture, device robustness in the harsh ocean environment (e.g., gaskets, biofouling, impact tolerance), the effectiveness of foundation and tethering solutions, and overall power generation, storage, and transmission economics in at-sea and on-shore scenarios. The key is connecting the technologies to applications for which they are currently fit for context.

Potential applications and contexts of use can also be characterized technically, based on average and maximum power demand, required power quality, tolerance for intermittent power availability (e.g., primary vs. supplemental vs. back-up power), typical activity location and related hydrodynamic conditions, spatial constraints, and cost tolerance. Typical power demand for potential applications ranges from low Watts for personal device charging and exterior lighting applications, to 10's to 100's of kWs for ocean observation and navigation buoys and underwater vehicle charging stations, to 100's to 1000's of kWs for aquaculture and supplemental power for ship support, to 10,000 to 10,000,000 kWs for community microgrids, large desalination operations, and hyperscale datacenter cooling (LiVecchi et al., 2019). Among this vast array of applications, near-shore low power opportunities like shoreline sensors offer contexts that can employ small form factor devices in accessible and thus maintenance friendly settings. Off-shore non-critical use cases, such as monitoring buoys and unmanned underwater vehicle charging stations, offer additional low power demand contexts, albeit with more difficult access. Supplemental power could be acceptable for situations such as facility level ecotourism operations and small-scale disaster relief desalination, again near-shore, but with a step-up in power demand. Public safety beacons and commercial operations like aquaculture represent example contexts that demand greater reliability for critical back-up and primary power needs. Applications like community microgrids and large desalination plants require the utmost performance in reliability, survivability and cost-competitiveness.

Ultimately, this ladder of performance demand can be meshed with technology capability and contextual applicability to define a high probability sequence of lily pad applications for which available technology performance is matched with needs, and likely growth in performance demand over time will support investment and subsequent technology advance to facilitate more demanding use cases. This solution-application matching process and the resulting sequence of probable lily pads, however, must be further informed by exploring systemic barriers to MRE advance and scale, and by rigorously structuring the diverse landscape of potential applications, as outlined in the following sections.

4.4. Barrier identification and sequencing - MRE

Like any enabling innovation, MRE faces several systemic barriers that have prevented the technology from advancing and scaling. Despite government support and significant developments on new means to harness marine energy, there has yet to be technological convergence in MRE hardware design that could help drive economies of scale (Bucher et al., 2016; Leete et al., 2013; MacGillivray et al., 2013; Magagna and Uihlein, 2015; Neary et al., 2014; The Power of Change, 2016). Following a lily pad philosophy to overcome this challenge, access to capital is required in the near term to pursue applications that place limited performance demands on MRE yet offer significant opportunity for learning and advancement, and to pursue FPC R&D. Effort is also needed to establish a common basis for objective and holistic technology evaluation as well as performance guidelines and related technical advances to achieve availability and acceptability of power for baseline MRE applications. As technology advances and applications increase in complexity, reliability can become a focus, and attention should be dedicated to overcoming a general lack of knowledge sharing in the industry that has impeded development progress (Bucher et al., 2016; Jeffrey et al., 2013; MacGillivray et al., 2014). This knowledge sharing can help foster topology convergence, while additional efforts encourage adoption of MRE among potential communities of users. Further out in time, issues of overall device survivability, maintenance, and cost-competitiveness will need to be addressed, but these complex topics can be more efficiently tackled through focus on a narrower set of converged technological solutions than exist today (Bucher et al., 2016; Jeffrey et al., 2013; Leete et al., 2013; MacGillivray et al., 2013; Mueller and Wallace, 2008). Identified systemic barriers (Table 2) serve as major milestones that the sector must overcome, through lily pads and targeted FPC R&D, to ultimately achieve the enabling innovation vision.

Table 2
Systemic barriers to MRE adoption and scaling.

NEAR TERM	MID TERM	LONG TERM
• Access to capital/ revenue/ support • Technology evaluation guidelines • Availability and acceptability of power • System reliability	• Competition/ collaboration • Topology convergence • Social acceptance	• Device survivability • Cost-competitiveness • Device maintenance

While the exact order in which barriers will be overcome cannot be known and may shift as the sector evolves, the general focus in each of the three phases will likely remain. Achieving baseline technology readiness that offers acceptable and reliable marine power is critical for the sector to gain momentum early on, and only once that is achieved can there be some certainty about which technology types, from the large list of options available today, are most suitable for scaling. Then, after the sector has reached technology convergence, investment could focus on making technology winners more resilient and MRE cost-competitive at scale with other energy sources.

4.5. Lily pad identification - MRE

An enabling technology that is in development is by definition premature for the ultimate envisioned context of use, and thus, lily pads highlight applications that require lesser performance relative to the long-term goal. As noted above, these opportunities may reside within or outside the sector of focus, and make use of one or more (but not all) FPCs underlying the envisioned enabler that are "fit for context." In the case of MRE, due to the historical underpinning of MRE development in the RDD&D-based (moonshot) philosophy that tends to delay commercialization until full technology maturity, a host of less demanding opportunities for MRE exist that have been largely ignored (IRENA and OEE, 2023). Sometimes referred to as "niche" opportunities in recent literature (Hemer et al., 2018; LiVecchi et al., 2019; Renzi et al., 2021), these opportunities remain "in-sector" and thus have the potential to provide rapid and highly relevant capability development, revenue generation, or/and cost reduction to build momentum toward a MRE blue economy.

In order to thoroughly identify these applications, a purpose-context logic was used to rigorously break down and organize the MRE opportunity landscape, leading to generation of over 150 possible applications in a short span of time. In this opportunity landscape, explored purposes, at the highest level, include generating energy - by building new structures or repurposing existing structures, or reclaiming energy – by recouping energy from existing processes, as shown in Fig. 4.[1]

Within the "generate energy" purpose associated with "building new structures", three user contexts comprehensively cover the opportunity space and likely involve applications that use marine power and help generate revenue. The first context of use - user exists at the site of generation - offers a range of potential lily pad applications that can be further grouped according to the distance from shore (on-shore vs at-sea) and the objective fulfilled by the marine power (primary vs supplemental). On-shore or near-shore applications are those that make use of ocean energy but still offer value to users who are likely based on land and include applications like desalination or sea water pumping (e.g.,

[1] Note that mobile purpose-built energy generation platforms are left out of this discussion for simplicity.

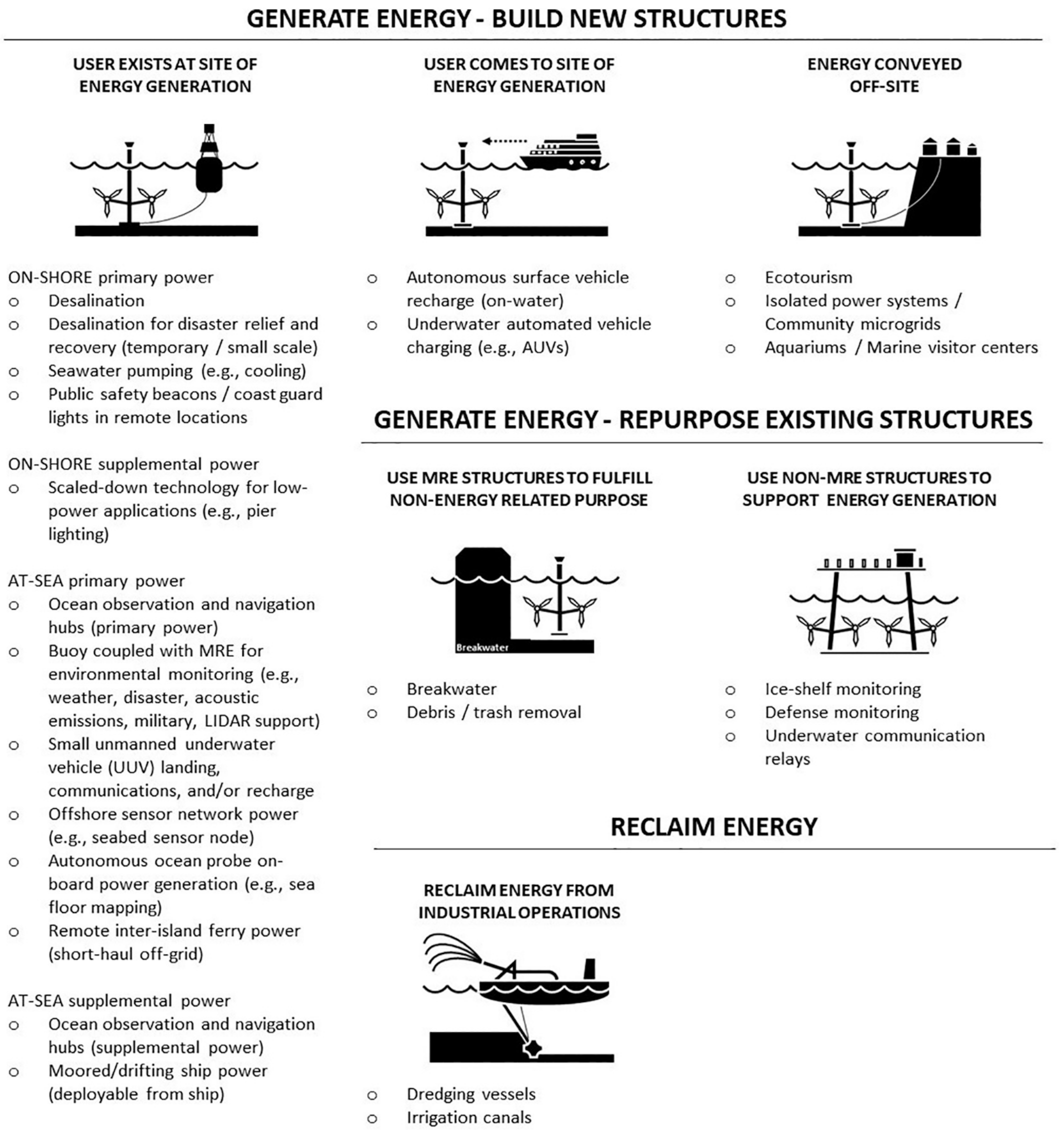

Fig. 4. Potential MRE lily pad opportunities.

for cooling). On the other hand, at-sea or offshore applications are those that take place in the deep ocean, offer value to more niche users, and are relatively smaller in scale due to higher installation complexity. At sea, marine power could facilitate a host of navigation, observation, monitoring, and sampling activities that are performed in the deep oceans but are often limited by lack of accessible energy. In the second user context, user comes to site of generation, the user is mobile and comes to the MRE-generating structure to recharge power. Here applications could include support of autonomous surface vehicles or autonomous underwater vehicles (AUV). The third user context, power conveyed offsite, likely constitutes stationary applications that are on land but still see value in marine power. This could include applications like ecotourism, aquarium centers, or isolated community microgrids where MRE has competitive advantage. The applications in this context would not only require lower technological complexity for set up, but could also serve as important early adoption cases that could positively influence general social acceptance of MRE.

Within the "generating energy" purpose sub-category of "repurposing existing structures", two user contexts emerge that involve applications that would share the installation cost of a marine energy-generating structure by coupling the objective of energy generation with a non-MRE objective. The first context involves applications that use a MRE structure to fulfill a non-MRE secondary purpose (e.g., the MRE structure also serves as a breakwater), while the second context involves applications that use a non-MRE structure to fulfill the secondary purpose of generating energy (e.g., adding MRE capability to an oil platform). The second high-level purpose of "reclaiming energy" primarily involves applications that recoup hydrokinetic energy from industrial operations like dredging or from places like irrigation canals. Among this large array of opportunities, those that satisfy multiple evaluative criteria spanning the opportunity's technological feasibility, the competitive differentiation of an MRE solution for the intended purpose and context, the significance of the technical gains that can be realized, and the potential for learning and/or monetary benefits, are deemed qualified to be risk-mitigating lily pads. Examples of lily pad applications that are likely to adhere to these criteria are shown in Fig. 4.

4.6. FPC and lily pad sequencing - MRE

The optimal sequence of FPCs and lily pads – that is the sequence that could likely achieve a fully realized MRE enabling innovation – was determined by linking lily pads and R&D opportunities with the barriers they address and FPCs they help develop, and then ordering these initiatives to logically advance cumulative capabilities and overcome

Table 3
FPCs organized by barrier-term.

	NEAR TERM	MID TERM	LONG TERM
ENERGY GENERATION	• Low-speed, high torque force generation	• Energy transduction capability • Kinetic to potential energy conversion • Pumping/compression technology optimization	
ENERGY STORAGE	• Short term energy storage		• Energy storage optimization/selection
ENERGY MANAGEMENT	• Power quality optimization		• Load shedding design
SITE CHARACTERIZATION	• Resource assessment/modeling		• Wave dynamics assessment
INSTALLATION	• Single device placement/micro-siting		• Multi-device placement/siting
DEVICE OPTIMIZATION	• Power cycle optimization • Solid mechanics • Kinematics design • Device control engineering • Computational fluid dynamics engineering • Co-design of power electronics and integration • Design for recovery/ removal/disposal	• Design for manufacturability • Device material selection/optimization	• Advanced materials development • Non-rigid material development (inflatable/ collapsible) • High fatigue synthetic fiber development • Autonomous deployment and recovery • Design for cost/material minimization
MAINTENANCE AND REPAIR	• Device reliability improvement	• Maintenance and repair strategy • Remote monitoring	• Survivability control strategies • Predictive maintenance • Autonomous deployment/ recovery • Design for recovery/removal/ disposal
ECONOMICS	• Investor community cultivation • Early market identification capability	• Business model innovation	
SOCIAL	• Targeted awareness building	• Coastal site/access management	

Table 4
Lily pads organized by barrier-term.

		NEAR TERM	MID TERM	LONG TERM
USER EXISTS AT SITE OF GENERATION	ON-SHORE Primary power	• Desalination for disaster relief and recovery (temporary and small scale) • Seawater pumping (e.g., cooling)	• Public safety beacons/coast guard lights in extreme/ remote locations	• Desalination (at-scale)
	ON-SHORE Supplemental power	• Scaled down technology for low power applications (e.g., lighting)		
	AT-SEA Primary power	• Ocean observation and navigation hubs (primary power) • Buoy coupled with MRE for environment monitoring (e.g., weather, disaster, acoustic emissions, military, LIDAR support) • Small unmanned underwater vehicle (UUV) landing, communications, and/or recharge station • Ice-shelf monitoring • Underwater communication relays	• Offshore sensor networks (e.g. seabed tsunami detection nodes) • Trash/debris removal • Autonomous ocean probe on-board power generation (e.g. sea-floor mapping)	• Remote inter-island ferry power (short-haul, off-grid) • Off-shore network power
	AT-SEA Supplemental power		• Ocean observation and navigation hubs (supplemental power)	• Moored/drifting ship power (deployable from ship)
USER COMES TO SITE OF GENERATION			• Underwater automated vehicle charging (e.g. AUVs w/ image processing)	• Autonomous surface vehicle recharge (on-water)
POWER CONVEYED OFFSITE		• Ecotourism • Isolated power systems/ Community microgrids (far off grid)	• Aquariums/visitor centers	• Ecotourism (at-scale) • Community microgrids (at-scale)

phase specific barriers. As noted above, despite investments over the past decade or so, MRE has not seen significant advancement due to focus on complex deployment projects rather than specific in-demand capabilities, as well as general perceptions of the sector as high risk. Under the lily-pad philosophy, in order to make progress, the sector must focus on required capability development balanced with attention to opportunities that can garner early-market success and related revenue. The early term will require access to basic capital and support to develop a baseline-performing MRE technology. This should likely be achieved through the development of basic capabilities in core functional areas (e.g., energy generation, energy storage, and energy management) as well as capabilities associated with device control, without excessive focus on complete and costly device designs. In addition to technological capabilities, there needs to be focus on the development of basic social and economic capabilities. The capital expenditure needed for R&D must be balanced with revenue generation through lily pad applications, especially in contexts with lower performance requirements. Early successes will likely drive performance improvements, and lead to interest of purveyors and an increase in investor confidence, which are crucial to build sector-wide momentum. Categorized views of the FPCs and lily pads positioned across the near-, mid- and long-term are shown in Table 3 and Table 4, respectively.

As baseline performing and reliable marine power is achieved, the sector must continue to pursue and refine the R&D and lily pad applications to funnel toward technological convergence. The most promising device architecture(s) can then be transitioned toward modularity and/or economies of scale through the development of relevant capabilities such as design for manufacturability and device material selection. In addition, the economic and social capabilities like business model innovation and coastal site management must be enhanced to

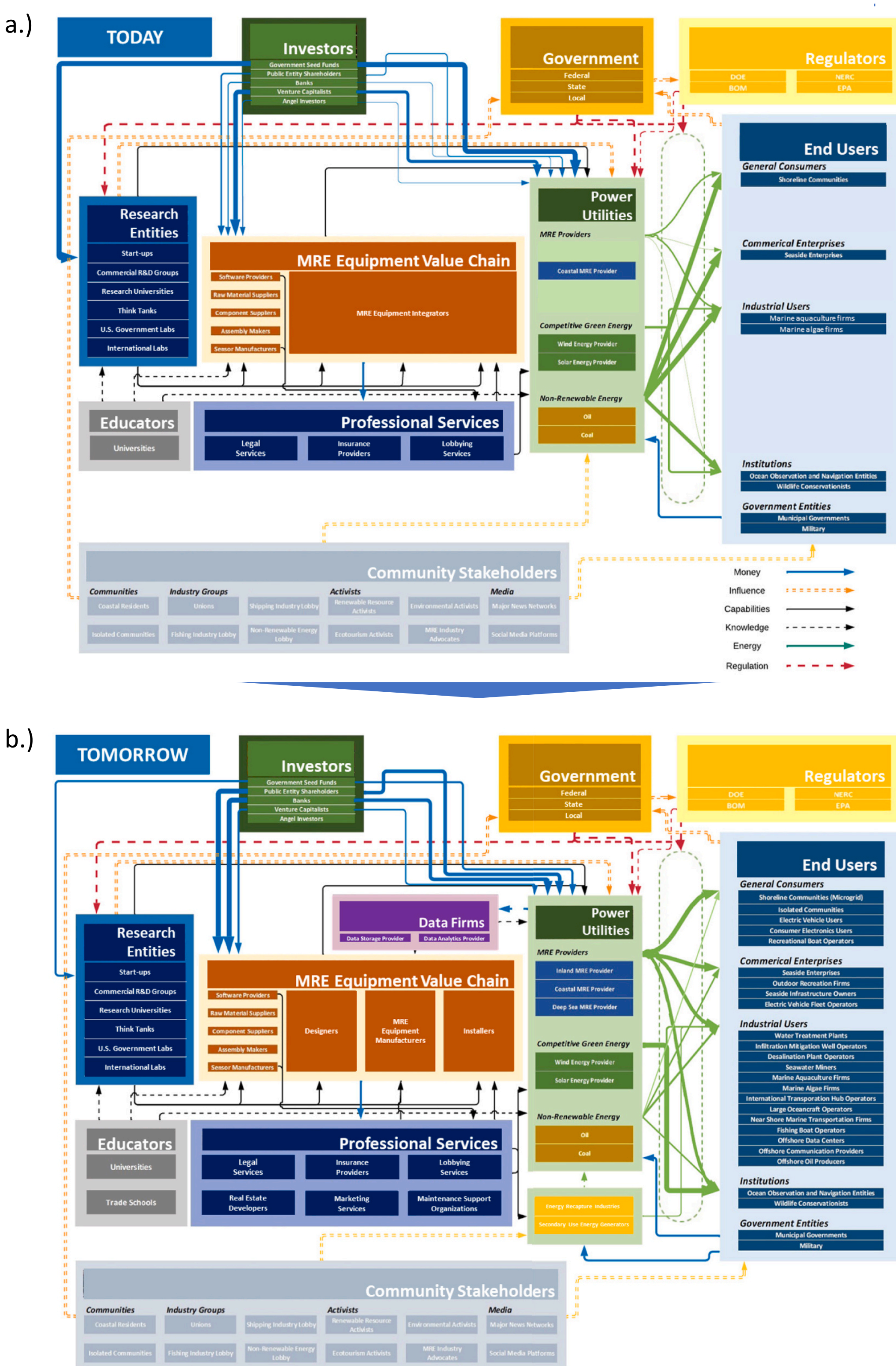

Fig. 5. Illustration of MRE stakeholder-ecosystem: a.) today, b.) tomorrow.

Table 5
Asset-role characterization of current and emerging business entities in MRE.

	CONVENTIONAL ROLES -NEAR/MID/LONG TERM-	NOVEL ROLES -MID/ LONG TERM-
PHYSICAL ASSET	Manufacturer *Equipment/device/ infrastructure producer* Designer *Equipment/device designer* Distributor *Equipment/device/ infrastructure installer*	Lender *Equipment lessor* Broker *Real estate developer*
FINANCIAL ASSET	Manufacturer/ Designer/ Distributor *Commercial bank*	Lender *Capital lending org, MRE venture funds* Adder/ Broker *Carbon credit broker, Enterprise M&A broker* Connector/ Aggregator *Mortgage aggregator*
TALENT	Manufacturer *Education entity, Talent development org* Connector *Talent search/placement org*	Lender *MRE expert consultancy*
INTANGIBLE ASSET	Manufacturer *Rights litigation firm* Designer *MRE modeling/design software provider* Adder *IP producer*	–
SERVICE	Manufacturer *Vehicle charging service provider* Distributor *MRE microgrid utility* Broker *Recapture/backhaul energy broker* Aggregator *Independent energy generator aggregator*	Manufacturer *Maintenance support organization* Designer *MRE engineering/ planning/ design services firm*
OUTCOME	–	Manufacturer *Guaranteed power provider*
RELATIONSHIP	–	Designer *University partnership developer/manager* Connector *Community relationship manager*
KNOWLEDGE/ CONTENT/ DATA	Manufacturer *Data provider* Adder *Data/knowledge network operator* Broker *IP broker*	Distributor *Patent portfolio manager* Lender *MRE data manager* Aggregator *MRE knowledge/data aggregator*

ultimately cultivate a more collaborative development environment and to achieve wider social acceptance.

With attainment of baseline technological performance in the near-term and convergence in the mid-term, in the long-term, the sector should focus on optimizing survivability and the resilience of MRE infrastructure for greater scale and to ultimately overcome the barrier of cost-competitiveness with other renewables and non-renewable alternatives. This will require the advancement of already developing capabilities related to energy storage, device optimization, and maintenance and repair, and the development of newer capabilities related to advanced materials and autonomous deployment and recovery (Mueller and Wallace, 2008). Again, capital expenditure should be balanced with revenue generation by scaling previous applications (e.g., desalination, ocean observation and navigation hubs, community microgrids) and pursuing more sophisticated applications (e.g., autonomous surface vehicles, moored ship power).

Agglomeration of the needed set of fully developed technological, social, and economic capabilities through risk-mitigating market lily pads and targeted FPC/R&D offers the potential to accelerate realization of the enabling innovation to achieve a thriving Blue Economy. Several new competencies, non-existent in the current paradigm, will likely need to emerge, facilitating a cascade of progressive innovations in different purpose-contexts, and consequently, generating growth and societal impact.

4.7. Ecosystem influence analysis - MRE

Proactive pursuit of MRE's enabling vision will require increased engagement from current ecosystem participants as well as involvement and/or creation of numerous additional entities. Today, the ecosystem is composed primarily of pioneering enterprises, a small number of private investors, limited user communities, research universities, and supportive government entities (Fig. 5a). To achieve the desired future vision for MRE, a host of new organizations will likely need to be engaged (Fig. 5b).

Technology convergence will require significant fundamental work by focused research enterprises (e.g., universities) and research-pursuing private firms. This will demand investment and necessitate involvement of lenders, lessors, and brokers to provide efficient access to financial and physical assets. Existing and new firms will need to efficiently manage different roles along the value chain ranging from production of raw materials to equipment and data analysis needed for device operation, maintenance, and specific applications. Increasing demand for talent will also likely require development of training and educational groups. Numerous application-oriented organizations will become MRE consumers and will need to be served by power utilities that seamlessly deliver power from MHK devices to user-locations. Further, MRE engineering, planning, and device service entities will be important to connect service providers with service utilizers, and community relationship managers will influence social perception of the industry.

Moreover, there will likely be considerable complexity in the private sector that is directly and indirectly involved with MRE. A more comprehensive view of the business landscape was visualized through an asset-role matrix. The identified set of lily pads were used to define several conventional and novel asset-role pairs for MRE, as shown in Table 5.

Besides fostering conventional roles like manufacturers and distributors, novel business roles, like lenders and brokers, should be recognized as important because they can positively change the perception of risk (investments required) and lower the barriers to entry (e.g., skill, resources needed). Lender and broker roles for different assets may be fulfilled by entities like equipment lessors and real estate developers that can provide easier and quicker access to physical assets like MRE equipment, devices, and infrastructure fostering supplemental, back-up, or even rental markets; capital lending organizations and carbon credit brokers that can provide streamlined access to capital that is often required for asset-intensive MRE projects; and MRE expert consultancies that can offer need-based access to talent and expertise. Similarly, MRE engineering/planning/device service entities (asset: service; role: designer) can connect service providers with service utilizers, and community relationship managers (asset: relationship; role: connector) can influence social perception of the industry.

Finally, the U.S. Department of Energy, may also consider employing a variety of levers to support the key stakeholders in the ecosystem. Fig. 6 provides a host of support levers, categorized based on different modes of influence, and hinged on the organization's strong reputation, physical assets, technical competency, convening power, and accumulated experience. Overall, a holistic approach to ecosystem development through FPC-driven lily pad pursuits, barrier breakdown, ecosystem

Build awareness
- Model and illustrate economic impact (+) of MRE
- Encourage blue + green policy (bundle)
- Disseminate PSAs on merits of blue energy
- Train on potential business model variants

Convene
- Encourage pursuit of MRE start-up tax incentives
- Convene VC MRE roundtable
- Spur industry association education meetings

Ally
- Establish academic center partnerships
- Develop start-up alliance with major corporations
- Build partnerships with Green Energy actors

Provide shared resources
- Develop public database of MRE device readiness/ performance
- Develop shared "siting model/ tool" to reduce avoidable failures
- Provide "in-kind" contributions for non-profit returns
- Create open access/source "capabilities"
- Avail shared test beds to reduce up-front risks

Reduce pitfalls
- Couple RFAs with holistic assumption analysis oversight
- Institute virtual modelling pre-tests for downstream funding
- "Package" historical pitfall inventory

Establish standards
- Define technology performance classification

Lower entry barriers
- Offer patent / licensing assistance
- Develop simple licensing rights/ processes
- Aggregate marginal cost capacity of suppliers
- Develop blanket power purchasing agreements

Share risk
- Co-own (non-profit) developed IP in return for sponsorship
- Create a "liability alliance" to expand risk pool

Provide incentives
- Offer rebates for blue energy production and/or usage
- Encourage "blue" carbon credit markets
- Develop data monitoring/ storage partnerships

Build fundamental knowledge
- Sponsor enabling tech research with shared results

Encourage collaboration
- Develop land and water rights access consortium
- Create first principle technology R&D consortium
- Create supply/ transmission access alliances

Develop supply chain
- Develop a purchasing cooperative

Develop workforce
- Start work-study programs to seed industry talent pool
- Develop talent certification programs

Fig. 6. Potential MRE ecosystem influence levers.

shaping, business model cultivation, and targeted support strategies can likely foster enabling technology advance and realization of the Blue Economy.

4.8. *Resulting enabling innovation strategic roadmap for MRE*

Synthesis of the outputs stemming from each of the above analyses inform a strategic roadmap for evolution of the MRE sector and related technologies as pictured in Fig. 7. Time is represented on the horizontal axis and the impact produced (not to scale) is represented conceptually on the vertical axis.

The figure is presented as an inflecting s-curve, consistent with the theoretical framing of enabling innovations put forward by Sinfield and Solis (2016) and conceptualized in Fig. 2. Windows of opportunity are demarcated along the s-curve by curved arcs representing barriers to technology advance and socio-cultural adoption drawing directly from the content and sequencing of Table 2. Lily pads, drawn from Fig. 4 and sequenced as in Table 4, are aligned within the windows of opportunity on the underside of the s-curve, falling, respectively, between the prior barriers that must be broken for them to succeed and the future barriers that they can help break. MRE technological advance, First Principle Capabilities (FPC's) and related R&D activities needed along the way are aligned below the s-curve graphic as a function of time (near-term, mid-term, long-term), and are sourced from Table 3. Finally, along the very bottom of the graphic the transition from the current to future ecosystem is visualized, employing the graphical ecosystem representations of Fig. 5, with key influence strategies from Fig. 6 documented in the space between them.

While the exact path that will ultimately drive the scale and scope of adoption of MRE cannot be known, systematic analyses such as those presented herein highlight opportunities to risk mitigate the sector, foster open-minded scenario consideration, help prioritize supporting technological, economic, and social innovations, and prepare leaders to anticipate likely ecosystem change. In contrast to the conventional resource intensive moonshot approach to MRE that has persistently focused on grid competitiveness in the energy space, proactive and systematic pursuit of several lower-risk early impact opportunities, or lily pads, that target systemic barriers can likely drive accelerated and financially sustainable advancement of the sector. Ultimately, pattern-based analysis rooted in innovation science principles helps overcome presuppositions and historical or status quo biases and reduces unknown unknowns.

5. Discussion and conclusions

This paper introduces a unique approach to understand and proactively guide the evolution of high impact enabling technologies. The outlined methodology, framed as development of an enabling innovation strategic roadmap, draws on the pattern of enabling innovation that suggests that innovations that achieve significant impact do so only when an agglomeration of technical, economic, and socio-cultural factors overcome fundamental barriers to advance, adoption, and scale.

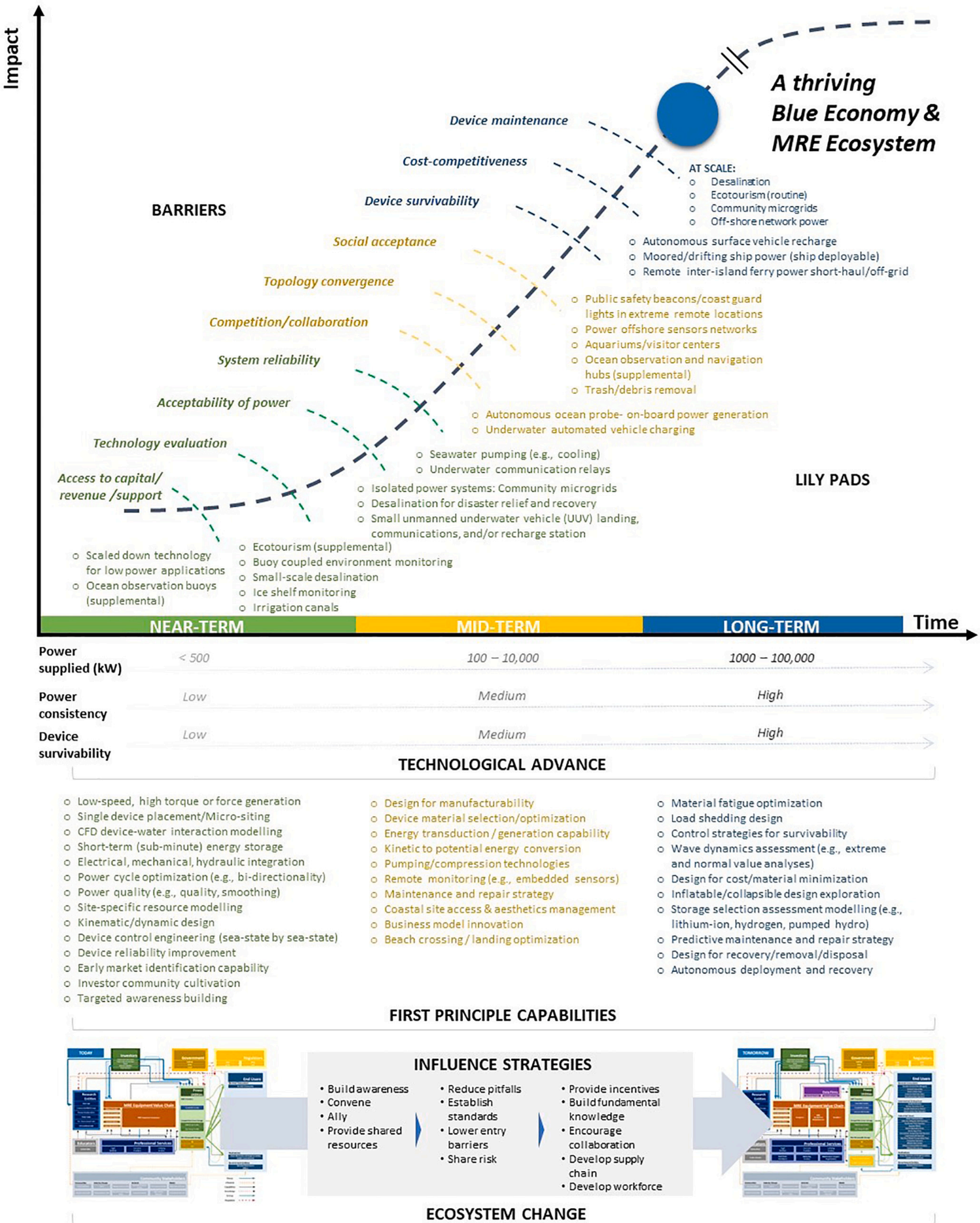

Fig. 7. Strategic roadmap for evolution of the MRE sector and related technologies.

This prepares the receiving ecosystem for a cascade of progressive (enabled) innovations that fulfill different purposes in different contexts, through what amounts to a complex socio-technical transition. Importantly, innovation science literature emphasizes that the traditional pitfalls of this type of transformation, such as capability-need mismatch, technology lock-in, investor reluctance, and a related valley of death, have historically been largely avoided when fundamental capabilities are tested and advanced individually or in small sets in fit-for-context applications and subsequently aggregated and informed by application-driven learning to address increasingly demanding needs that reach toward a direction-setting vision. This philosophy stands in stark contrast to traditional roadmapping approaches that are rooted in a moonshot or RDD&D philosophy that emphasizes iterative, generational advance of increasingly complex prototypes of a dominant design toward a defined goal.

The holistic nature of the enabling innovation strategic roadmap is achieved through combined focus on technology viability and adoptability, and relies on 7 key analyses that proactively and systematically target the end vision. The vision analysis breaks down the end goal into finer dimensions to reach a clear, shared understanding of the desired end state that can serve as a guide during decision making and analysis. FPC identification defines a holistic set of capabilities that must be systematically developed to achieve the vision – shifting focus from advancing a technological design to advancing underlying capabilities that will drive technology convergence and garner support for development and adoption. Technology evaluation defines prominent performance metrics that establish the current state of required capabilities, the headroom and/or need for improvement on these dimensions, and the potential for any given set of capabilities to meet the expectations of a given use case. Barrier identification and sequencing highlights the major technical, social, and economic obstacles that a technology's ecosystem must systematically overcome to achieve the vision. Lily pad identification and sequencing seeks out fit-for-context opportunities, related or unrelated to the envisioned goal, that can employ the evolving components of the ultimate enabling solution (in the form of FPCs or underdeveloped technology) to sequentially address the systemic barriers, and helps visualize the evolution of the combined enabling innovation. Finally, ecosystem influence analysis explores the likely transformation of the supporting ecosystem and helps anticipate means to proactively influence key stakeholders. Although presented linearly out of necessity in the above prose, there is continuous feedback between these analyses, particularly between the examination of required capabilities, systemic barriers, and potential lily pads.

These analyses were applied herein for hydrokinetic energy technologies, an enabling innovation that has been unable to scale and gain traction despite substantive investment over the past two decades, in order to outline a robust approach to alter this trajectory and foster a thriving MRE-powered Blue Economy. This example highlights several important aspects of a roadmapping methodology capable of handling technical, economic, and socio-cultural dimensions when attempting to guide and/or support the evolution on an immature high-potential technology. The vision analysis, anchored in an enabling paradigm, encouraged those involved in the effort to put forward a goal to develop a thriving Blue Economy and MRE ecosystem founded on a portfolio of robust, versatile, and scalable MRE technologies that is notably different from the conventional sector vision tied to large scale MRE designs that achieve levelized cost of energy parity with non-renewable alternatives. FPC analysis identified a holistic set of over 100 technology-agnostic capabilities, 30 of which were deemed to be high significance with high headroom for growth in contributing to the end-state vision. These capabilities, particularly for a government agency, draw immediate attention to R&D opportunities that merit support. Technology evaluation analysis, framed with multiple metrics that inform fit-for-context-applications, rapidly called out small scale, moderate to high maturity systems and related components that could be employed for use cases with modest performance requirements. The barrier analysis helped identify 10 technical, economic, and/or socio-cultural obstacles, like availability of baseline power, technology convergence, social acceptance, and device serviceably, that are likely to demarcate phases of application potential and adoption in the MRE market, and are critical to overcome to reach the end vision. The lily pad analysis employed a purpose-context lens to unveil a comprehensive opportunity landscape of 150+ opportunities spanning the MRE sector. In this particular case, there were extensive in-sector small scale/modest performance needs that satisfied evaluative criteria related to technological feasibility, business viability, and significance to the end vision and that offer opportunity to garner investment and drive learning and thus there was little need to go outside the sector. However, beyond-sector opportunities could also be readily envisioned, such as broader application of advances in computational fluid dynamics modeling, soft-ground foundations, biofouling mitigation, and even gasket and seal technologies that all support the end vision. Through FPC and lily pad sequencing, informed by the barrier analysis and technology evaluation results, an overarching evolutionary trajectory for MRE technologies and related applications was put forward that risk-mitigates the development of fundamental capabilities and aggregates advances to address increasingly more demanding use case on a path toward the vision. Ecosystem analysis, reflective upon this vision of the future, then highlighted a host of influence levers that a government agency like the DOE could employ to proactively foster the envisioned ecosystem.

Overall, this example called out the important interconnections between needed and available capability, supporting economics, and socio-cultural adoption that are inherently part of any emerging technology development path and are incorporated in the proposed strategic roadmapping methodology, emphasizing that failure to consider the multi-faceted nature of what is a complex socio-technical system is likely to significantly compromise derived perspectives. The roadmapping methodology presented herein is thus likely of great need as the collective of government leaders, scholars, and practitioners increasingly work to take advantage of advances in our most promising technologies to address society's grand challenges. While it may be clear that we will likely require highly innovative technologies that depart from mainstream paradigms to address these urgent needs, the enabling innovation lens emphasizes that the approach taken to bring these technologies to fruition may benefit from a similar departure from prevailing thinking.

Author statement

The data presented in this article represent the synthesized outputs of stakeholders involved in multiple working sessions. The opinions and analysis inputs of individuals are confidential.

CRediT authorship contribution statement

J.V. Sinfield: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **A. Ajmani:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **W. McShane:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

None.

Data availability

The data that has been used is confidential.

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