Ocean Energy: Markets – Currency – Impact Dimensions of & Choices in the Technology Development Space

J. Weber

Abstract—**This paper presents considerations of the employment of ocean wave energy to support different energy demand side applications. The key aspect in these considerations is the wave energy supported achievable positive impact and associated tangible contribution in service of common societal good and of the natural commons. The level of impact that can be delivered is dependent on both, the level of contribution of the supported energy use application, and the compatibility and unique suitability of the wave energy resource and its characteristics with the needs of the application. Thus, a variety of ocean wave energy markets, the key value indicators or "currency' in which these markets trade the value delivered and the achievable positive impact, are reflected upon. Ocean wave energy supported acquisition of high quality ocean system data across a wide spectrum of system properties is identified as a highly impactful application enabling and/or improving a comprehensive range of impactful ocean system activities.**

The technology development process towards these markets and desired impacts requires relevant technology development progress guidance and metrics. Going beyond technology readiness levels and technology performance levels, the notion of further technology development progress scales towards high impact and high contribution are proposed. These scales and the associated technology properties can be regarded as additional technology development dimensions to span-up the technology development space in which desired system capability and functional requirement choices and subsequent ideation, innovation, research and technology development decisions can and are to be made.

Keywords—**Ocean wave energy market, impact market, data market, technology development scales, technology impact levels, technology development space.**

I. Introduction

Reflecting on the acceleration of the changes in ecological, climatological systems and generally in planetary health, specifically the decline thereof, it is essential to further develop and deploy renewable energy forms, including ocean wave energy, at large scale and across all possible applications.

Furthermore, it is critical to identify and employ the combinations those renewable energy sources with those energy use cases that are of the highest ratio of benefit to effort and deliver the most valuable and impactful, tangible contribution in service of natural commons and common societal good. Such considerations hold for all renewable energy types, all ocean energy types, as well as and especially for ocean wave energy.

Thus, it is not only important to consider the energy resource that is accessed and converted into the standard form of usable energy, that is, in the form of electricity, and to deliver to the most prominent marketplace, that is, the continental grid; it is equally important to consider the use, purpose and impact of the converted energy in their particular use case and associated markets.

Considering the entire value chain from the marine renewable energy resource through the usable energy to the actual energy use case and enabled purpose, may lead to the identification of highly impactful implementations with more direct delivery of the renewable energy to the valued impactful application. On such more direct paths from resource to impact the extracted energy and the applied energy is a mean to the purpose rather than a means to an end with the specific use undefined.

The increasing appreciation and higher valuation of such high impact applications may further shift the investments and research efforts towards a larger inclusion and greater focus thereof within the wave energy research and technology development domain.

Identification, assessments and investigation of marine

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J. Weber is with the National Renewable Energy Laboratory, Boulder, Colorado, USA (e-mail: jochem.weber@nrel.gov).

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renewable energy markets other than powering the continental grid, such as "powering the blue economy" (PBE) [1] alongside numerous research and development efforts have been underway for several years and are gaining traction. However, to fully maximize the achievable contributary impact of ocean wave energy it is critical to extend the consideration from replacing the energy source in existing applications with wave energy, to the enablement of highly impactful applications that are currently not existing or are currently not affordable or not operated at the magnitude possible or when powered by ocean waves.

II. MARKETS, CURRENCY, IMPACT

In this section the main characteristics of four classes of ocean wave energy markets are being considered with respect to their value chain from the wave energy resource to both, the resulting monetary value and the impact value. Both value propositions are functions of efficiency, that is unit value output per unit energy input, and of the market size.

Depending on the market characteristics the unit value output may not always be expressible in monetary units but may be measured, expressed and traded in different "currencies" associated with the benefits delivered to the market and their positive impact and tangible contribution in service of natural commons and common societal good.

For the simplified high level considerations suggested here, negative impacts such as undesired environmental implications are regarded as outside of scope as the initial focus is set on the potential positive impact. Clearly, potential negative impacts need to be assessed and considered in detail once markets and applications of high potential of positive impact have been identified and warrant the investment of further investigation, research and development.

The four classes of ocean wave energy markets reflected upon in the following subsections are

- Grid market
- Blue economy market
- Impact market
- Data market

A. *Grid market*

Evidently, the most prominent and by far largest energy market for ocean wave energy is the continental grid market. Fig. 1 depicts the value conversion from wave energy to the achievable values on the grid market. Wave energy is converted to electricity at large farm scale and delivered as bulk energy to the electricity grid, where it is primarily traded in a strongly competitive environment alongside land-based renewable energy forms, primarily via levelized cost of energy (LCOE) as the relevant monetary value unit. As was the case for other renewable energy forms, dedicated market mechanisms are most likely required to facilitate wave energy market entry. Due to the overall wave resource and the immense size of the grid market the potential monetary value is enormous. However, given the highly competitive unit prices, market entry represent a significant hurdle and scale up will require market corresponding investment.

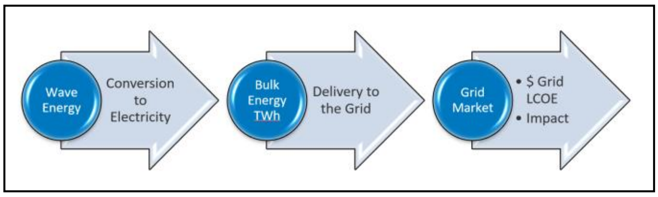

Fig. 1. Wave energy converted to electricity and delivered as bulk energy to grid market.

In terms of impact value delivered, clearly the provision of clean and renewable energy and the associated reduction or future avoidance of fossil fuel based energy generation is at the forefront.

Additional value of wave energy delivery to the grid is associated with the characteristic temporal nature of the wave energy resource. Increased predictability and low correlation with other renewable energy forms, both marine and land based, provide benefits with respect to energy balancing with increased capacity factors of combined or co-located plants of mixed renewable energy source and associated energy supply and grid resilience.

B. *Blue economy market*

A wide variety of blue economy markets have been identified. Under the powering the blue economy initiative [1], these are classifies into two the groups of power at sea and resilient costal communities, including; ocean observation, underwater vehicle charging, offshore marine aquaculture, marine algae, seawater mining and desalination, isolated communities, costal resilience and disaster recovery, respectively. Fig. 2 depicts the value conversion from wave energy to the achievable values on the blue economy market.

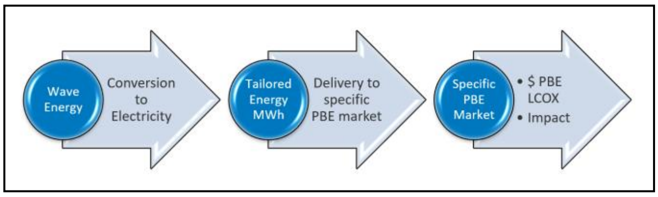

Fig. 2. Wave energy converted to electricity (predominantly) and delivered as tailored energy to specific PBE market.

Wave energy is predominantly converted to electricity, is tailored in form and amount to the needs to the targeted application and delivered to the specific PBE market. Dependent on the application, production site, location, jurisdiction and several other factors, the monetary and impact value delivered to and gained on the PBE market can vary significantly. The served clients can be both legacy and emerging industries to be supported to meet economic, social, and environmental goals. The monetary value as well as the competitive environment vary in both, magnitude and unit as indicated by LCOX in Fig. 2, as a placeholder for the levelized cost of variable x. Apart from the use of LCOE as for instance in the case of the PBE market of costal communities, the monetary unit of levelized cost of water (LCOW) is appropriately used in the water desalination PBE market. In other PBE markets such as the energy provision in remote coastal communities, the driving monitoring metric may also be reflected by the levelized avoided cost of electricity (LACE), as the local energy production based on wave energy avoids otherwise incurred significant transmission infrastructure cost. In other situations the voided cost of alternative effort or possible damage represent the monetary driver, as for instance in the avoidance of inefficient manual labor in aquaculture operations or the avoidance of secondary damage or harm in disaster recovery operations, respectively. Furthermore, both, market size and potential positive impact also varies significantly across the different PBE markets.

The energy markets considered within the blue economy primarily are existing markets and the replacement of a different currently used form of energy by marine renewable energy, in this case wave energy, is targeted. The replacement of these energy types by wave energy may have a range of different consequences associated with the technologies delivering to these markets. These may vary from a) maintaining the market share and size of the operations as these are dependent on other criteria within or outside the monetary value chain, while providing benefits through the use of wave energy, b) increasing the market share of the operations by changing profitability or providing other benefits to the relevant stakeholders within or outside the monetary value chain, c) or increasing the overall market size and therewithin the market share and the size of the operations by providing benefits to the relevant stakeholders within or outside the monetary value chain.

C. *Impact market*

Markets that are primarily initiated and/or driven by their potential positive impact and tangible contribution in service of the natural commons and common societal good are here referred to impact markets.

Fig. 3 depicts the value conversion from wave energy to the achievable values on the impact market. Wave energy is predominantly converted to electricity, is tailored in form and amount to the needs to the targeted application and delivered to the specific impact market.

Similarly to the PBE markets the market size as well as the level of monetary value and impact value vary significantly across the different applications and use cases. However, the motivation and driver for the impact market and the related missions are based on the resulting positive impact. Hereby, the achievable monetary value of LCOX based sales provide addition benefit and most importantly may serve as the enabling driver for the operations, with the value of the operation through the creation of, however not directly monetized societal and environment benefits is a larger value than the value gained within the direct monetary value chain. Thus, in theses circumstance the business case powers the operations and also facilitates the high value impact case.

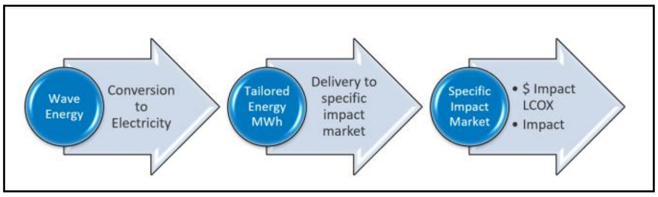

Fig. 3. Wave energy converted to electricity (predominantly) and delivered as tailored energy to specific impact market.

As opposed to the replacement of fossil fuel based energy supplies through the use of the wave resource in existing operations, those cases where the use and conversion of ocean wave energy enables the application in the first place, thereby initiating and kickstarting a corresponding and new market, provides significant opportunity for wave energy powered impact. Furthermore, as mentioned in the introduction, the efficiency of the operations with respect to the ratio of invested energy input, based on wave energy, to the achieved impact, greatly influences the realizable effect and magnitude of the impact. Examples for high potential wave energy impact markets are separately provided in subsequent sections.

D. *Data market*

As the 4th category of viable ocean wave energy markets the data market considered. Fig. 4 depicts the value conversion from wave energy to a mission relevant energy form, predominantly electricity, driving ocean data acquisition missions and delivering the collected data to data market.

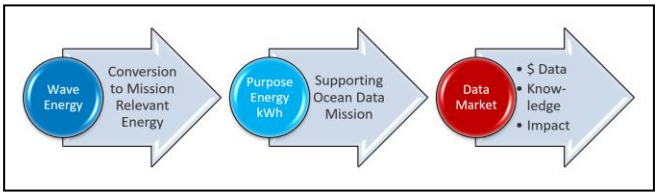

Fig. 4. Wave energy converted to mission relevant energy form, predominantly electricity, driving ocean data acquisition mission delivering data to data market.

Tradable currencies on data markets are both monetary currencies as well as the data itself. With the extraction of highly valuable knowledge from the data content through analysis, evaluation and interpretation, both the monetary as well as the impact value are substantially increased. The operation gathering ocean data this included within the blue economy markets as ocean observation. Key findings on ocean observation within the PBE report [1] include:

- Despite increasing investigation and development of infrastructure almost 80% have not been mapped or explored
- Ocean instrumentation and sensing operations are often limited by energy constraints, battery capacity, data storage and transmission capabilities, also significantly limiting mission durations and unattended time at sea
- Marine energy can meet the energy requirements for ocean observation missions and is uniquely suited through in situ and high spatial and temporal resource availability
- The existing and serviceable world market for ocean observation and navigational instruments is in the order of $10s billion and growing

At this point it is important to recall that highest effectiveness and efficiency with respect to invested energy and gained monetary and impact values is achieved when the uniqueness of the renewable energy form matches the unique needs of the targeted application. For ocean wave energy the uniqueness lies in relative consistency, high degree of forecastability, energy density and the ubiquitous nature across the oceans. These properties are uniquely well suited to service ocean data acquisition and delivery operations across all ocean data types and acquisition locations. Furthermore, the value density and portability of ocean data is by orders of magnitude higher than the value density of and other service or product producible from ocean wave energy.

III. POWERING THE SMART DATA OCEAN

The range of highly impactful ocean data applications and markets that are significantly benefiting from and/or fundamentally enabled and dependent on ocean data is substantial. There are practically no ocean operations that would not benefit from the availability of operationally relevant ocean data. In order to appropriately serve the high impact data applications, ocean data of high spatial and temporal resolution at high quality standards of both the rough and the smart data structures are required.

Building on the findings of the previous section and the current status of ocean observing infrastructure and capabilities, as well as recognizing that dedicated marine energy based technology can be developed to drive global ocean data acquisition operations, it is realistic and achievable that ocean wave energy will be capable of effectively "powering the smart data ocean" (PSDO).

Fig. 5 displays a selection of highly impactful ocean data applications and markets that are enabled and greatly benefiting from market relevant smart ocean data. It is evident from Fig. 5 that the ocean data market is the most potent high impact market as it fuels and supports a wide range of data-driven high impact markets.

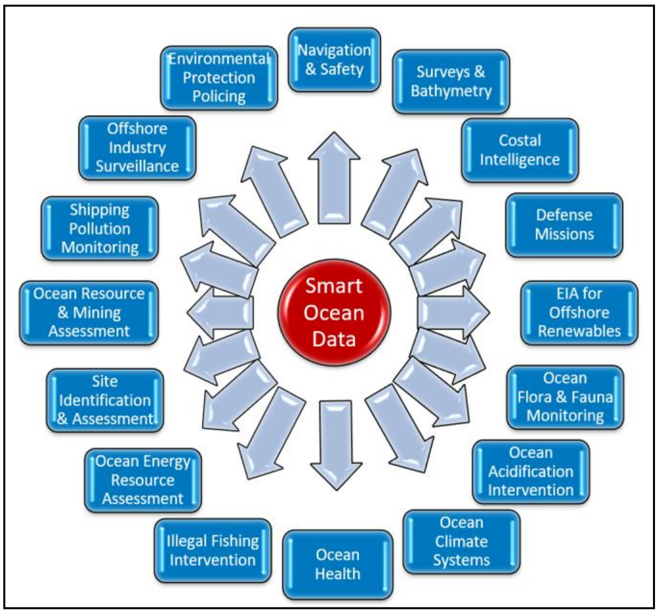

Fig. 5. Selection of smart ocean data benefiting and enabling high impact ocean data applications and markets.

IV. WAVE ENERGY IMPACT MARKETS

A small selection of highly impactful and smart ocean data-driven markets and related operations are briefly described in the following sections. As previously concluded, it is regarded as realistic and achievable that ocean wave energy will be capable of effectively powering the related ocean data acquisition operations.

E. Ocean health

For the assessment of the ocean's health essential ocean variables that characterize the status of the ocean's biodiversity and ecosystems, a wide variety of ocean system data is required. Evidently, the ocean's health is declining. Any possible interventions and health supporting measures will require high quality ocean data at high temporal and spatial resolution prior, during and following the intervention process and to support critical decision making.

F. Marine energy site development

The duration of the marine energy site development process is critically dependent on the licensing and environmental impact statement data requirements. The overall site development process duration may range between four and seven years while the fast deployment of offshore renewable energy, primarily from fixed and offshore floating wind, is required in order to achieve decarbonization targets, and driven by policymakers and industry. With increased availability of highly resolved ocean data and accelerated ocean data acquisition operations it can be expected that the duration of marine energy site developments can be notably reduced. Assuming, for exemplary purposes, a duration reduction of the licensing process by one year, and the associated earlier deployment of the vast numbers of planned offshore wind projects and associate capacity globally, an additional annual renewable energy deployment could be expected, that would significantly surpass the projected global deployment and associated capacity from wave energy plants delivering power directly to the grid.

G. Carbon capture

The oceans are the predominant planetary carbon sink and offer additional interventions to increase ocean carbon capture. An effective, promising and also ocean health supporting carbon capture methodology is provided through kelp farming. The identification of suitable kelp farm sites that satisfy the required spatial, thermal, biological, and chemical conditions is critical. Improved availability, quality and resolution of ocean data could significantly increase the rollout and the success of kelp farming operations. Using autonomous and wave energy powered data acquisition systems that are capable of controlling their observation routing based in the acquired data, effective kelp farming site identification and high quality mapping could be delivered.

H. Enforcement of legislation

The enforcement of legislation related to environmental protection of the oceans, as well as shipping, trade and offshore industry operations is critical and requires high degree and standards of ocean observation and data acquisition, evaluation and validation activities.

V. TECHNOLOGY DEVELOPMENT PROCESS

In an effort to drive the technology development of ocean wave energy systems that deliver the ocean acquisition function at the required level of spatial and temporal resolution across the wide range of measurement quantities, the technology development process to target these systems will need to be adapted.

I. Technology development process scales

A key requirement for successful technology development is the precise formulation of the problem and opportunity statement and the determination of the desired system capabilities and the associated enabling functional requirements. The application specific functional requirements will drive concept ideation and technology development processes and the system capabilities will support the definition of the associated market specific technology performance levels (TPL) [2,3] for the assessment of system concepts and designs.

A number of PBE market specific TPL formulations and assessment tools have been under development at NREL and Sandia. Example include remote costal communities, desalination and ocean observation.

J. Technology development space

In order to ensure that the technologies achieve the desired impact it is important that the relevant capabilities are reflected in the technology development process scale. Dependent on the market, the impact-relevant capabilities may be fully in line with the technology performance relevant capabilities that ensure techno-economical performance and support the satisfaction of the monetary-relevant capabilities. In those cases the pursuit of high impact technology is facilitated though the use of TPLs specific to the high impact market and the technology development space is two-dimensional and spanned up by technology readiness levels (TRL) [4] and technology performance levels as displayed in Fig. 6.

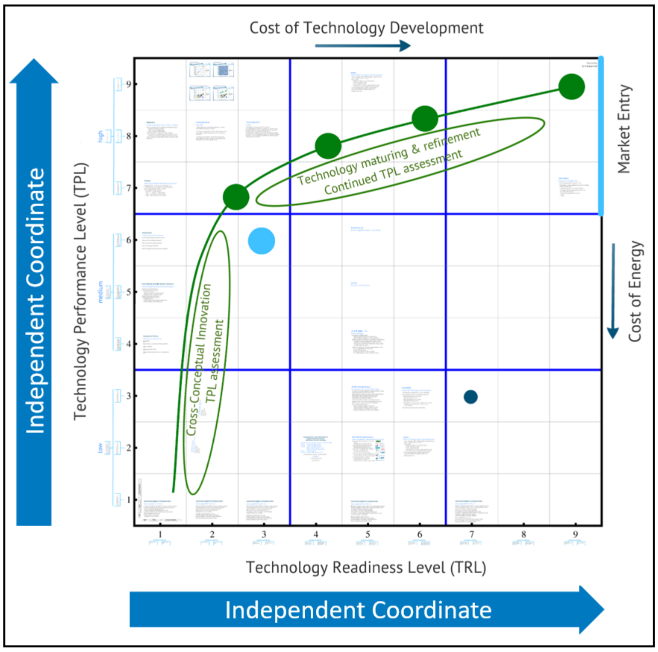

Fig. 6. Image of TRL – TPL – Matrix based on a Prezi Presentation [2,3], representing a two-dimensional technology development space spanned up by two independent coordinates

It is important to recall that within the two-dimensional technology development space of the TRL – TPL – Matrix, each dimension represents an independent coordinate and with it provides the freedom and the responsibility to make technology development choices that reduce development cost, time and risk and lead to successful market entry and achieve and maintain economic system performance during commercial operation.

As mentioned above, in some impact market cases the achievement of impact value may not be aligned with the achievement of monetary value through the operation of the technology. In those cases it is not sufficient to span up the technology development space in two dimensions provided by TRL and TPL only. In order to be able to formulate and pursue high impact value of the technology operating within a potential high impact market it may be required to define dedicated technology impact levels (TIL) and introduce these as a further dimension to describe the actual technology development space. With technology readiness, technology performance and technology impact represented as individual development process scales, a three-dimensional technology development space is spanned up, as displayed in Fig. 7. Again the emphasis is on the fact that the three dimensions are represented as independent coordinates providing the freedom and the responsibility to make technology development choices that lead to the desired outcome. Evidently, these decisions include the choices whether the technology, when fully developed to a product, delivers predominantly high techno-economic performance and thus monetary value or predominantly high impact value to deliver tangible contribution in service of common societal good and of the natural commons, or a desired, best possible level, a combination thereof.

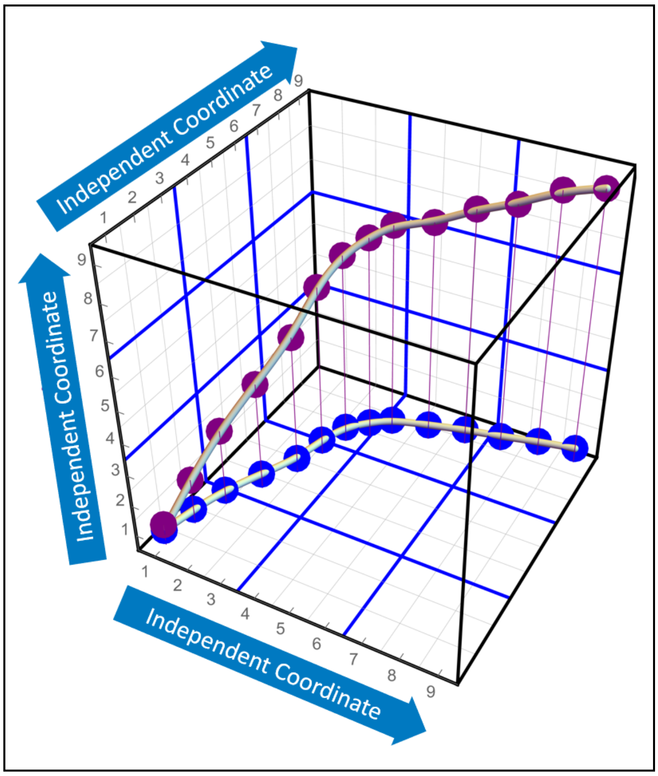

Fig. 7. Image of the three-dimensional technology development space spanned up by three independent coordinates representing technology readiness, technology performance and technology impact.

VI. Technological Problem Statement

A few fundamental aspects of the technology development problem and opportunity statement for the ocean data acquisition functions to drive the PSDO initiative though the use of wave energy powered systems are briefly discussed here.

The required qualitative and quantitative range and depth of capabilities to support PSDO goes well beyond the currently available capabilities and infrastructure in the ocean observation industry. This observation is based on the envisaged volume, depth and characteristics of the desired ocean data structures, as well as on the anticipated supporting functional requirements of to technology.

The goal is to technologically enable the provision of high quality, rich ocean data at high special and temporal resolution with large ocean space coverage, comprising all necessary quantities across physical, chemical and biological domains and detailed characterization of ocean flora and fauna to increase the body of knowledge of ocean processes, enable a wide range of high impact ocean markets and related system applications of the PSDO initiative, whereby the functions to support these system capabilities shall be powered by ocean wave energy.

Hereby the selection of the high impact ocean data markets, displayed in Fig. 5, merely presents a subset of the currently known, existing and or envisaged markets and ocean data applications. Thus, the PSDA initiative provides the potential to support, transform, improve and extend ocean data markets as well as enable and initiate new applications and associated ocean data markets. This vision is well supported through the experience and substantial growth observe in other terrestrial and space-based data domains and supported data markets.

In order to achieve the required envisaged special and temporal resolution and the desired response capability to deploy, mobilize, distribute, concentrate and relocate the ocean data acquisition capabilities and functional technology assets, as well as considering the ranges and sensor and scanning equipment and the limitations thereof, it is likely necessary to require capabilities for propulsion, positioning and orienting, alongside the sensing, data acquisition, management and delivery capabilities and that these capabilities will be delivered by technology solutions in the form of fleets of autonomous ocean data gathering systems with all functions powered predominately by ocean wave energy.

VII. Conclusion

The realization of the PSDO initiative provides the capability to facilitate a wide range of ocean data supported markets and applications and enables a variety of impact markets and applications that have the potential to deliver significant impact value and achievable positive impact and associated tangible contributions in service of common societal good and of the natural commons. Monetary value generation through the exploitation of the these markets and applications along with the associated business cases will further encourage the operations and also initiate the implementation and fuel the exploitation of the impact cases.

Out of the identification of the highly impactful ocean data acquisition applications results an engineering and technology development requirement to identify wave energy powered technologies that enable the provision of these important high quality, high content data structures, highly resolved, in space and time. Ongoing and future development work will have to include the consideration of qualificative, and where possible, quantitative characterization of the impacts and their contributory common value to society with the natural comments. Prominent examples of such value expressions are for example found in the definition of the 17 sustainable development goals [5] and within framework such as those of the nine planetary boundaries [6]. The quantification of such values is often difficult, does require the use of different types of quantifying units and in many cases is not reducible to the simplification to a single scalar monetary value. It is critical in this context to emphasize the importance of characterization and qualification and the employment of qualitative characteristic alongside, in comparison, and when necessary with prioritization over the ability, and often the consequential reduction to quantifiable values. These is ample evidence that such non quantified characterizations and associated technology assessment and decision making processes are of high value and utility and are widely established in a large range of applications, particularly in the form of multi-criteria decision making tools within and outside of the core disciplines of scientific, engineering, management.

Closer to home in relation to technology development generally and specifically to technology development in renewable energy and in ocean wave energy in particular, is the use of TRL [4], which exemplifies an stablished case of largely non-quantified characterizations employed to formulate a technology progress scale describing the precommercial of technology maturation.

TPL thrives to provide quantitative technology assessment criteria but does not neglect technology cost and performance driver if these are not quantifiable. The mere knowledge or potential that a certain characteristic is relevant to identify ultimate technology performance of the commercial product or to the cost, time and risk during the technology development constitutes a full justification of this criterion to be considered [7]. It is in this context to set the approach for the formulation of impact relate TIL scale and assessment tool. The full definition of the desired capabilities and associated functional requirements will allow assessment of ocean data acquiring technology system concepts and designs, as well as initiate technology system concept ideation and drive technology research, development and innovation, respectively.

These capabilities and functional requirements need to be formulated within the landscape of other existing ocean data acquisition technologies and within their overall ecosystem.

Such technologies include stationary and mobile data acquisition systems that are currently driven by non-renewable energy sources with consequential limitations of their mission duration and/or other capabilities. Novel prominent renewable energy driven systems include autonomous wind driven surface vessels such as Saildrone [8] and autonomous wave energy driven surface vessels such as Wave Glider [9].

It is the vison and the hope of the author that the PSDO initiative will grow substantially, facilitate the numerous ocean based impact markets and applications and accelerate their urgent activation and growth to deliver significant impact value and achievable positive impact and associated tangible contribution in service of common societal good and of the natural commons, especially in relation to climate mitigation and ecological restoration to strengthen ecological diversity and natural resilience.

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