SCENARIO ANALYSIS OF TIDAL TURBINE ARRAYS: SUSTAINABLE DESIGNS IN RESPONSE TO HOLISTIC CONSIDERATIONS

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INTRODUCTION

Large-scale deployment of tidal turbine arrays are likely to require more than merely replicating individual turbines from pilot projects [1]. Future tidal turbine arrays must be cost-effective and reliable, but also guided by environmental and societal priorities [2]. This range of holistic considerations may increase the likelihood for tidal energy projects to be accepted and ensure that they are sustainable [2]. This research explores potential future design scenarios for utility-scale turbine arrays that could overcome limitations of existing concepts, particularly societal concerns about new uses of ocean spaces. Incorporating holistic considerations at an early stage is necessary to ensure that tidal energy has a practical, as well as technical, potential to contribute to energy needs.

HOLISTIC DESIGN CONSIDERATIONS

There are a wide range of tidal energy technologies under development [3], involving a mixture of components (e.g., rotors, foundations). Many of these components, and related design options, are technically feasible and may be economically viable, but have latent environmental and societal considerations [2]. A design philosophy that encompasses a holistic set of considerations can be used to evaluate these options for future arrays. For this research, a matrix of considerations was developed, based on expert opinion, with an emphasis on the outcomes from a proposed tidal energy project in Puget Sound, WA, USA [4]. Elements of that project encountered unexpected societal resistance from some user groups, such as a marine cable company. While this is not atypical for marine energy projects [5], proactive identification of such conflicts may enable more sustainable array designs. Elements of an array (e.g., rotors, foundations, environmental monitoring requirements) were considered from the following viewpoints:

- *Environmental*: environmental effects based on stressors and receptors [6]
- *Socio-environmental*: environmental aspects with societal ramifications (e.g., culturally significant species)
- *Social*: non-valuated social considerations
- *Socio-economic*: valuated social considerations (e.g., catch productivity)
- *Economic*: primary drivers to cost of energy
- *Techno-economic*: considerations where technical options are constrained by economics
- *Technical*: considerations associated with existing technology

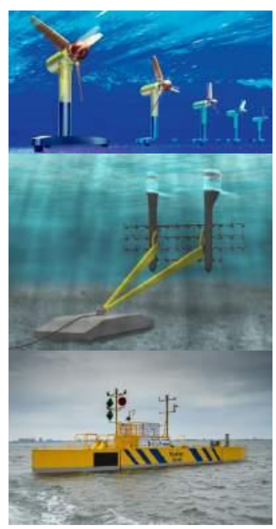
A sustainable design philosophy addresses as many considerations as possible. This approach is summarized in Table 1 for three project components: rotor type, foundation type, and environmental monitoring to reduce risk uncertainty [7].

TABLE 1. HOLISTIC CONSIDERATIONS INFORMING DESIGN PHILOSOPHIES: ROTOR TYPE, FOUNDATION TYPE, AND ENVIRONMENTAL MONITORING.

CONSIDERATIONS	Rotor Type	Foundation Type	Environmental Monitoring
Environmental	Collision risk may be proportional to rotor speed	Benthic zone and natural process impacts vary with foundation type	Monitoring required over broad range of spatio-temporal scales
Socio-Environmental	Novel designs may be perceived as having different environmental risks	Artificial reef effects and collision risks may vary by foundation type	Advocacy for culturally important species
Social	Some rotor types may be more compatible with other users	Some foundation types may be more compatible with other users	Rigor of monitoring plans may affect social acceptance of projects
Socio-Economic		Some foundations may have economic benefits (e.g., fisheries)	Advocacy for economically important species
Economic	Capital and operating costs vary with rotor type	Capital and operating costs vary with foundation type	Monitoring plan cost increases with complexity
Techno-Economic	Levelized cost of energy likely to be lower for more mature designs	Geotechnical surveys of foundation contact points are costly	High cost to spatially distribute stand-alone sensors
Technical	Efficiency and durability vary by rotor type	Installation and maintenance logistics vary by foundation type	Difficult to identify species when monitoring
DESIGN PHILOSOPHY	Balance social and environmental benefits of novel designs against technology maturity and cost	Minimize contact points with seabed; be compatible or adaptable with other ocean users	Hypothesis driven, site specific, spatially distributed, and adaptable monitoring

When considered against an ideal design philosophy, options for project components may excel in some areas, but perform weakly in others. For example, consider three options for foundations: gravity-based, mid-water column, and floating foundation types. These three foundation types are shown in Figure 1 with their techno-economic strengths and weaknesses. Further impacts emerge when larger scales of deployment are considered. For example, consider the use of gravity foundations in large arrays. These are large structures that use their mass to resist forces on a turbine and have been used successfully in several pilot projects. For large arrays, these structures would displace existing benthic communities over a significant area, which is environmentally undesirable. From a techno-economic perspective, full characterization of seabed geotechnical properties at each turbine location could be costly and contribute to foundation over-design to accommodate uncertainty in seabed bearing capacity and scour resistance. Similarly, extensive structures on the seafloor increase likelihood of socio-economic conflicts with existing users, as well as perceived impacts, especially in sites with high place attachment and cultural importance. A more holistically sustainable design option would minimize the number of contact points with the seabed for the array and incorporate adaptive elements that allow it to share the space with other users.

FIGURE 1. FOUNDATION DESIGN ALTERNATIVES [8-10].



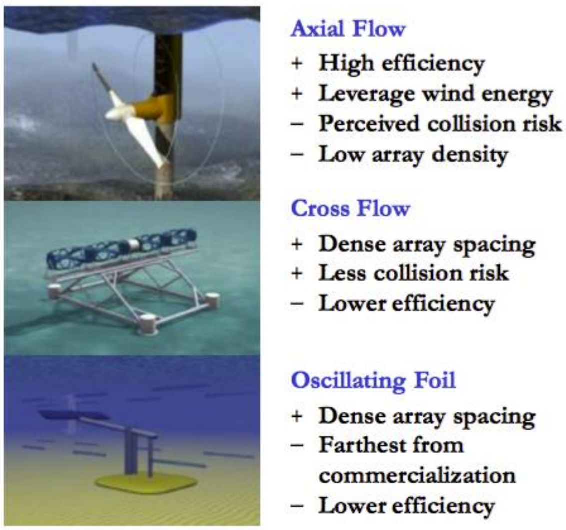
Gravity-Based
- \+ Well-defined design
- – High drag
- – Turbines close to seabed

Mid-Water
- \+ Turbines positioned in more energetic flow
- – More difficult to design
- – More complicated dynamics

Floating
- \+ Simplified deployment & maintenance
- – Platform subject to extreme waves and currents

Similarly, consider three options for turbine rotors: axial flow, cross flow, and oscillating foils, as shown in Figure 2. From a technical standpoint, rotors must be efficient and durable to contribute to a low cost of energy. However, some rotor types may elevate the risk for collision, which remains a significant, but uncertain socio-environmental risk [11]. Certain rotor types may allow for denser spacing [12], while others may be more amenable to adapting the array layout (e.g., lowering to the seafloor to increase overhead clearance). In this case, a sustainable design philosophy is to balance the social and environmental benefits of novel designs against their technological maturity and cost.

FIGURE 2. ROTOR TYPE DESIGN ALTERNATIVES [13-15].



Similar to engineering options, the development of environmental monitoring strategies for arrays must also balance technical, economic, environmental, and social considerations. To effectively reduce risk uncertainty, environmental monitoring should be conducted at relevant spatial and temporal scales [16]. Monitoring plans should incorporate site-specific requirements, while maintaining sufficient standardization to streamline the process and allow comparison of data across sites [17]. A sustainable monitoring strategy is one that does not pose an undue economic burden to developers, is hypothesis driven to resolve impact uncertainty, and can adapt over time. Some social concerns are driven by environmental uncertainty, so monitoring that reduces uncertainty may contribute to greater social acceptance [2].

EXAMPLE FUTURE VISION

In aggregate, these design philosophies can drive towards "future visions" for sustainable arrays. One future vision was developed as an array constructed around a large-scale "mezzanine mooring" (Figure 3) that connects multiple tidal turbines in a compliant network (annotation 1). The design is scalable (annotation 2) and buoyancy is provided by faired structures (annotation 3). This future vision addresses a number of holistic considerations. First, the mezzanine layout minimizes the number of contact points with the seafloor (annotation 4). This limits the need for geotechnical data collection in high energy environments and the potential for conflict with existing uses of the seabed. Second, the mezzanine provides a structure for aggregating turbine power output to a single export cable without the complexity of laying down multiple interconnection cables on the seafloor (annotation 5). From an environmental standpoint, the mezzanine structure provides a flexible vantage for environmental monitoring instrumentation to be dispersed throughout an array (annotation 7). Similarly, autonomous inspection crawlers can use the mezzanine structure to minimize energy expenditure when moving between turbines. The turbines themselves are two-bladed, axial-flow designs (annotation 6). During normal operation, the mooring structure can optimally position turbines in the water column, while lowering the array during storm events to minimize extreme loads. Further, if the blades are braked in the horizontal plane, the entire array can also be lowered to the seabed, providing full water column access for large, but infrequent vessel traffic. This addresses social concerns of navigation conflicts with the turbines.

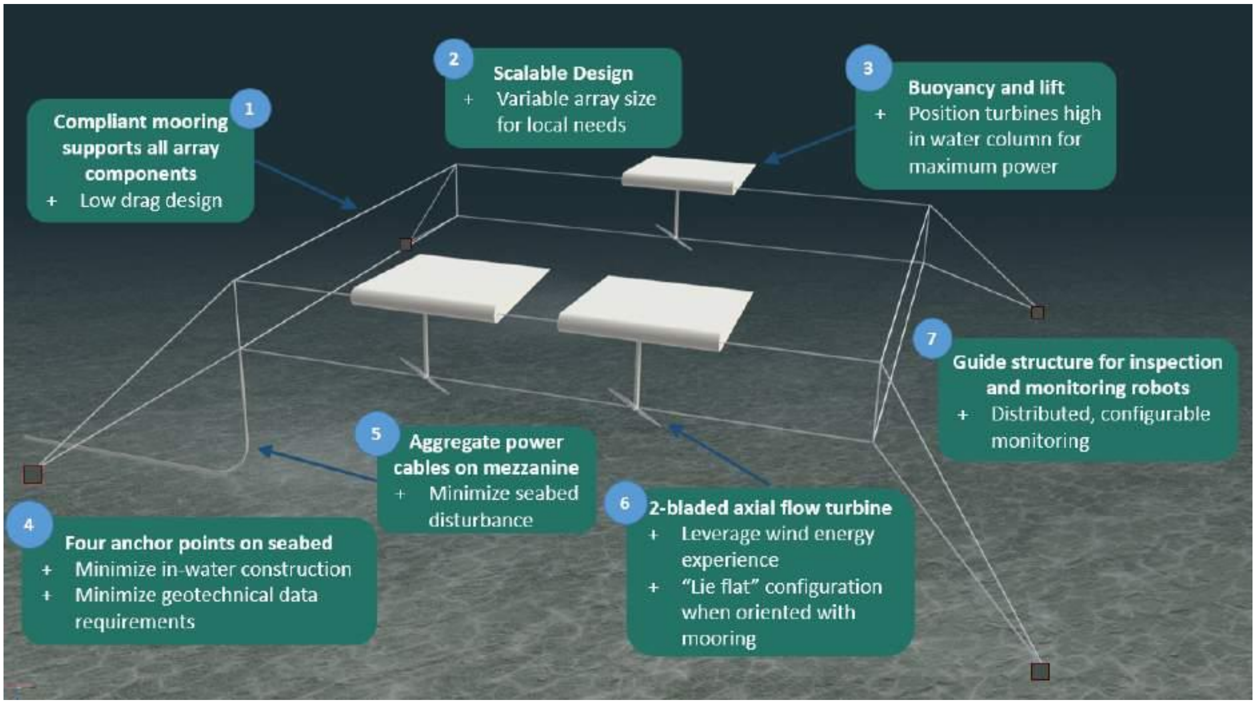


FIGURE 3 MEZZANINE MOORING CONCEPT [18]

While adhering to a sustainable design philosophy, implementing this future vision would require a number of technological advancements. First, maintaining mezzanine position and orientation would require advances in dynamic control of large-scale compliant moorings. Second, new strategies would be required for installation, maintenance, and removal of large scale structures. Finally, advances would be required in autonomous environmental monitoring and inspection systems that could make use of the mezzanine structure.

Of equal importance to these technical challenges are changes in the way environmental and societal considerations are incorporated into the design process [2]. In many cases, public funding does not incentivize holistic design, but rather focuses on the valuated cost of energy [19].

SCENARIO ANALYSIS WORKSHOP

Future visioning exercises may be useful to communicate the scale and function of tidal energy to the public. Similarly, the inclusion of stakeholders in the design process [2, 5] can inform a more acceptable technology convergence [3]. Beyond the mezzanine concept described here, there are likely many viable scenarios, each of which are considered optimal by specific user groups [2].

The next stage of this research is to engage stakeholders in a scenario analysis workshop [20]. The goal is to incorporate a wide range of perspectives and debate, in real time, the merits and drawbacks of different options for sustainable arrays. Stakeholders will be drawn from diverse backgrounds in biology, regulation, engineering, navigation, fishing, and industry. The group will be presented with a range of design options and tasked with holistically considering their strengths, weaknesses, and alternatives.

In traditional scenario analysis, there tends to be an optimistic, pessimistic, and most likely scenario [21]. For future tidal energy arrays, a worst case scenario may be envisioning scaling up pilot projects with extensive spatial use of the water column and benthos. A most likely scenario may be a conservative design near commercial readiness that is appropriately sited. Finally, a best case scenario may be an adaptable design that is compatible with multiple ocean users.

CONCLUSIONS

Holistic design of tidal turbine arrays may enhance the commercial prospects for the industry by including environmental and societal priorities. Future visions were developed through a holistic framework of design philosophies. A scenario analysis workshop will further explore sustainable tidal arrays in a participatory manner to be inclusive of diverse perspectives. The results can be used to convey overarching future visions for tidal energy to a wide audience, shape research priorities, and influence policy decisions. Ultimately, approaches that consider holistic views of tidal energy may provide greater opportunities to develop the resource sustainably.

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