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Marine Hydrokinetic (MHK) systems: Using systems thinking in resource characterization and estimating costs for the practical harvest of electricity from tidal currents

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ABSTRACT

Continuous and predictable shallow water tidal currents represent a promising renewable energy resource for investigation and additional exploitation. A systems thinking approach identifies aggregate properties of MHK systems such as turbine efficiency, transmission and power conditioning losses and leads us to propose that an overall project efficiency value (E_{EFF}, the kW-hours of electricity effectively inserted into the grid) should be used for resource characterization and as an estimate of the practical extraction of energy from tidal currents. This project efficiency value can lead to better cost estimates and ultimately serve as a marker for decisions whether to proceed. By using a systems engineering approach we first determine the practical extraction of kinetic energy from Maine to Texas using National Oceanic Atmospheric Administration (NOAA) CO-OPS' Mapping and Charting Services Program data. Then, based on case studies of two generating stations and one discontinued station in the United States, we superimpose how those installed costs per kW compare to the resource characterization. This work identifies installed cost per kW for potential locations that exceed a kinetic power density of 100 kW for three array sizes with a goal of showing how the key attribute of cost might affect the decision making process when considering Marine Hydrokinetic (MHK) extraction systems.

1. Background and introduction

Interest in harvesting electricity from tidal currents[1] by those countries with the resource has grown over the last several years. England, Scotland, Ireland, India, Brazil and other countries with the resource, including the United States, need to accurately characterize the resource in terms of the practical extraction of kinetic energy. Such accurate characterization should be based on machine dynamics and include a comparison of costs. We analyzed licensee data from three licensed marine hydrokinetic projects in the U.S.A. (East River, NY, Cobscook Bay, ME, and Admiralty Inlet, WA) and conducted a systems engineering approach to develop a comparison of costs.[2]

For an excellent discussion of MHK systems see [1] and for periodic status reviews see [2–8]. Axial-flow and cross-flow turbines operate on lift based principles. That is, a pressure differential is created across the blades, where the additive forces of lift and drag produce enough torque to overcome shaft inertia leading to a generator [1]. Fig. 1 depicts major steps of capturing and transmitting MHK derived electricity into the AC distribution network. We present general descriptions of a systems engineering process to showcase the im-

Abbreviations: AC, Alternating Current; CapEx, Capital Expenditure; DOE, United States Department of Energy; DC, Direct Current; E, Theoretical hydrokinetic energy; E_{EFF}, Electricity effectively transmitted to the grid, or the practical extraction of electricity from tidal currents inserted into the grid; FERC, United States Federal Energy Regulatory Agency; ICT, Information and Communication Technology (ICT) Industry; LCOE, Levelized Cost of Electricity; LF, Load Factor; LLC, Limited Liability Corporation; MHK, Marine Hydrokinetic; NOAA, United States National Oceanic Atmospheric Administration; NEP, New Ecological Paradigm; NY, New York; NREL, United States National Renewable Energy Laboratory; O & M, Operational and Maintenance; PV, Photovoltaic; PPAs, Power Purchase Agreement(s); RECs, Renewable Energy Credit(s); R, Financial discount rate (investor desired rate of return); RTO, Regional Transmission Organizations; SCI, Capital cost of the project in $/kW; SNOPUD, Snohomish Public Utility District at Admiralty Inlet, State of Washington; SROI, Social Return on Investment

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[1] Tides are the vertical movement of water caused by gravitational and centrifugal force interaction between the sun, moon, and earth and best defined by the relational aspect of size and distance between bodies and their rotational speeds. The differential forces caused by gravitational attraction between the moon and Earth and the sun and Earth are the principal forces producing a tidal effect. Because gravitational and centrifugal forces and orbits of the moon, earth, and sun are predictable, so are the tidal currents, ranges and frequency over a 24.833h period.

[2] The U.S. Federal Energy Regulatory Commission (FERC) holds primacy of the permitting process if tidal energy projects involve electricity generation and are located in navigable waters. Hydrokinetic Pilot Project Licensing Procedures are found at: http://www.ferc.gov/industries/hydropower/gen-info/licensing/hydrokinetics.asp.

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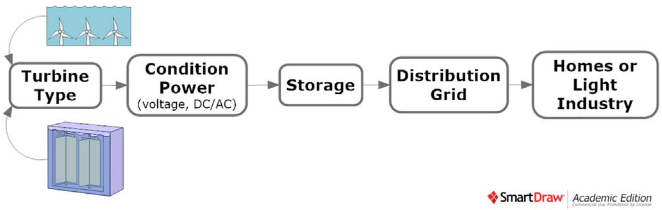

Fig. 1. Simplified block diagram of electricity from tidal current turbines.

portance of conversion efficiency, transmission, and power conditioning losses when conducting resource characterization and cost determinations.

1.1. Renewable energy economic trends & wholesale markets

Economic opportunity for exploiting renewable energy resources is rising along with a general trend toward public acceptance. Steel et al. [9] studied attitudes in Oregon and Washington toward bioenergy, wind, geothermal, and solar energy sources and found that age and education determined outcomes regarding acceptability when measured against government promotion of those technologies. Finding that younger and more educated people are statistically significantly more likely to support promotion policies aimed at those technologies, they also found that when comparing scores against the New Ecological Paradigm (NEP)[3] variable, all were statistically significant [9].

Along with these developments, political and market preference seem to be converging. In November 2015 HSBC pledged $1B to its Green Bond Portfolio aimed at renewable energy projects, energy efficiency, clean transportation, and climate change adaptation projects [10]. The Climate Bond Initiative also confirmed that climate aligned bonds reached $600 billion mid-way through 2015 since bond initiation in 2005 [11]. In January 2016 New York pledged $5 billion toward a clean energy fund and a commitment to obtain half of its electricity needs through clean sources by 2030. The $5B will help leverage $29 billion in private sector financing for clean energy. New York estimates that the CO_2 impact from renewable energy is the same as removing 1.8M cars from the roads [12].

The US Department of Energy (DOE) continues to fund development of MHK systems. On March 2, 2016 it announced a $22 million funding opportunity aimed at new research, development and demonstration projects that reduce the cost of electricity, protect the environment, and increase sustainability [13]. Projects already in existence and systems design, test, and validation of interactions between marine species and MHK devices are sought.

According to the U.S. DOE Green Power Network, institutes of higher education are also moving toward renewable energy to reduce the impact of greenhouse gas emissions. Vermont School of Law expects a 500 kW solar photovoltaic (PV) project to power 68% of its total needs over the next 10 years. In Pennsylvania, Elizabethtown College's 2.6 MW PV array will produce over 3 million kW h and save 20% of its annual needs. In Massachusetts, Bristol Community College Fall River Campus is building a 34 million kW h PV system as a parking canopy which will power one-half of the school's needs. Over 60 Colleges and Universities have entered into power purchase agreements (PPAs) with sourcing from PV projects.

The U.S. Information and Communication Technology (ICT) Industry is also moving toward renewable energy over fossil based fuels according to the National Renewable Energy Laboratory. Companies within the ICT industry are increasing their renewable energy purchases through on-site generation, PPAs, unbundled renewable energy credits (REC), utility green pricing, or competitive green power [14]. Companies making aggressive and innovative moves toward renewable energy include Apple, Cisco Systems, Dell, eBay, and Google among many others.

Several firms have announced goals to obtain 100% of their electricity needs from renewable sources. Firms can purchase renewable energy credits via closely regulated exchanges either separately or together with the underlying electricity. Purchasers obtain a REC to prove compliance of either a voluntary or involuntary objectives. In the US, 10 regional electronic markets track the creation, purchase, and sale of RECs. These markets assign a unique serial number to each created REC thereby ensuring it is a single unit and not duplicative. Table 1 shows recent solar based REC prices on an exchange in New Jersey as an example (one REC equals 1 MW h of electricity production).

Electricity from renewable energy sources is generally sold into an auction type market. Wholesale markets include electricity provided at cost-based and market-based rates. In other US regions, electricity markets are managed by two broad market types: Regional Transmission Organizations (RTO) or Independent Systems Operators (like New York or Texas). In the buying and selling of electricity, both broad market types manage the real-time and Day 2 markets which are designed to ensure demand is met through capacity generation. The real-time market is volatile as power is traded in one-hour and five-minute increments based on uncertain demand and demand responses. Electricity is also traded over the counter as a stock and as a commodity in futures markets such as that offered by the New York Mercantile Exchange with daily clearing. As in most markets there are hedge, leverage, short, and long positions and strategies to protect investments.

1.2. Permits

In the U.S., applicants are responsible for costs associated with a MHK permit and subsequent monitoring and operating costs if granted a license to proceed. The FERC Final Application includes a project description and its potential effects, plans for safeguards and communication records, requests for waivers, and a request to act as a Non-Federal representative for the Endangered Species Act and the National Historic Preservation Act. Statutorily, the applicant must comply with regulatory requirements of the Federal Power Act, Clean Water Act, Endangered Species Act, Marine Mammals Protection Act, Magnuson-Stevens Fishery Conservation and Management Act, Coastal Zone Management Act, and the National Historic Preservation Act.

Compliance with the Clean Water Act involves water quality standards and a navigable waterways permit from the U.S. Army Corps of Engineers. The Endangered Species Act involves compliance with the U.S. Fish and Wildlife Service and National Marine Fisheries Act ensuring that the project does not add insult to any threatened or endangered species or their habitat. The Marine Mammals Protection Act allows small takings but mitigation must be explored to minimize the possibility of adverse impacts. The Magnuson-Stevens Fishery Conservation and Management Act is focused on maintaining essential fish habitat such as that required to support a sustainable fishery and a healthy ecosystem. The applicant ensures compliance with the Coastal Zone Management Act in that project objectives are compatible with a state's coastal zone management plan. The applicant must also take into account any impact on property registered or eligible for listing in the National Register as part of the National Historic Preservation Act. The U.S. Coast Guard also certifies that the project provides for navigational safety and traditional uses of the waterway under the Ports and Waterways Safety Act. Since FERC has final license authority, it ensures that the applicant's license to operate includes any conditional aspects (such as that which might be required by any of

[3] Following Rachel Carson's 1962 environmental book, *Silent Spring,* attitudes toward the environment were measured by the dominant social paradigm (DSP). In 1978 Riley Dunlap, et al. developed the original NEP with 12 statements which was later modified to 15 statements measuring agreement and endorsement with the NEP and DSP. The 'new' NEP statistically measures environmental concern, albeit with some controversy, as determined by a sample populations' environmental world view [44].

Table 1
Value of Solar Renewable Energy Credit (SREC) in the New Jersey Market for electricity. http://www.njcleanenergy.com/renewable-energy/project-activity-reports/srec-pricing/srec-pricing accessed January 27, 2016.

Month	Year	Active kW DC	SREC Quantity Issued in Month	Traded in Month	Monthly High ($/MW h)	Monthly Low ($/MW h)	Cumulative # of SRECs Traded	Weighted Avg Price ($/MW h)
Nov	2015	1,481,973	141,713	145,921	$485	$100	757,299	$203.95
Oct	2015	1,470,847	158,205	310,438	$488	$70	611,378	$200.49
Sep	2015	1,454,195	202,528	208,071	$480	$70	300,940	$191.06
Aug	2015	1,442,768	185,530	92,869	$480	$50	92,869	$193.25
July	2015	1,436,356	153,510					
	Total		841,486	757,299				

the representative agencies mentioned above) required for mitigation of potential impacts.

The applicant is also required to comply with state and local statutes, seek additional permits, and bear all costs associated with the process at that level.

2. The systems engineering approach

2.1. The systems engineering approach

Systems' thinking informs the engineering approach to tidal current power extraction by considering the entire life cycle from concept to disposal/decommissioning. Distinct phases include concept of operations development, defining requirements and architecture, design (high level and detailed to include maintainability and reliability), implementation, integration testing and verification, system verification and validation, transition to operations and maintenance, and decommissioning and disposal (Fig. 2). A systems engineering approach also serves to identify emergent properties which are a relational consequence between system components and which may not be observable by just examining singular attributes below the system level. It also serves to identify aggregate properties. Supporting systems engineering is a broad network of policy making, financial services, education, research and development, and consulting [15].

Our systems approach considers the requirements by examining a resource characterization methodology identifying expected outcomes by applying consideration for turbine surface area, turbine efficiency, and transmission losses as in Eq. (3.3), below. Following requirements definition, system design allows one to determine characteristics—what characteristics must an extraction system have (the subcomponents) to fully capture the available kinetic energy in terms of array, efficiencies, and losses—to meet the stated requirements. Our systems engineering process then allows one to fully specify criteria based on extraction system knowledge.

Proper resource characterization leading to preferred site selection for tidal energy generating stations is critical to determine socio-

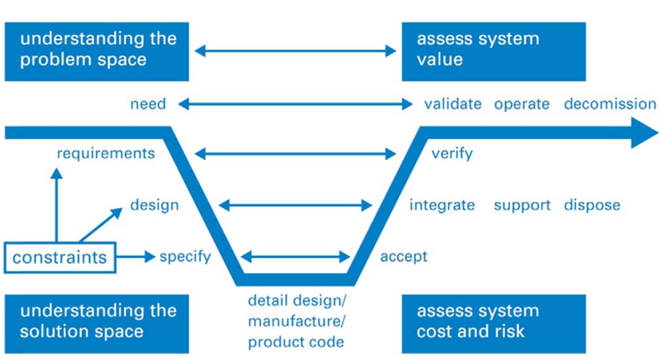

Fig. 2. Systems engineering process. Conceptual Systems Engineering process using the "Vee" diagram. (From INCOSE-UK.).

economic returns and costs associated with tidal current exploitation [16]. Factors affecting the electricity inserted into the grid include a determination as to how much kinetic energy is available for conversion, efficiency of the turbine system to convert that energy, array size, transmission and power conditioning losses, cost to produce that electricity, and the price paid for the electricity. Determination as to whether to proceed ultimately depends upon the kW h of electricity derived from the tidal current and an expectation from stakeholders as to whether the socio-economic costs are worth the socio-economic rewards. Culley (2015) et al. argue that economic costs of tidal current energy projects are significant and array design is a critical component [17].

2.2. Systems engineering process model

Our approach begins with a process model displaying the systems interactions between major components of a kinetic energy harvest in an effort to understand the problem space of identifying variables, inputs, costs, and economic output which is the interaction between system elements, the end-state, and future vulnerabilities [18–20].

This understanding provides a range of decisions by allowing for tradeoffs in the solution space as variables change. Characteristically, our system model (shown in Fig. 3) examines interactions of elements and sub-elements of the system at each phase of the life cycle. After a determination as to the practical harvest, primary consideration should be given to three pillars of sustainability: social, economic, and environmental.

2.3. Socio-economic relationship and the social return on investment

These interrelationships allow for identification of potential problem areas or serve to focus mitigation when determining which potential sites hold marked differences when engaged in resource characterization. For example, challenges in the economic realm include permitting, capitalized, operational, and management costs as they relate to potential revenue from feed-in tariffs (if any), to outright sale of electricity to local communities or the wholesale market, investor enthusiasm, and economic contributions such as jobs and business creation. Environmental challenges such as noise, aesthetics, water quality and turbidity, sediment transport, erosion control, and surface and groundwater flow are a few of the many interrelationships in a siting model which affect, in some degree, the terrestrial, riparian zone, and marine ecosystems.

Within the realm of social impact, issues to consider include avoided CO_2 and its relationship to local and regional technical and political objectives. For example, positive social benefits might accrue from renewable energy exploitation with multiplier effects such as improved livelihoods, jobs, and economic development to name a few. (For a detailed review of economic benefits from renewable energy development see [21].) Benefit might also arise from employing a micro-grid concept where relatively small, low voltage tidal current

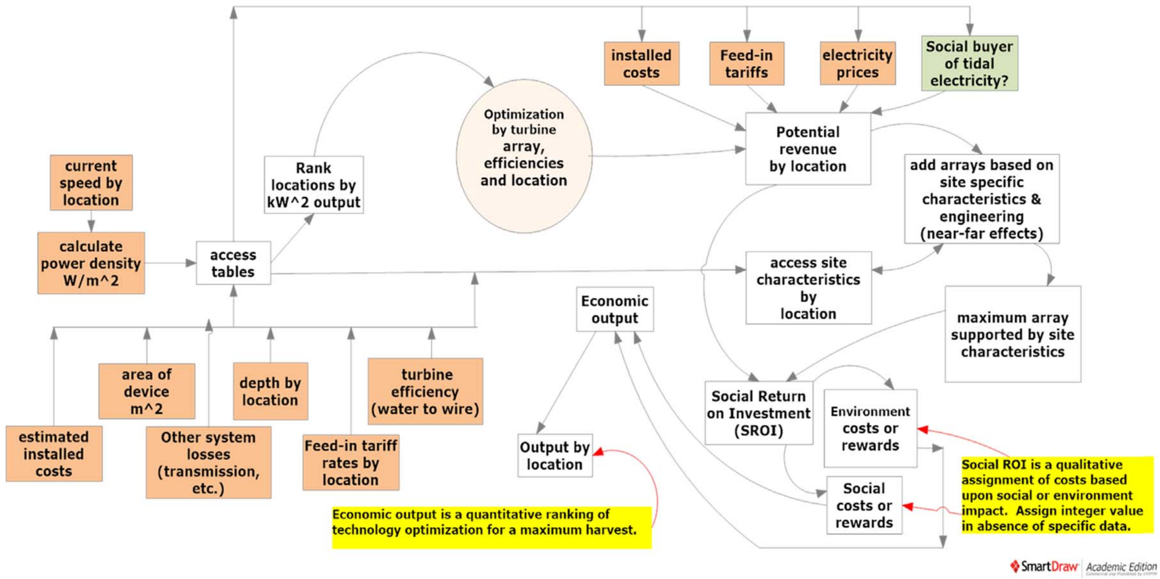

Fig. 3. Systems engineering process model. Our proposed systems engineering models enable resource characterization, optimization and decision making.

systems insert electricity directly into the distribution network [22]. Other social issues might include land-use and locational aspects of where the extraction might occur highlighting the need for community engagement.

Bryce et al. also looked at the idea that sustainability in a multi-criteria problem requires tradeoffs between cost effective outcomes [23]. Because of the multiple stakeholders, each theoretically representing a vested interest in the outcome such as fishing, duck hunting, water sports, commercial vessel transit, profitability, jobs creation, environmental impact, etc., each grouping might value different outcomes as best case. Gutierrez-Arriaga, et al. (2013) used a life cycle assessment approach to maximize annual profit and minimize environmental impact while studying electricity generation sustainability [24]. Their results showed that different designs were represented by a Pareto curve clearly showing optimal versus sub-optimal alternatives.

The value of our approach, which aids the multi-criteria analysis techniques outlined above, is that multiple stakeholders can be provided with known outcomes versus theoretical values so that tradeoffs between competing outcomes can be fully vetted thereby enabling a forecast of the total cost of ownership which enhances decision making. Proper application of a multi-criteria approach can result in optimization if instituted early enough but at the right time in the systems engineering process.

The multi-criteria analysis approach can also serve as a baseline for estimating and valuing social impacts, good and bad, via the calculation of a social return on investment (SROI) for MHK systems.[4] Providing SROI values as part of the resource characterization process might yield different conclusions than a process ranking potential sites without one.

The value of a SROI is that it facilitates comparison among different program impacts [25]. SROI aids decision makers who focus on both sides of environmental and social impact of choices. For example, communities with a special environmental interest may value avoided CO_2 emissions and monetize it highly or, conversely, a fishing community might negatively value potential turbine related fish kills with equal zeal. Another way of systems thinking is that the SROI outlines value created based on stakeholder feedback and monetization of indicators. Practical benefits, to name a few, include compatibility with existing financial systems, the ability to conduct sensitivity analysis during decision making stages of the systems engineering process and transparency between the MHK system owner and affected social groups.

Providing SROI values for program impacts are not without controversy, however, and firms wanting to submit SROI values to decision makers face organizational challenges. Getting stakeholders to define impact measures, gaining consensus on indicators and measurement techniques, determining and measuring the degree of change of a specific activity, and maintaining a participatory commitment among the stakeholders are but a few [26].

SROI is a lifetime performance indicator [27]. As such, determining a SROI in terms of impact to the local community and society should be part of any life cycle model where stakeholders and decision makers determine whether the socio-economic costs are worth the socio-economic rewards.

Our paper proposes a systems thinking process along with a rapid methodology to estimate the practical extraction of electricity from tidal currents which, in combination, can be a "screening tool" for rank ordering potential sites. Incorporating a systems approach ultimately supports decision making which could then lead to more robust characterization of the most promising locations. The efficiency of this process enables the beginning of estimating potential revenue and costs for deployment and operation of MHK extraction systems and serves to effectively screen out locations that have no practical extraction promise.

3. Methodology

Using a systems approach we identify the practical extraction. As such, the theoretical hydrokinetic energy (E) in a fluid at a given Δtime and Δspace with no perturbation is explained by [28,29]:

$$E = 0.5\ \text{p}\ \text{U}^3 \tag{3.1}$$

where, **p** is fluid density, and $\mathbf{U^3}$ is the velocity cubed. Inserting a cross sectional area into the fluid flow for extracting E with 100% efficiency, the available kinetic energy is reduced by the Lanchester-Betz factor (LB_{FACTOR}) of 16/27 with respect to the upstream E due to the pressure drop and work accomplished by the fluid as it moves through the cross sectional area:

$$P_{(extracted)} = 0.5\ \text{p}\ \text{U}^3 \text{A}\ LB_{FACTOR} \tag{3.2}$$

[4] SROI is a metric similar to a cost-benefit analysis but it goes further in attempting to monetize social costs of a program with monetized social outcomes (see generally [25]). SROI values are usually associated with programs implemented by "not-for-profit" organizations and oftentimes not part of traditional financial statements associated with programs of "for-profit" organizations.

We note that the common formula for determining extracted power ($P_{(extracted)}$) [28,30,31] does not consider electricity transmission or power conditioning losses from the turbine to the point of grid insertion. We also note that in Eq. (3.2), $\mathbf{U^3}$ is not the average of flood and ebb speeds cubed as taking an average potentially understates power density and could affect decision making. Knowing that not all turbine systems perform equally over the range of tidal currents due to type and design,[5] we modify Eq. (3.2) to account for system variances:

$$E_{EFF}(\text{kWhrs}) = [(U^3(\text{flood})) + (U^3(\text{ebb}))]\,A\ p\ t_{(E)}\ W_{(E)} H_{(yr)} \quad (3.3)$$

where $\mathbf{E_{EFF}}$ is the kW-hours of electricity effectively inserted into the grid, $\mathbf{U^3}$ is the tidal current velocity cubed for both flood and ebb currents, **A** is the area of water intercepted by the turbine device, **p** is seawater density, $\mathbf{t_{(E)}}$ is the turbine efficiency of extracting kinetic energy from the water (commonly referenced as water to wire) and turning it into electricity, $\mathbf{W_{(E)}}$ is the wire efficiency of transmitting electricity from the turbine to the grid in percentage. ($\mathbf{W_{(E)}}$ includes cabling losses, and power conditioning losses.) $\mathbf{H_{(yr)}}$ represents the time (yearly hours) the system is generating electricity and includes losses due to downtime for maintenance/repair and inoperable hours when differential forces affect slower tidal current speeds.

3.1. Factors affecting efficiencies

The systems engineering approach begins to identify potential locations by accounting for variables in an undisturbed current and excludes near, far, and back-effects consideration. The aggregate of variables report as the amount of electricity effectively transmitted (E_{EFF}) to the grid[6] after knowledgeable input as to the estimated percentage loss during electricity transmission from the turbine to the point of grid insertion. Thus, we believe our methodology yields a *practical* harvest of the kinetic energy transformed into electricity and inserted into the grid at a particular location. Clearly, this aggregate property of *overall efficiency* (E_{EFF}) indicates potential project success or failure when provided with an understanding of life cycle costs.

3.2. Levelized cost of energy (LCOE)

Mortimer correctly identified that future costs of energy technology is an essential point of decision making [32]. To that end, we endeavor to bin costs as a way of helping decision makers determine whether tidal current exploitation is worth the effort. For tidal current harvest to become a viable alternative to conventional sources, technical risks such as design, construction, installation, and operation needs extra scrutiny [33]. In electricity production, determining a levelized cost of energy (LCOE) is a common metric [34] and first determined by a load factor (LF):

$$LF = AEP/(CF \times 8760) \times R \quad (3.4)$$

where AEP is the annual energy production, CF is the capacity factor (the % of time the generator provides annual electricity), 8760 is the number of hours in a year, and R is a financial discount rate (investor desired rate of return).

Overall, LCOE increases with an increasing discount rate, R. Capital costs include foundation, electrical, cabling, planning, permitting, turbines, and generators among others. Culley et al. [17] observes that cabling, water depth, or difficulty of installation may impact project financial success since wind experience shows connection costs to be 18–20% of total capital costs. To that end, they developed a cable routing algorithm for use in conjunction with an array placement optimization scheme [17].

Carbon Trust observes that capital costs for MHK systems are: Rotor and Powertrain (30%), generator and equipment (12%), structure/foundation (25%), on-shore electrical equipment (13%), installation (16%), and design engineering and management (4%). Notably, Carbon Trust did not provide for decommissioning and/or replacement systems which it should have done in accordance with a systems engineering approach. O & M costs include repair, inspection, maintenance, replacement, insurances, on-going monitoring, and support vehicles to name a few. Strategic Initiative estimates that O & M costs for a tidal array are 19% of lifetime project costs [34]. Turbine location, in terms of distance to shore and nearest grid tie-in, can affect O & M costs as distance increases due to time and the expense of marine repair.

Jenne et al. at the National Renewable Energy Laboratory (NREL) estimated LCOE costs of 1–100 units by assuming rated power of a theoretical MHK farm at 1.115 MW and a capacity factor of 30% [35]:

$$LCOE = [(R \times SCI) + (OM)]/AEP \quad (3.5)$$

Not surprisingly due to scale, Jenne et al. found that LCOE for tidal current converters ranged from \$1.99/kW h (for one unit) to a low of \$0.17/kW h for a 100 unit array. Denny (2009) used PLEXOS™ software for power systems to estimate the breakeven capital costs for tidal energy projects off the Irish coast [36]. She found that capital installed costs would have to be less than \$606,000/MW (2015 estimate[7]) for breakeven, which she termed an unrealistically low value.

Our work for this cost discussion used Eq. (3.3) along with array dimensions of 64, 100 and 144 m^2, turbine efficiency ($t_{(E)}$) of 30%, transmission and distribution losses of 10% ($W_{(E)}$), and 4380 operating hours ($H_{(yr)}$) to determine electricity production leading to a greater cost understanding. Raw tidal current data was obtained from National Oceanic Atmospheric Administration (NOAA) CO-OPS' Mapping and Charting Services Program.[8] We selected all locations with a kinetic power density greater than 100 kW per array from Maine to Texas. NOAA data, statistically valid, consists of flood and ebb mean tidal currents averaged over the 18.6 year cycle [37].

4. Results

Literature shows a range of MHK cost estimates. For example, work by the National Renewable Energy Laboratory estimated capital costs in 2012 at approximately \$1150/kW with more than one system [38], and in 2015 estimated LCOE for one unit at \$1.99/kW h [35]. A 2014 Sandia National Laboratory report estimated capital costs ranging from one unit of \$31,900/kW to \$3170/kW for a 100 unit array [39].

Permitting, operational and maintenance (O & M) costs, and capital expenditures (CapEx) were derived from license application materials for the three licensed marine hydrokinetic projects in the U.S. filed with the FERC. These costs are not insignificant. Snohomish Public Utility District (SNOPUD), for its project at Admiralty Inlet, estimated permitting costs and the cost to file the application at \$2.7 and 2.5 million respectively. Its capital equipment (CapEx) estimated costs at the time of application filing were \$23 million of which \$16 million was for the turbine system. O & M costs were estimated at \$886,000/year.

Ocean Renewable Power Company (ORPC) Maine, LLC as part of

[5] Betz limit: maximum efficiency of a turbine blade in air is ~59%. Higher or lower power extraction for tidal turbines is possible under certain bathymetric conditions and effects from other turbines in the flow [43]. In our larger study of tidal current turbines, we selected a variable water to wire efficiency $t_{(E)}$ range from 25% to 35% due to the broad range (~15% to 50%) of manufacturer stated, but uncertain, capture and efficiencies over the range of tidal current speeds. There are other, often ignored, system losses.

[6] Lalander, et al., use the term 'degree of utilization' [42], others call it 'capacity factor' or 'overall efficiency' when used as a ratio of annual electricity transmission to the grid to device rated power multiplied by hours of operation in that year. Our approach provides a raw number which eases decision making for financial estimates.

[7] The authors performed conversion from € to \$ against 2015 exchange rates. At that capital cost, \$/kWh would be on the order of 0.08 at 90% utilization and about ½ the NREL 2015 estimate for a large array of 100 units.

[8] see https://tidesandcurrents.noaa.gov/currents15/table2ac4.html#29.

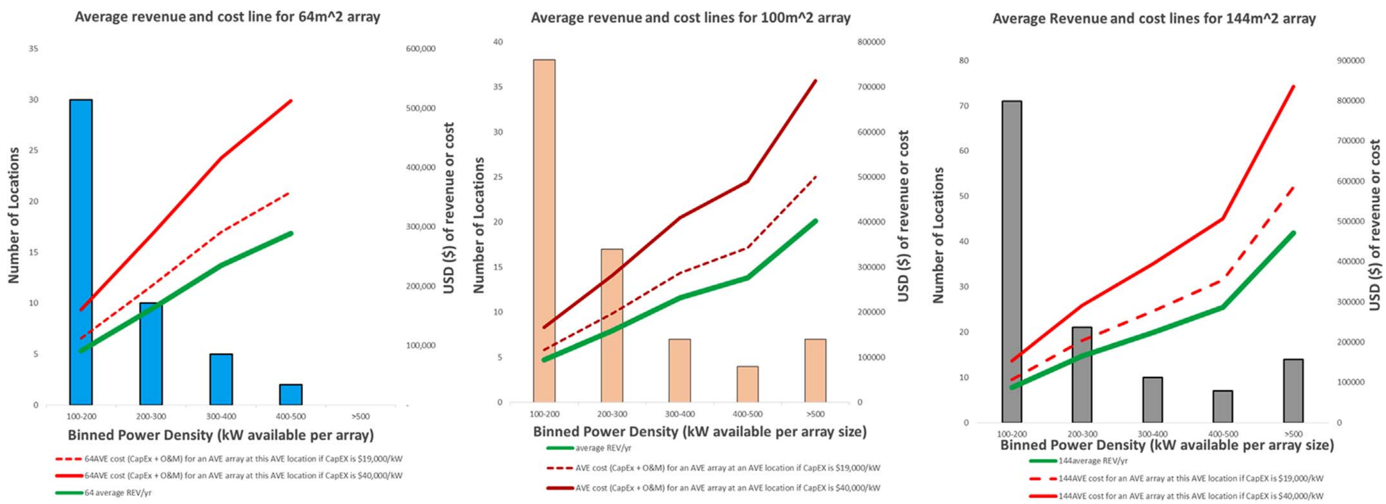

Fig. 4. Revenue and cost lines for the three arrays. Costs associated with MHK arrays of 64, 100, and 144 m^2 exceed revenue at $0.15 retail rates amortized over 30-years. Costs are more pronounced when amortized over 20-years or compared to wholesale rates. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

its Final Application for Cobscook Bay, estimated monitoring costs associated with administration of the permit at $2.4 million over five years. It estimated CapEx at $11.5 million. The East River project by Verdant Power, LLC estimated its O & M costs at $900,000/year and installed capital costs at $19.6 million in 2012.

To start, we used NOAA data from Maine to Texas to determine the practical extraction of electricity using Eq. (3.3). Data were binned and averaged for those locations with a power density > 100 kW/array. Lacking robust cost data we then used the cost per kW of installed power ($19,000) from the East River, NY site in 2012 dollars as representative across the three array sizes (64, 100, and 144 m^2). (The Cobscook Bay project only installed one turbine. Installed power costs were estimated at approximately $165,000 per kW assuming the anticipated costs of $11 million for the entire 300 kW project (five turbines) ended up as the correct cost estimate for just that one turbine. Consequently, we did not use costs associated with Cobscook Bay. Project costs for Admiralty Inlet were also not used due to its high cost of installed power per kW.)

Fig. 4 shows the average cost per kW of installed power for locations from Maine to Texas that exceed an extractible kinetic power density of 100 kW per array. The “dashed red” line represents averaged installed power costs using the East River, NY cost of $19,000 per kW (in 2012 dollars) as an index. The higher cost line (“solid red”) essentially doubles that cost per kW of installed power ($40,000) as a marker to show where the 2014 Sandia National Laboratory estimated capital costs line ($31,900 per kW) would fall. Costs, amortized over 30-years, are compared to revenue from a hypothetical retail rate for electricity of $0.15 per kW h (thick, solid green line). Average power density (x-axis) represents the practical extraction of power in terms of kW per array size as indicated in Section III, above.

We looked at the average revenue for each array over the binned average power densities and compared that to both the $19,000 and $40,000 per kW installed cost lines. In all cases, costs far exceed revenue at retail rates of $.015/kW h for each array. As expected, we find that revenue increases with increasing array size along with costs that are proportionally higher when the 144 m^2 array is compared against the 100 m^2 and 64 m^2 arrays. This matters because costs associated with environmental and monitoring studies are somewhat fixed and independent of array size but will vary by individual location depending upon site specific environmental characteristics. After identifying potential locations through resource characterization, follow-on studies should therefore seek to maximize the MHK array size (as in the systems thinking process, Fig. 3) so as to lessen the total impact of costs by amortization over the life cycle and across a larger E_{EFF} (Eq. (3.3)). Such action reduces the cost per kW h of generated electricity. Costs curves for a 20-year life cycle amortization would further widen the gap between revenue and should caution decision makers to explore generally accepted accounting principles before embarking on a course of action.

We then compared NREL cost methodology and find that it provides a lower, but reasonably close, cost estimate to the 2012 East River project costs of approximately $0.91/kW h. At the macrolevel, NREL estimated costs of $1.99/kW h equate to about $17,432 per installed kW and is compared to Verdant 2012 estimated costs of approximately $19,000/kW installed. Accounting for a consumer price adjustment between the years 2012 and 2015, the 2015 Verdant estimated installed cost/kW is $20,089. We standardized NREL estimated cost to Verdant estimates of expected electricity production (2,400,000 kW h). Through this methodology, we find that NREL's estimated cost of $0.69/kW h to Verdant's 2015 estimated cost/kW h of $0.96 is still reasonably close given the dearth of actual cost data associated with MHK systems in the U.S.

Table 2 provides our estimates of expected electricity costs per kW h for the three licensed generating stations.

MHK proponents argue that general experience with wind turbines, wherein costs per kW h decreased as technology application increased, could be similar for marine based systems. But, until a complete process is developed to estimate extraction potential and costs, and therefore a breakeven analysis, MHK pursuits are likely hampered. The efficiency of our proposed methodology is that it applies machine dynamics (variables such as turbine efficiency, transmission losses, and flood and ebb currents, etc.) as a basis to estimate the practical extraction and the impact such variables might have on MHK systems, a breakeven analysis, and LCOE. Judicial application of variables provide decision makers the ability to estimate a practical extraction of electricity from a known database of tidal currents. While there are more sophisticated methodologies to estimate extraction potential of a particular tidal current, such methodologies are usually employed to provide a detailed assessment of a specific location in which one is siting an actual MHK system and not as a screening tool as proposed here. Further, this proposed process and methodology initiates a discussion that SROI is an overlooked variable but one that should be considered in future efforts to determine overall output value of rank-ordered promising and specific locations.

5. Conclusions & future work

The life cycle of a project is often uncertain without proper

Table 2
Expected costs ($/kW h) for electricity from tidal currents at three licensed sites in the U.S.

Location	Stated Power (kW)*		Stated electricity output (MW h)*	Operating hours/yr	Estimated electricity output (MW h)	Costs			Average retail*** ($/kW h)	Loss ($) per kW h
	per unit	array				CapEx**	O & M**	$/kW h*		
East River, NY	35	1050	2.400	2286	2.400	21.30	0.980	0.96	0.1876	0.77
Cobscook Bay, ME	60	300	1.250	4166	0.250	12.50	2.610	2.27****	0.1542	2.12
Admiralty Inlet, WA	300	600	0.244	6132	0.244	23.74	0.920	7.58	0.0934	7.4866

* Obtained from license application filed with the FERC. Levelized cost of operation/yr normalized to 2015.
** Millions, USD normalized to 2015. See appendix for original filing dates.
*** Residential rates, July 2015.
**** Only one turbine installed for 60 kW vs 300 kW licensed. For 300 kW, levelized annual cost is $1.17.

attention to a systems thinking approach. We propose a systems engineering process that uses National Oceanic Atmospheric Administration (NOAA) CO-OPS' Mapping and Charting Services Program tidal current data for estimating a practical extraction of electricity and application as a screening tool to identify promising locations for siting MHK systems.

Our proposed methodology accounts for machine dynamics by aggregating variables such as turbine efficiency, transmission, and power conditioning losses, etc. Accounting for machine dynamics leads us to propose a value, $\mathbf{E_{EFF}}$, which represents the practical extraction of electricity from tidal currents where it is effectively inserted into the grid. The efficiency of a systems engineering approach is that once the practical extraction value is known it can then be compared against cost estimates and ultimately serve as a marker for decision makers when considering whether to proceed to more robust, site specific study. This systems approach also reveals a delta between revenue from tidal current exploitation and costs associated with MHK systems proposed or installed at three U.S. locations. We note and discuss the importance of SROI and how inclusion of that variable might serve to enhance or detract from the output value proposition on a site specific basis thereby widening or shrinking a revenue and cost delta.

While no formal study shows a 1-n ranking of promising exploitive U.S. locations, this work represents a potential path for follow-on studies to provide such a ranking. Any ranking, to be useful for decision makers, entrepreneurs, policy makers, and other interested parties should be based on the practical extraction of electricity for meaningful cost estimate comparisons.

Much work remains to further develop cost estimates or overall output value associated with harvesting electricity from tidal currents. Future studies should attempt to bound permitting, O & M, and CapEx costs by array field so as to better understand costs per kW of installed power as it relates to tidal current speeds. Equally important is consideration and inclusion of SROI when determining an output value since a SROI may have profound causal effects on value estimates of promising locations. A thorough understanding of costs and output value would serve to quickly discount marginal locations and emphasize exceptionally promising locations when decision makers consider potential sites for generating stations.

In an effort to quantify and potentially reduce costs, U.S. DOE announced two major funding awards in 2015. In August, Verdant along with Pennsylvania State University, received a contract to study and integrate health management technology into its turbines so as to increase the warning time of potential component failure for the mechanical and electrical systems [40]. In December, as one of six firms, Verdant also received an award to focus on reducing uncertainties associated with turbine development by optimizing spacing and support structures to allow for cost-effective installation, operations, and maintenance costs (IO & M) [41].

We expect, if the current trend of high costs for power derived by MHK systems continue, that fewer exploitation engagements will be possible due to the delta between potential revenue and cost and enterprise scale. The relatively small operational scale of current systems require the same permitting costs as would larger, utility scale projects. These costs, as shown by this study have an extraordinarily large impact on small scale systems—larger scale projects would allow amortization of these costs over the life cycle and across a larger E_{EFF}. Larger scale projects (larger array sizes) with the same upfront permitting costs would serve to reduce the cost per kW h of generated electricity. Other ways to achieve a larger E_{EFF} include higher turbine efficiencies, smaller power conditioning and line losses, and longer operational hours to name a few.

Consequently, the current trend of high capital expenditures, permitting, and operational costs for small scale projects combined with little revenue is not promising for entrepreneurial activity. This is especially true when comparing costs of tidal current electricity against retail electricity rates associated with non-renewable sources such as coal, natural gas and nuclear. Such disparency calls for even more significant funding aimed at reducing the delta between potential revenue and costs such as permitting, CapEx and O & M for the small scale systems currently in-place in the U.S. (Specific areas for further study include finding ways to improve turbine efficiency so that electricity can be produced over the entire range of tidal currents, and methods to decrease life cycle costs of submerged systems.) Consideration of a SROI may serve to reduce the delta but such possibilities are theoretical without studies to show value of a SROI, if any, when exploiting tidal currents as a renewable energy source.

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