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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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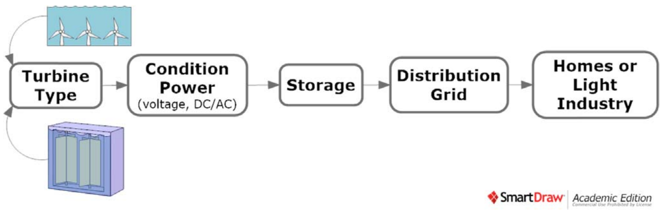

Fig. 1. Simplified block diagram of electricity from tidal current turbines.

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].