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Feasibility analysis of offshore renewables penetrating local energy systems in remote oceanic areas – A case study of emissions from an electricity system with tidal power in Southern Alaska

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HIGHLIGHTS

- A numerical model was developed to simulate energy systems in remote oceanic areas.
- The reduction of negative environmental impacts by introducing offshore renewable energy sources was presented.
- Introducing 56 kW of tidal power results in an annual emissions reduction of almost 244,000 lb of CO_2.
- The analysis also suggested that storage systems have the potential to provide additional system benefits.

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ABSTRACT

In many remote areas, expensive fossil fuels such as diesel are used to meet local electricity demand. However, their environmental impact is significant. Consequently, some of these areas have started to use hybrid systems that combine renewable energy sources and fossil fuel generation, such as wind-diesel systems, although wind is not feasible in some remote locations and fossil fuels remain the only resource in these areas. Fortunately, offshore renewable energy sources are available in many remote areas close to the ocean. In order to understand the feasibility of using offshore renewables in remote oceanic areas, we recently conducted a systematic study by developing an integrated model. This model includes a supply module, demand module, environmental impact module, and integrating module. Using this model, we mainly study the reduction in emissions resulting from offshore renewable energy penetration in local energy systems. In this article, we present this integrated model and an example study of tidal energy in the Southern Alaska community of Elfin Cove, which relies on diesel fuel for all of its electricity requirements. With 56 kW of tidal power penetrating the energy system, we found that almost 12,000 gallons of diesel fuel are displaced per year. This results in an annual emissions reduction of almost 244,000 lb CO_2 and about 1400 lb CO, as well as considerable reductions of PM-10, NO_x, and SO_x. The newly developed integrated model is expected to be used to analyze other aspects of tidal energy (and offshore renewable energy in general) in remote areas. For example, since the electricity demand in some remote areas varies significantly throughout the year, we recommend that tidal power should be used with a storage system.

1. Introduction

With the ever-increasing negative environmental impacts from traditional fossil fuel energy sources and the foreseen depletion of the fuel reserves, many countries and regions have started to integrate renewable energy resources and develop their own renewable portfolio standards (RPSs) [1,2]. Furthermore, international and intergovernmental agencies such as the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) are heavily facilitating this process.

From a cost-effective point of view, it is understood that optimally expanding the transmission system is very important for lowering the cost of integrating renewable energy resources [3]. However, it is not feasible to build transmission lines between existing renewable power plants and remote areas such as islands, highlands, high altitude locations, or areas with minimum population. Many of these remote locations have to use expensive energy

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sources such as diesel fuel while they are considering integrating renewable sources at the same time. For example, the Scottish government shows that about 35% of the electricity demand in Scotland is supported by renewable energy sources, primarily wind [4]. Lund and Matheson [5] presented wind-dominant 100% renewable energy scenarios for Denmark in 2030 and 2050. Suomalainen et al. [6] studied the wind penetration impact in Portugal. However, wind resources are not dominant or their utilization is not feasible in many of the remote oceanic areas. Fortunately, another energy resource, offshore renewable energy (mainly offshore wind, wave, and tidal energy), is often very easy to access in these areas. In this research, we use tidal energy as an example, and the popular technology that converts the energy in tidal currents to electric power is the tidal current turbine, which is similar to a wind turbine in working principle. Readers who are interested in offshore wind energy technology can refer to Musial et al. [7] and those who are interested in wave energy technology can refer to Falcao [8] and Li and Yu [9].

1.1. Relevant studies

During the past couple decades, several researchers have studied tidal current energy systems. Peter Fraenkel gave an early outlook of tidal current energy in 2002 when Marine Current Turbines deployed their first large-scale system [10]. Then, many resource assessment efforts started. For example, Myers and Bahaj [11] estimated the electric power potential of tidal current turbines. Garrett and Cummins [12] developed an analytical approach. Hagerman et al. [13] developed a practical method. Li and Calisal [14] developed an engineering perturbation approach that can be used for optimization. Recently, researchers began to conduct integrated analyses on tidal current energy systems. Douglas et al. [15] presented a life cycle assessment of the turbine produced by Marine Current Turbines. Particularly, Li et al. [16] developed a systematic approach to estimate and optimize the cost of electricity of a tidal current turbine farm. In short, most of the above approaches can be used to develop integrated energy system models. Since part of the integrated model in this paper is developed based on Li et al. [16], from here, we cite Li et al. [16] as LLC11.

Regional integrated energy system models are often used for renewable energy system analyses [17]. There are a number of popular models, such as the National Energy Modeling System (NEMS), developed by the US Energy Information Administration (EIA) [18], and the Regional Energy Deployment System (ReEDS), developed by the National Renewable Energy Laboratory (NREL) [19]. They focus on relatively large areas such that no remote area study is reported. Nonetheless, there are other models or analyses studying hybrid renewable energy and fossil fuel systems for rural communities and remote areas [20–22]. However, few have evaluated offshore energy penetration into energy systems in remote areas.

1.2. Objective of this study

In order to understand the feasibility of utilizing offshore energy to support the local electricity demand in remote oceanic areas, we conducted a comprehensive analysis by developing an integrated model. This model is expected to analyze various aspects of ocean energy penetrating local energy systems in remote areas. Specifically, after presenting the framework of the integrated model, we detail key modules, i.e., *Supply Module*, *Demand Module* and *Environmental Impact Module*. With this model, we show a simulation result of tidal energy penetrating a local energy system in a remote region of the US: Elfin Cove, Alaska, which currently relies on diesel fuel for 100% of its electricity requirements. We also show how to use this model to study energy policy with offshore renewables, and suggest that they should be strategically integrated with storage systems.

2. Framework of the analysis

Similar to our previous study about cost in LLC11, the analysis in this article integrates sub-level analyses in the disciplines of engineering, economics, and the environment, and an integrating module connects all the sub-level analyses. Specifically, this regional offshore energy analysis (ROEA) includes a *Supply Module*, a *Demand Module*, an *Environmental Impact Module*, and an *Integrating Module* (Fig. 1). It should be noted that for a more complicated region, a *Macroeconomics Module* and an *Electricity Market Module* are very necessary. In this article, since we focus on a remote region in Alaska, the economics and electricity market calculations are conducted in the *Integrating Module*. We shall discuss them as individual modules in future papers.

The *Supply Module* consists of two sub-modules, the *Tidal Power Module* and the *Other Power Source Module*. These modules calculate the annual energy output from tidal power and other energy sources by cost-effectiveness-based optimization approaches. The *Tidal Power Module* optimizes the utilization of tidal power with various tidal power penetration strategies. The *Demand Module* consists of a *Regional Electricity Demand Module* which provides the regional electricity demand from the residential, transportation, industrial, and commercial sectors. The *Environmental Impact Module* estimates the emissions under different scenarios. The *Integrating Module* integrates each module and conducts the final calculation. To formulate this integrated model, the following assumptions are made:

- All assumptions in LLC11 apply, unless specified otherwise (e.g. Section 3.1).
- There is no failure of the power generation system to affect the electricity distribution; failure of power generation system results into cost of the electricity.
- No power is generated when the flow velocity is slower than the cut-in speed.
- No permitting or other issues delay or prevent using ocean energy.
- *Demand Module* treats all consuming sectors as one for the purpose of simplifying the optimization.
- The electricity market is assumed to be regulated.
- No international trading activity is included.
- Tidal power can be curtailed when necessary.

2.1. Simulation process

We use scenario-based analysis to conduct the simulation. During the past decade, many researchers have used scenario-based

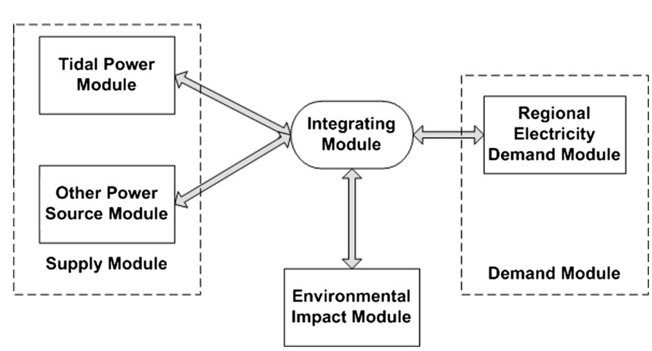

Fig. 1. Main structure of regional offshore energy analysis model.

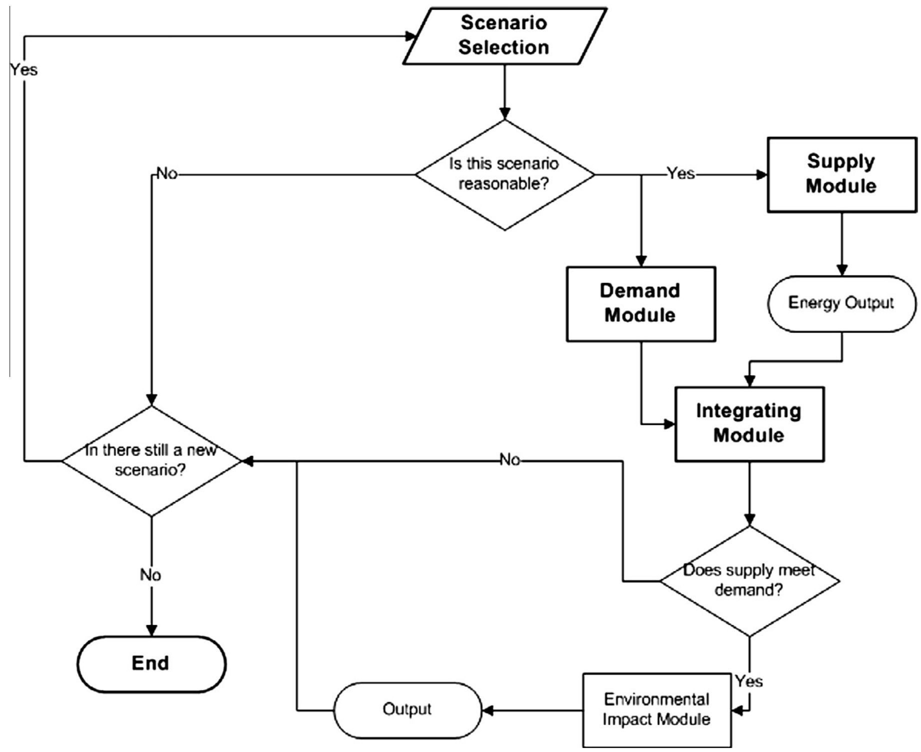

Fig. 2. Simulation procedure of the regional offshore energy analysis model.

analysis in the energy field to study how technical, political, economic, social, and behavioral changes might influence energy consumption and demand, renewable energy penetration, and CO_2 emissions [23,24]. This method allows for the examination of a range of possible outcomes based on uncertainty, assumptions, and the simultaneous variation of several parameters.

Fig. 2 shows the flowchart for the whole simulation process. The simulation starts from *Scenario Selection*, and the model will check whether the selected scenario is a valid scenario under all constraints and given conditions, e.g., the upper and lower limit of the tidal power capacity. If the selected scenario is not valid, the model will check whether there is a new scenario to run or terminate the simulation. If the selected scenario is valid, the model will call both the *Supply* and *Demand Modules*, and the *Integrating Module* will integrate these modules and check whether the supply can meet the demand. If it cannot, the model will check whether there is a new scenario to run or terminate the simulation.[1] If the energy supply meets the demand, the *Environmental Impact Module* will calculate the effluents that are produced by generating the electricity. Finally, the model will check whether there is a new scenario to run. In the next few sections, individual modules are presented in detail.

2.2. Integrating Module

The *Integrating Module* integrates the *Supply Module*, *Demand Module*, and *Environmental Impact Module*. It controls the entire model solution process as it iterates to determine a general economic equilibrium between the demand and supply side in all the consuming and generation sectors. For a complicated region, it will also control and maintain a cost-effective relaxation on selected variables for the convergence purpose and update all key variables when time marches to maintain a computational stability.

3. Major Modules

In this section, we present the major modules: Supply Module, Demand Module, and Environmental Impact Module.

3.1. Supply Module

The *Supply Module* calculates the electricity generated by various energy resources such as wind, solar, coal, gas, oil, geothermal, hydro, nuclear, wave, and tidal power. For each resource, the *Supply Module* treats each generation technology individually. For example, for gas, there are combined cycle and combustion turbines. For wave energy, there are floating point absorbers and floating terminators. In this study, since we focus on introducing tidal power in remote areas where the major power sources are diesel and hydro, we discuss energy sources by dividing them into tidal and other power sources. Therefore, the supply, $Energy_{Supply}$, can be written as follows:

$$Energy_{Supply} = Energy_{Tidal} + Energy_{Other} \tag{1}$$

where $Energy_{Tidal}$ and $Energy_{Other}$ denote the energy production from tidal power and other energy resources, respectively. In the next two sections, we will discuss these two components in detail.

3.1.1. Tidal Energy Sub-Module

As tidal power is a new power source, we need to develop a comprehensive sub-module to estimate its power output. Fig. 3 shows the main structure of the *Tidal Energy Sub-Module*. To avoid terminology redundancy, we use "sub-module" to refer to any level of sub-module under a module but do not use "sub-sub-module" or a term with more than one "sub" as a prefix. The *Tidal Energy Sub-Module* includes an *Engineering Sub-Module*, an *Energy Potential Sub-Module*, a *Cost Sub-Module*, an *Integrating Sub-Module*, and site info input. Similar to the high-level model, the *Integrating Sub-Module* integrates all other sub-modules; however, rather than

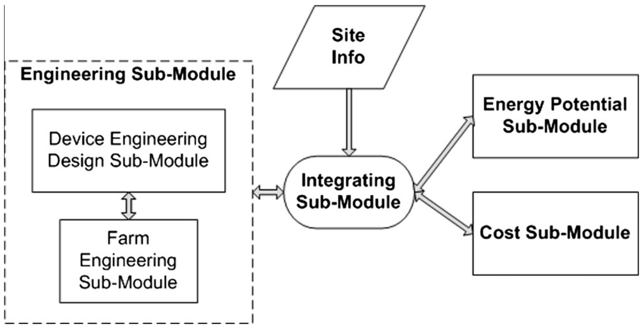

Fig. 3. Sub-structure of tidal energy sub-module.

maintaining an economic equilibrium as the *Integrating Module* does, the *Integrating Sub-Module* here minimizes the cost of electricity, i.e. Eq. (2).

$$c_{energy} = \frac{Cost}{AEP} - C\&I \tag{2}$$

where c_{energy} denotes the levelized cost of electricity, *Cost* denotes the total cost, *AEP* denotes the annual energy production, and *C&I* denotes the tax credit or other annual incentive such as the Production Tax Credit and the Renewable Energy Production Incentive (see Appendix A). Because the *Engineering Sub-Module* and *Cost Sub-Module* are developed based on the *Tidal Energy-UBC Model* presented in LLC11, some descriptions in LLC11 will be restated here.

3.1.1.1. Engineering Sub-Module. The *Engineering Sub-Module* calculates the power output of a tidal current turbine farm with given tidal current turbine designs and turbine farm plans. It includes the *Hydrodynamic Design Sub-Module, Mechanical Design Sub-Module*, and *Electrical Design Sub-Module*. These modules calculate the hydrodynamic power output, mechanical power output, and electrical power output, respectively. The total power output can be written as follows:

$$P_{out} = \sum_{i=1}^{M}\sum_{i=1}^{N} P_{N,M} \leqslant P_{extract\_\max} \tag{3}$$

where $P_{N,M}$ denotes the power output of turbine N of Farm M. $P_{N,M}$ is determined by a specific set of engineering design parameters such as device scale, device geometry, power system architecture, power cable type, and site information such as incoming flow velocity. $P_{extract\_\max}$ denotes the maximum extractable power of the site, and it is calculated based on the perturbation method developed by Li and Calisal [14]. Detailed engineering descriptions and the formulation for individual turbines are documented in Li and Calisal [25] and Li and Calisal [26]. It is worth noting that the power output of an individual turbine in a farm is not only determined by its own design but also by the design of the rest of the turbines in the farm. Mathematically,

$$P_{i,j} = \mathbb{P}(\Theta_{1,j}, \Theta_{2,j} \cdots \Theta_{i-1,j}, \Theta_{i,j}, \Theta_{i+1,j} \cdots \Theta_{N-1,j}, \Theta_{N,j}) \tag{4}$$

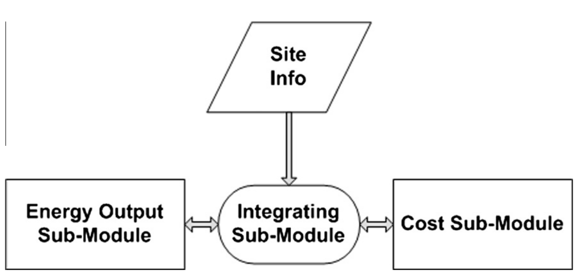

Fig. 4. Sub-structure of other power source sub-module.

where $\Theta_{i,j}$ denotes the set of turbine design parameters, site information, and the location of turbine i of farm j. LLC11 shows the linearized approximation of mechanical and electrical power loss from the hydrodynamic power output, while the hydrodynamic power output and nonlinear interactions are discussed in Li and Calisal [27] and Li and Calisal [28] in detail.

It is noted that we assumed uniform flow in a vertical plane in LLC11. This assumption is good for first-order assessments. In this research, we introduced a vertical flow profile into the calculation. Recently, Li et. al. [29] showed that a 1/7th power law can be used to approximate the flow as follows:

$$U(z) = U_0\left(\frac{z}{z_0}\right)^{1/7} \tag{5}$$

where $U(z)$ is the horizontal velocity at depth z and U_0 is the surface velocity at the surface height z_0 (depth of the channel). With Eq. (5), we conduct a more accurate assessment for the inflow condition.

3.1.1.2. Energy Potential Sub-Module. The *Energy Potential Sub-Module* calculates the energy output of a number of tidal current turbine farms in a given region and a given time period, usually one year for the Annual Energy Production (*AEP*). Mathematically, the energy output can be written as

$$Energy_{Tidal} = \int_0^T P_{out}dt = E_{ideal} - E_{down} - E_{over} \tag{6}$$

$$E_{down} = E_{down,main} + E_{down,lowts} \tag{7}$$

where E_{ideal} denotes the energy output from all turbines when they are operating freely without any shutdown or mechanism to limit the torque of the turbine when the flow velocity is over the rated speed. E_{down} denotes the sum of the downtime energy losses during maintenance, $E_{down,main}$, and the energy that could be generated but is not generated when the incoming flow velocity is lower than the cut-in velocity, $E_{down,lowts}$. E_{over} denotes the energy difference between extra energy that could be generated over the rated power and the energy generated at the rated power when the incoming flow speed is beyond the rated speed. When the incoming flow velocity is lower than the cut-in velocity, the turbine is shut down; when the incoming flow velocity is higher than the rated speed, pitch control or other mechanisms may be used to limit the torque load on the turbine and thus limit the turbine power output at its rated power. The determination of cut-in speed and rated speed are both related to the turbine reliability such that they interact with turbine design and maintenance strategies. In short, they affect both annual energy production and cost, and are optimized by the *Integrating Sub-Module*.

3.1.1.3. Cost Sub-Module. The *Cost Sub-Module* calculates the total cost that the farm encounters. It includes a *Capital Cost Sub-Module* and an *Operational and Maintenance (O&M) Sub-Module* to calculate the capital and O&M cost; mathematically, the total cost can be written as follows:

$$Cost_{Tidal} = CRF \times (CC + Fee) + O\&M \tag{8}$$

where *CRF* denotes the capital recovery factor, *CC* denotes the capital cost, *Fee* denotes various fees, and *O&M* denotes the annual operation and maintenance cost. In the *Capital Cost Sub-Module*, the capital cost is calculated; it includes all onetime costs such as the turbine purchase cost, construction and decommission costs of the farm, and transmission and integration costs. Thus, it is determined by not only the turbine design, but also the turbine location. Mathematically, the capital cost of farm j, CC_j, can be obtained as follows:

$$CC_j = \mathbb{C}(\Theta_{1,j}, \Theta_{2,j} \cdots \Theta_{i-1,j}, \Theta_{i,j}, \Theta_{i+1,j} \cdots \Theta_{N-1,j}, \Theta_{N,j}) \tag{9}$$

where i denotes the index number of a turbine in the farm and N denotes the total number of turbines in the farm. We assume that the capital cost of an individual farm does not affect the capital cost of another farm. Therefore, the total capital cost of the turbines in that area can be written as Eq. (10).

$$CC = \sum_{j=1}^{M} CC_j \tag{10}$$

The capital recovery factor is given as

$$CRF = \frac{f_r(1+f_r)^n}{(1+f_r)^n - 1} \tag{11}$$

where f_r denotes the interest rate and n denotes the project lifetime.

The *O&M Sub-Module* calculates the O&M cost, which is uncertain and variable because of the unexpected factors such as weather and sea states which may lead to uncertain O&M needs. Mathematically, the O&M cost can be written as

$$O\&M_{i,j,k} = EC_{i,j,k} + RC_{i,j,k} \tag{12}$$

where $EC_{i,j,k}$ and $RC_{i,j,k}$ denote the levelized emergency maintenance cost and routine maintenance cost of turbine i of farm j in year k, respectively. The emergency maintenance cost, EC, is the sum of the material, equipment, transportation, and labor costs for emergency maintenance, and the routine maintenance cost, RC, is the sum of material, equipment, transportation, and labor costs for routine maintenance. They can be written as follows:

$$EC_{i,j,k} = ELC_{i,j,k} + ETC_{i,j,k} + EEC_{i,j,k} + EMC_{i,j,k} \tag{13}$$

$$RC_{i,j,k} = RLC_{i,j,k} + RTC_{i,j,k} + REC_{i,j,k} + RMC_{i,j,k} \tag{14}$$

where $ELC_{i,j,k}$, $ETC_{i,j,k}$, $EEC_{i,j,k}$ and $EMC_{i,j,k}$ denote levelized emergency labor, transportation, equipment, and material costs incurred for the emergency maintenance of turbine i of farm j in year k, respectively. $RLC_{i,j,k}$, $RTC_{i,j,k}$, $REC_{i,j,k}$ and $RMC_{i,j,k}$ denote levelized routine labor, transportation, equipment, and material costs of turbine i of farm j in year k. More details of O&M cost formulations can be referred to in LLC11.

3.1.2. Other Power Source Sub-Module

The *Other Power Source Sub-Module* calculates the energy output and cost of electricity of other power sources such as traditional hydro, diesel, coal, natural gas, and nuclear. Many energy-related models such as NEMS have comprehensive formulations for these existing generation types. We could develop similar sub-modules. Considering the simple generation portfolio in Alaska, we include all other power sources in this single sub-module. Fig. 4 shows the main structure of the *Other Power Source Sub-Module*. Similar to the *Tidal Energy Sub-Module*, the *Other Power Source Sub-Module* includes an *Energy Output Sub-Module*, a *Cost Sub-Module*, an *Integrating Sub-Module*, and site info input. The *Integrating Sub-Module* integrates the other sub-modules. In the following sections, we will briefly describe the *Energy Output Sub-Module* and the *Cost Sub-Module*.

3.1.2.1. Energy Output Sub-Module. The *Energy Output Sub-Module* calculates the energy output from existing technologies. Since most remote communities only have one or two existing power sources, we assume that the energy output from these sources will meet the portion of the demand that is not met by tidal power. As a result, the energy output from existing power sources is dependent on the tidal energy output as well as the regional electricity demand. Mathematically, the energy output from existing sources can be written as

$$Energy_{OtherSource} = Demand - Energy_{Tidal} \tag{15}$$

where *Demand* denotes the regional electricity demand, which is described in Section 3.2. Energy from individual sources is assumed to maintain the same ratio that exists when there is no tidal power, and it can be obtained as follows:

$$Energy_{AOS} = Energy_{OtherSource} \frac{\widehat{E}_{AOS}}{Demand} \tag{16}$$

where $Energy_{AOS}$ denotes the energy output from any other source, e.g., diesel, natural gas, traditional hydro, or wind, and $\widehat{E}_{AOS}$ denotes the energy output from the source when there is no tidal power. If the tidal power and existing renewable sources are within the acceptable range of the local RPS, we assume that the energy output from existing renewable sources remains the same and the non-renewable sources meet the rest of the demand. For example, if a region has diesel and traditional hydro but can hardly meet the RPS, the energy output from diesel and traditional hydro when tidal power is integrated can be obtained with Eqs. (17) and (18).

$$Energy_{Hydro} = \widehat{E}_{Hydro} \tag{17}$$

$$Energy_{Diesel} = Demand - Energy_{Tidal} - Energy_{Hydro} \tag{18}$$

3.1.2.2. Cost Sub-Module. The *Cost Sub-Module* calculates the total cost of other power sources. Since the local electricity market is regulated, we assume that the cost of other sources can be obtained with the relationship between the energy output and cost. Specifically, the cost can be obtained with Eqs. (19) and (20).

$$Cost_{AOS} = \mathbb{C}(Energy_{AOS}) \tag{19}$$

$$Cost_{OtherSource} = \sum Cost_{AOS} \tag{20}$$

where $Cost_{AOS}$ denotes the cost of a given other source. Its relationship with the energy output can be obtained from existing scenarios where no tidal power exists, and it includes various costs, e.g., fees, transportation cost, and insurance.

3.2. Demand Module

The *Demand Module* provides the regional electricity demand from various demand sectors, e.g., residential demand, commercial demand, industrial demand, and transportation demand. Considering the complexity of local demand structures, each sector can have its own sub-module and lower level sub-module (cf. NEMS). In remote areas, the demand structures are rather simple. The demand is typically divided into the following sectors: residential, commercial, community facilities, and government facilities [30]. Therefore, in this study, the local demand can be written as follows:

$$Demand = Demand_R + Demand_C + Demand_{CF} + Demand_{GF} \tag{21}$$

where $Demand_R$, $Demand_C$, $Demand_{CF}$, and $Demand_{GF}$ denote residential demand, commercial demand, community facilities demand, and government facilities demand, respectively. More specific demand sectors are used in lower level sub-modules, such as water system demand and public health system demand under government facilities demand, and school demand and library demand under community facilities demand. In this module, they are linearly added together. Thus, we will not describe them in greater detail.

3.3. Environmental Impact Module

In the *Environmental Impact Module*, we estimate the various emissions that are produced during the energy supply and demand process. To predict these emissions from electricity generation, we

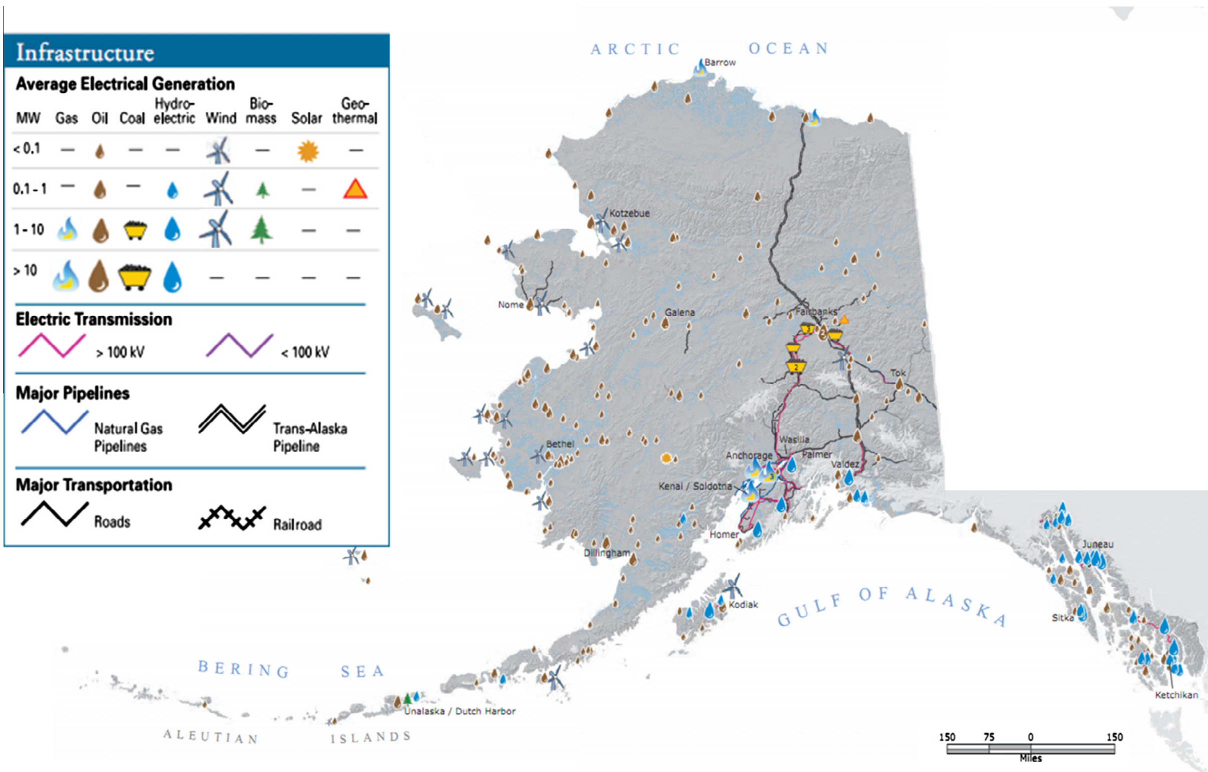

Fig. 5. Alaska Energy Infrastructure (adapted from Ref [33]).

use Environmental Protection Agency (EPA) emissions factors [31]. Mathematically, emissions estimates can be obtained as follows:

$$Emission = Energy_{AOS} \times Em_f \tag{22}$$

where *Emission* and Em_f denote the emissions and the emissions factor, respectively. It should be noted that both of them are scalar and include a number of different effluents such as CO_2, SO_x, and NO_x (see Appendix A for details).

4. Simulations

With this model, we studied the potential environmental and economic impacts of tidal power in rural areas in Alaska. In this article, we present the results of Elfin Cove as an example. To keep the integrity of the paper discussion, we only discuss the environmental impacts and key energy output results in this section, and leave site info and detailed power calculation results in the Appendices.

4.1. Why Alaska

In the US, there are many oceanic remote areas with considerable populations that rely on fossil fuels to supply their electricity demand, including Hawaii, Alaska, and Guam. Particularly, in Alaska, rural communities account for almost20% of electricity consumption, with a demand of about 1.17 million megawatt hours (MW h) in 2008 [32]. Due to Alaska's terrain and large land area, transmission lines do not connect these remote areas with major power plants. The majority of the electricity requirements in rural areas are met with diesel generators, with the fuel being shipped from the Lower 48 states or refineries near Anchorage [33]. Local governments have been trying to utilize other more matured renewable energy resources such as wind energy and hydro power [20]. More specifically, over ten wind-diesel systems are operating in remote communities. Numerous communities in Southern Alaska also have hydro-diesel systems. However, due to the operational environment and resource availability, wind energy is not feasible in some areas and is mostly located along the western coast (Fig. 5). As of 2010, most residents in remote communities relying on diesel paid between 40 and 60 cents per kilowatt hour (kW h), with some paying as much as $1.50 per kW h [34]. This price is considerably higher than most existing renewable sources. Furthermore, although tidal power is not commercial yet, the diesel price is higher than the estimated cost of tidal power from Carbon Trust [35], ETSAP [36], IPCC [37], and LLC11. In these coastal areas, we believe it is highly possible to use tidal-diesel systems where wind-diesel systems are not available. For example, in Southern Alaska, Cross Sound and Icy Strait includes four separate sites and is close to the communities of Elfin Cove and Gustavus. The sites are South Inian Pass, North Inian Pass, South Passage, and North Passage. All of them are within about 11 miles of each other. In the next section, we present simulation results from introducing tidal power into Elfin Cove where diesel is the only power source.

4.2. Results analysis

We use three-blade vertical axis turbines with a radius of 0.5 m and a height of 2.5 m. The detailed engineering specification of this turbine is documented in Li and Calisal [25]. We obtain the site information from several agencies including the National Oceanic and Atmospheric Administration (NOAA), the Alaska Energy Authority (AEA), and the EPA. Site operation strategy is adapted from LLC11. All cost and demand information are based on 2010 data. Detailed specifications are summarized in the Appendix A.

After reviewing the local demand (see Appendix A for details), we decided to have a scenario with a total tidal installation of 56 kW. Fig. 6 shows the monthly electricity generation by energy source for this scenario. The baseline result refers to existing conditions where no tidal power exists. The scenario result refers to the condition where tidal power penetrates the existing energy system. Because diesel is the only existing power source in Elfin Cove, the baseline generation is also equal to the local demand. For the same reason, we do not present sensitivity analysis results with various penetration amounts because the results are proportional to the tidal capability. From the result in Fig. 6, we can clearly see that the local demand peaks during the summer when tourists are in this region. Consequently, we can easily estimate the diesel fuel that is displaced in this scenario and the associated fuel cost savings (Fig. 7). Because the costs associated with tidal power are another complicated problem that needs extensive discussion, and the main purpose of this paper is to show the development of ROEA and demonstrate its capability to analyze environmental impact, we do not discuss the net savings from introducing tidal power here and will leave it for our future paper.

Fig. 8 shows the CO_2 emissions comparison between the baseline case and the scenario case. The tidal power results in an emissions reduction of about 244,000 lb CO_2 annually. As stated in Section 3.3, in order to systematically understand the impact of tidal power penetration on environmental emissions, we also calculate the criteria pollutant emissions, i.e., PM-10, SO_x, CO, and NO_x (Fig. 9). CO emissions are dominant among all four effluents and introducing tidal power can reduce more than 1400 lb CO annually. Because the emissions are proportional to the diesel energy output, the results in Figs. 8 and 9 are proportional to the results in Fig. 6. Thus, the emissions also peak in summer.

5. Discussion and conclusions

Assessing the feasibility of introducing offshore renewable energy sources in rural areas is a very complicated topic given all of the uncertainties that lie in the development of offshore renewable technologies and local conditions. Yet, to help the governmental policy makers and relevant decision makers, it is very important to evaluate the feasibility at this stage. Given existing knowledge, we developed ROEA to assess the feasibility of offshore renewable technologies in remote oceanic areas. Some further discussions of the model and conclusions are given in this section.

5.1. Discussion

The emissions results presented in Section 4 are based only on the diesel energy output. In reality, although no negative effluents are emitted during the tidal power generation, there are emissions during the manufacturing process of the tidal current turbines. Furthermore, there are also emissions during the maintenance process when the maintenance tug visits the turbines or other vehicles are on duty. Thus, we could rewrite Eqs. (22) as (23) to reevaluate the emissions. Therefore, the scenario emissions in Section 4 will increase.

$$Emission = Energy_{AOS} \times Em_f + N \times M \times Em_{turbine} + Em_{TidalO\&M} \quad (23)$$

where $Em_{turbine}$ denotes the unit emissions during turbine manufacture, which is determined by the turbine design, and $Em_{TidalO\&M}$ denotes emissions during the O&M process. $Em_{TidalO\&M}$ is determined by the O&M strategy, e.g., how often a tug visits a farm and what equipment is used during the maintenance. It is known that the failure rate of the devices decreases monotonically when the number of annual routine maintenance trips increases and when more advanced equipment is used. Additional routine maintenance trips and the use of more advanced equipment will increase the O&M cost. Additionally, the failure rate is also directly related to the annual energy production. Therefore, the O&M strat-

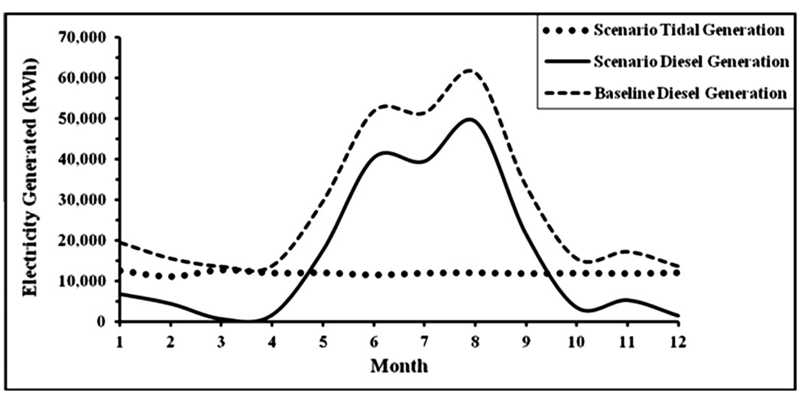

Fig. 6. Elfin cove electricity generation profile.

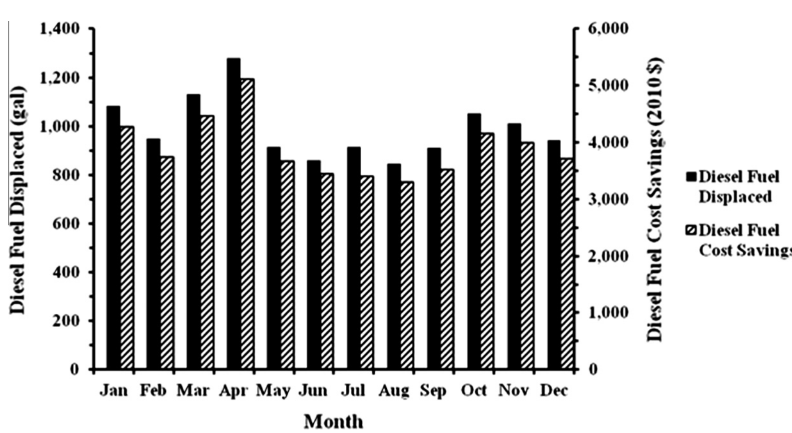

Fig. 7. Diesel fuel displaced and diesel fuel cost savings.

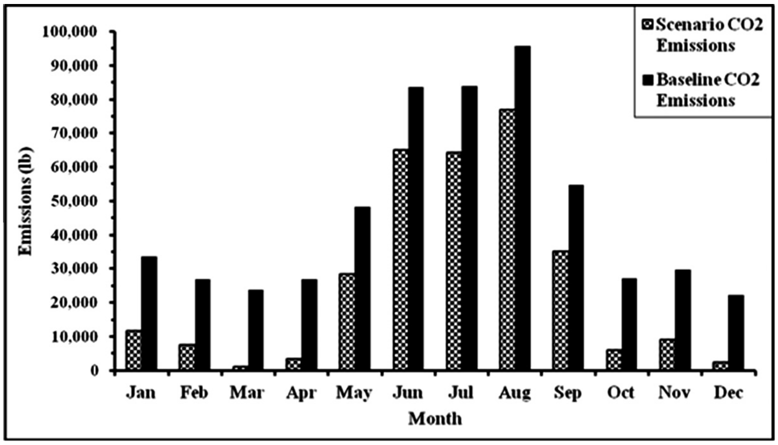

Fig. 8. Baseline and scenario CO_2 emissions from electricity generation.

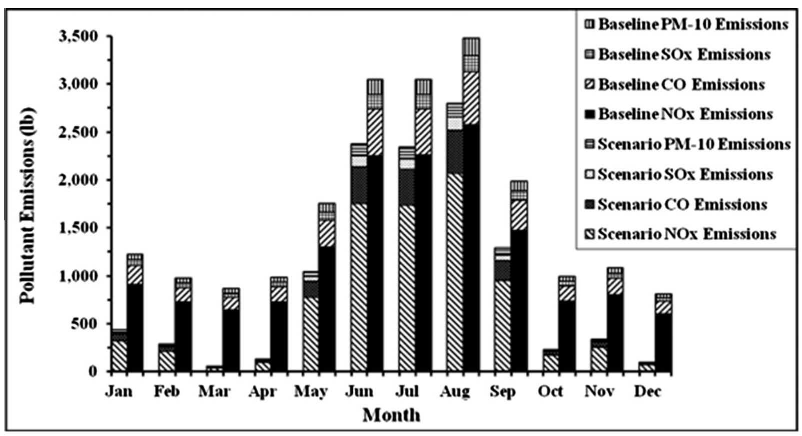

Fig. 9. Baseline and scenario criteria pollutant emissions from electricity generation.

egy is the key to bridge the O&M cost, the emissions during the O&M process, and the energy production. Overall, one needs to develop an optimal O&M strategy to balance emissions against the turbine lifetime and the energy production, and thus the total cost of electricity. To evaluate this more precisely, one has to conduct a life cycle assessment of tidal current turbines as well as balance of system components such as cable and supporting structures. However, since tidal power is still a new technology and no large scale commercial farm exists yet, it is still too early to do so. Thus, although we will not discuss this further here, the O&M strategy is a key topic that we will analyze when the technology is more mature.

The monthly results shown in Section 4 present the basic impact of introducing tidal power in a remote energy system. For detailed energy system and integration analyses, an analysis of hourly results is necessary. Fig. 10 shows the electricity demand and generation for a typical day in August 2010 when the demand is high compared to other months of the year. It is noticed that diesel is still dominant. Particularly, diesel supplies most electricity in the afternoon when there is almost no tidal, but the demand is at its peak. However, this does not indicate that we should increase the installed tidal capacity. For example, in March, when the demand is low, tidal power plays a very important role (Fig. 11). Furthermore, the tidal power is curtailed here. If not curtailed, the tidal power output is much greater than the demand during early morning and late afternoon when the tide is strong (Fig. 12). In this case, we can use a storage system to store the extra power generated by tidal. Then, Eq. (15) can be written as Eq. (24). However, as the utilization of a storage system is beyond the scope of this article, we do not discuss how to put the energy from storage back onto the grid here.

$$\begin{cases} Energy_{OtherSource} = Demand\text{-}Energy_{Tidal} \\ Energy_{Storage} = 0 \qquad \text{if} \quad Demand > Energy_{Tidal} \end{cases}$$
$$\begin{cases} Energy_{OtherSource} = 0 \\ Energy_{Storage} = Energy_{Tidal}\text{-}Demand \quad \text{if} \quad Demand \leqslant Energy_{Tidal} \end{cases} \tag{24}$$

One may note that we have only presented one scenario for a 56 kW tidal installation. This is mainly because the generation sources are only diesel and tidal power. If we take the no storage assumption, i.e., Eq. (15), the diesel we offset will be proportional to the tidal power generation. That is, we will obtain a set of results linearly offset from the results above. Given the space limitation here, we do not present those results, although they can be found in the preliminary studies [38]. Nevertheless, sensitivity analyses with different penetration strategies are very important for a market with multiple generation sources. Different strategies pose different environmental and economic impacts; as a result, this will be a key component of future work. On the other hand, the storage assumption, i.e., Eq. (24), requires some further investigation, as stated in the last paragraph.

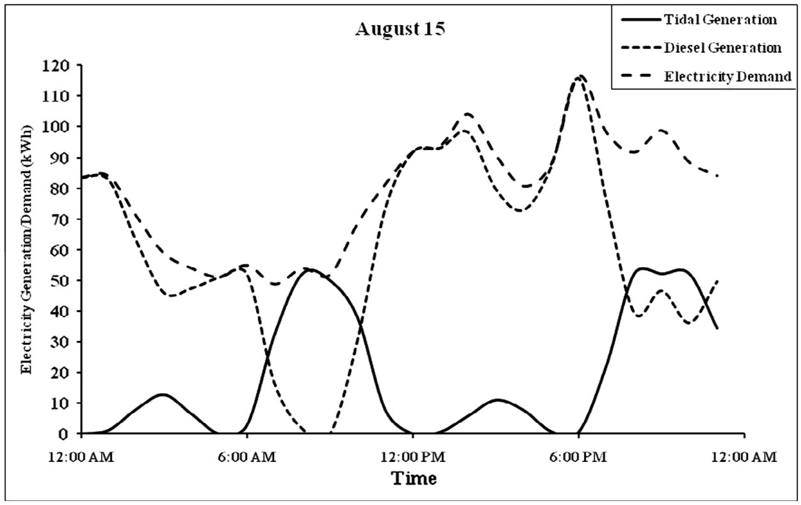

Fig. 10. Daily electricity generation and demand (August 15, 2010).

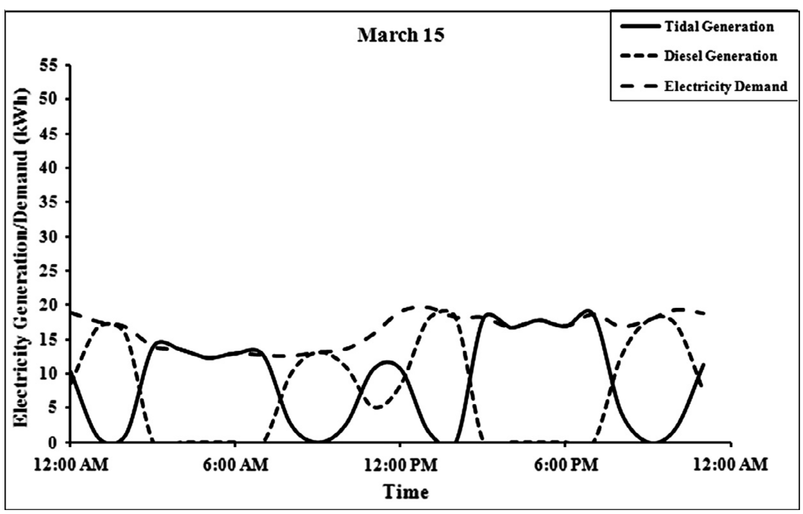

Fig. 11. Daily electricity generation and demand (March 15, 2010).

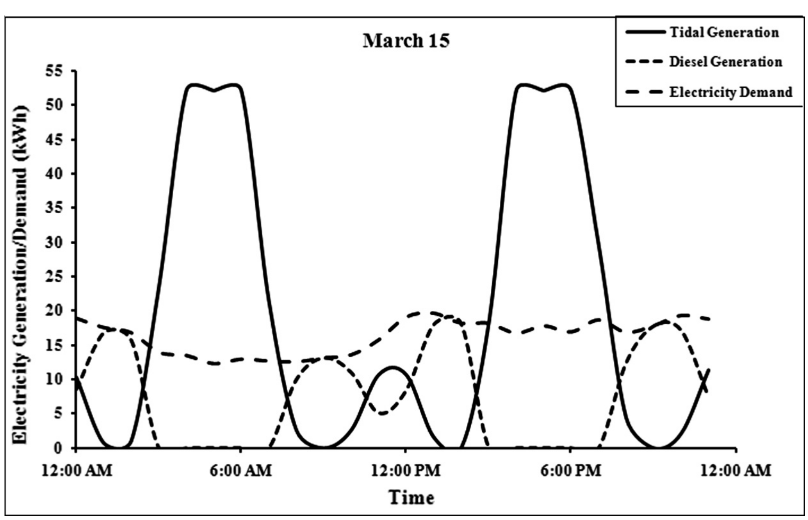

Fig. 12. Daily electricity generation and demand without tidal power curtailed (March 15, 2010).

Table 1
EPA emissions factors [31].

Pollutant	Emissions factor (lb/MMBtu fuel input)	Emissions factor (lb/hp-hr energy output)
NO_x	4.41	0.031
CO	0.95	0.00668
SO_x	0.29	0.00205
PM-10	0.31	0.00220
CO_2	164	1.15

Table 2
Elfin cove energy generation, diesel fuel use, and fuel cost (personal communication [30]).

Month	Diesel generation (kW h)	Fuel used (gal)	Fuel cost ($)
January	19,353	1672	6604
February	15,412	1330	5254
March	13,428	1193	4712
April	13,639	1464	5856
May	29,584	2261	9044
June	51,728	3906	15,624
July	51,299	3942	14,715
August	61,192	4323	16,860
September	33,285	2581	9964
October	15,384	1364	5388
November	17,101	1467	5795
December	13,500	1058	4179
Total	334,905	26,561	103,995

Table 3
Annual electricity sales by sector (personal communication [30]).

Residential sales (kW h/yr)	88,610
Commercial sales (kW h/yr)	176,680
Community facility sales (kW h/yr)	10,719
Government Facility sales (kW h/yr)	1704
Total Sales (kW h/yr)	277,713

Table 4
Fiscal year 2010 PCE statistics [34].

Total electricity sales (kW h)	277,713
PCE eligible sales (kW h)	75,281
Non-PCE eligible sales (kW h)	202,432
Non-PCE electricity rate (¢/kW h)	52.30
PCE subsidy (¢/kW h)	32.46
PCE electricity rate (¢/kW h)	19.84

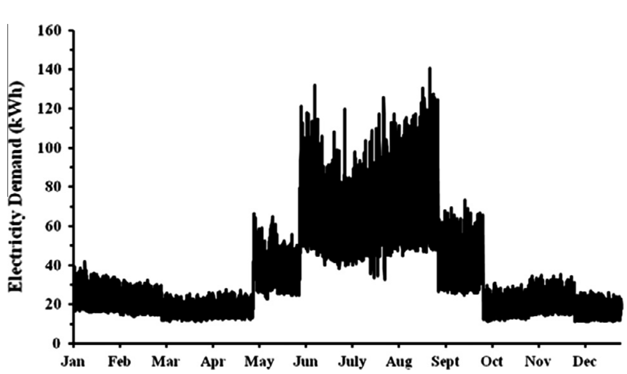

Fig. 13. Elfin cove hourly electricity demand.

Table 5
Site information [41].

Site	Average extractable resource (MW)	Average cross-sectional area (m^2)	Channel width (m)	Average channel depth (m)	Maximum surface current (m/s)
South Inian Pass	22.5	34,000	720	46	4.9
North Inian Pass	240	660,000	2800	230	4.1
South Passage	72.0	380,000	4300	90	3.3
North Passage	63.0	490,000	4600	110	2.9

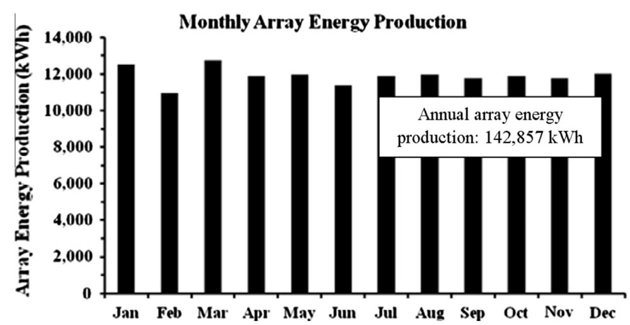

Fig. 14. Monthly and annual energy production.

5.2. Conclusions

The newly developed integrated model, ROEA, is capable of assessing the primary environmental and economic impacts of introducing offshore renewable power into remote oceanic areas. We demonstrate this by conducting a comprehensive analysis of remote communities in Alaska. Particularly, we present a scenario with 56 kW of tidal turbine power penetrating into Elfin Cove's energy system. We found that this tidal power penetration scenario can result in an annual emissions reduction of almost 244,000 lb CO_2 and about 1400 lb CO. It can also significantly reduce NO_x, SO_x, and PM-10 emissions. In terms of cost of electricity, we found that this scenario results in significant cost savings via displacing diesel, and using a storage system could be even more cost-effective, although a more detailed analysis and discussion should be conducted.

Beyond the scenario we present in this article, we expect ROEA to provide a platform for other analyses such as subsidy policy analysis, hybrid system analysis, and market analysis. For example, we take incentives and credits as deterministic inputs here. We could actually introduce various incentives and credits with different policies and study their impacts on the cost of electricity and the local market. This could be conducted with various RPS by advancing Eqs. (15)–(18).

6. Future work

This integrated model is still in its preliminary stage and we would like to improve it with the following tasks:

- As stated in the last paragraph of Section 5.1, we only present results of introducing tidal power in Southern Alaska. We intend to conduct studies in other remote areas with other renewable technologies, larger populations, and more complicated energy system structures, such as small islands in Hawaii and Puerto Rico.
- Since tidal power is very predictable, it is possible to use storage systems to balance the loads or help the penetration process. We intend to apply various optimization approaches to implement storage systems within this model following the discussion in Eq. (24).

- As we mentioned in Section 4, we intend to conduct an extensive analysis of cost and price under different scenarios. Particularly, we shall investigate various policies related to this subject. For example, the Power Cost Equalization (PCE) rate (subsidized electricity rate – see Appendix A) was available for only 27% of electricity sales in Elfin Cove [34], and only residential customers and community facilities are eligible for the PCE subsidy [39].
- In the future, it is highly possible that offshore renewable power can supply not only the local demand, but also the demand from other regions. Thus, distribution and transmission analysis is necessary.

Last but not the least important, this model only analyzes the penetration scenario at present. For a model to help governmental policy makers and relevant decision makers, the model shall have the capability to conduct future projections. We shall pay special attention to the learning curve of offshore renewable technology development given the uncertainties that lie in it.

Acknowledgements

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Appendix A

A.1. Emission information

We obtain the emissions factors from the EPA [31]. In this article, because we have diesel as the only fossil fuel power source, we only list the diesel-related emissions factors here (Table 1). These emissions factors apply to diesel engines up to 600 horsepower.

A.2. Site data collection

We obtain local energy system data from AEA. This data includes electricity generation by energy source, diesel fuel use and fuel cost, and electricity consumption by sector. We also obtain Power Cost Equalization (PCE) program statistics for each community [34]. This program subsidizes electricity rates for residential customers in remote areas in order to lower the cost of electricity for the first 500 kW h consumed by a customer each month. Community facilities are also eligible for a subsidy, whereas state and federal customers and commercial facilities are not. The program statistics provide electricity price information for the electricity that is eligible for the PCE subsidy and that which is not eligible. Here, we list the energy generation, diesel fuel use, and fuel cost for Elfin Cove for fiscal year 2010 in Table 2, annual electricity sales in Table 3, and PCE statistics in Table 4. Additionally, we present the local electricity demand in Fig. 13.

In terms of credits and incentives, we obtain the Renewable Electricity Production Tax Credit (1.1 cents per kW h) for commercial utility generators and the Renewable Energy Production Incentive (2.2 cents per kW h) for municipal utilities and rural electric cooperatives from the US Department of Energy database of state incentives for renewable energy and energy efficiency [40].

Additionally, since we focused on the feasibility study in this article, we did not discuss the tidal power resource in the main body other than describing the procedure for calculating the power output of a tidal current turbine farm with Eqs. (3)–(7). Here, we show the characteristics for each tidal site in the Cross Sound and Icy Strait location in Table 5. The monthly and annual energy production for a tidal farm in the South Inian Pass site location is shown in Fig. 14.

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