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GEOGRAPHICALLY SPECIFIC LIFE CYCLE ASSESSMENT OF ELECTRICITY FROM TIDAL TURBINES IN THE UNITED STATES

by

Breck Sullivan

A thesis
submitted in partial fulfillment
of the requirements for the
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College of Environmental Science and Forestry
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I am honored to receive a Master of Science degree from SUNY College of Environmental Science and Forestry. The success of my career at this institution would not have been achievable without the help and guidance from my advisors, Marie-Odile Fortier and Bob Malmsheimer. Their constant encouragement and thirst for knowledge fueled my drive to reach my greatest potential in graduate school. Thanks is also due to my committee member Tristan Brown and examiner Lemir Teron. The extra time they put aside to assist me in completing my degree is very much appreciated. Thank you to all that made my years at SUNY-ESF such a wonderful experience.

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Thesis Abstract

B. M. Sullivan. Geographically Specific Life Cycle Assessment of Electricity from Tidal Turbines in the United States, 120 pages, 5 tables, 42 figures, 2018. Global Change Biology style guide used.

Life cycle assessment can be used to determine whether electricity from ocean energy sources has a lower climate change impact than electricity from fossil energy sources. A mathematical model was developed to calculate GHG emissions of electricity from a tidal turbine across its life cycle processes, scaled to a functional unit of 1 kWh. It was applied to 23 “hotspots” sites on U.S. coasts. Daily peak tidal velocities were used to determine electricity generated over the turbine’s lifetime. The life cycle climate change impacts of electricity from tidal turbines varied significantly across deployment sites. For example, the carbon footprint for a tidal turbine in the Sitkinak Strait (AK) is over 11,000 percent higher than that of the East River (NY). This shows electricity from tidal turbines can have life cycle climate change impacts comparable to other renewable energy sources, fossil energy sources, or impacts even worse than fossil energy sources.

Key Words: Climate change, tidal turbine, tidal energy, life cycle assessment, velocity

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Thesis Introduction

Renewable energy plays a key role in combating climate change. The ocean's energy, a renewable energy source, provides the opportunity to curb carbon emissions. Ocean energy can generate electricity from six sources: ocean wave, tidal range, tidal current, ocean current, ocean thermal energy, and salinity gradient. Ocean energy's global development potential is predicted to be 337 GW, with 885 TWh of the electricity generated each year.[1] The International Energy Agency (IEA) Ocean Energy Systems Technology Collaboration Programme estimates ocean energy technologies could supply global annual electricity demand if worldwide deployment of the technologies is achieved.[1] There is tremendous resource potential in ocean energy, but the amount of commercially installed devices currently does not match this potential.

Technological development will boost ocean energy deployment. Two of the most advanced ocean energy sources are tidal range and tidal current.[2] Tidal barrages, which originated in 1966 in France, can be used to generate electricity from tidal ranges, but these technologies have high construction costs and damage aquatic ecosystems, and the installation of tidal barrages removes exposed mud flats, reducing the food availability for birds. Tidal barrages cause obstruction for passage of boats and fish, and electricity generation cannot start until construction is fully completed, which may take years.[3] Tidal current technologies are still in development, but their potential is larger than tidal range technologies.[1] Tidal barrages require a fixed location that creates a basin to store incoming water. The basin must be hundreds of square meters large to produce power comparable to tidal turbines due to tidal barrage's low power density in terms of surface area.[1] These requirements reduce the number of places for tidal barrage development. Tidal current technologies use tidal turbines to harness energy from the currents which are driven by the gravitational force of the Moon and Sun and the rotation of the

Earth. As a result, this energy source is less intermittent than other renewable sources. The majority of tidal current energy development has occurred in the United Kingdom, with some development in the United States with the installation of a Verdant Power, Inc. tidal turbine in the East River in New York, NY. Additionally, a 2011 Georgia Tech Research Corporation report to the Department of Energy identified hotspots for tidal energy on the coasts of the United States, which will assist in the global advancement of this technology.[1,4]

While there may be potential sites to deploy this technology, sufficient information on its life cycle environmental impacts is not currently available. It is important to know the impact that tidal turbines have on climate change if renewable energy sources are aimed to replace fossil fuels on this environmental basis. The life cycle climate change impacts of electricity from tidal turbines must be less than those of fossil fuel-fired electricity generation for it to be a suitable alternative. Life cycle assessment (LCA) is a tool that can quantify these impacts. LCA mathematically models all the phases of a life cycle, using a “cradle-to-grave” approach to account for environmental impacts associated with the extraction of materials, manufacturing, distribution, use, maintenance, and disposal of the product or system.[5] Measuring the environmental impacts for each phase emphasizes that renewable energy sources are not truly zero-emission systems and identifies which phases of their life cycle contribute the most to environmental impacts so that alternatives and design improvements may be considered.

There exist few published LCAs for tidal turbines.[6,7.8.9] Uihlein (2016), Rule *et al.* (2009), and Douziech *et al.* (2016) modeled tidal turbines from cradle-to-grave using their power rating and capacity factor to calculate the energy produced over the turbine’s lifetime. However, a power rating multiplied by a capacity factor is a single value representing a steady average rate. This method does not appropriately model resource availability as it changes over time. These studies, along with Douglas *et al*. (2008), also did not consider the life cycle climate change impacts of their device in locations beyond the single one studied in each analysis. The most influential variable in calculating the electricity generated for a tidal turbine is the velocity of the tidal current,[26] which changes based on location. This highlights the need for tidal electricity LCAs to include these geographically specific parameters.

This geographically specific LCA study is novel for ocean energy. It investigates how the carbon footprint of tidal turbines changes depending on the location of the device. This LCA models the life cycle climate change impact of generating electricity from a horizontal axis tidal turbine from cradle-to-grave in 23 sites identified as “hotspots” for tidal energy on the continental U.S. coasts and Alaska. These 23 LCA scenarios in different geographic locations incorporate differences in potential power generation across sites. The same technology was modeled across these geographic LCA scenarios with a functional unit of 1 kWh. A mathematical model was developed to determine potential electricity generated over the turbine’s lifetime using daily peak tidal velocities from the multiple sites and equations that represent the sinusoidal character of the tides. Input parameters (including turbine lifetime, distances transported, and daily peak tidal velocities, among others) were varied for uncertainty analyses and sensitivity analyses for each geographic LCA case study.

Science is the journal of choice to publish this research. It is an international journal focusing on publishing novel work in all fields of science. This study does not only apply to the United States, but to the global ocean energy industry. Tidal turbines are an alternative energy source with global potential. Tidal current velocities differentiate throughout the world and affect the electricity generated by a tidal turbine. Thus, these results need a global audience. *Science* encourages topics that advance the scientific understanding. This research is the first to study the life cycle climate change impacts of electricity from tidal turbines in different geographic locations and accounting for the change in resource availability. This study matches the scope and produces an article on a subject the journal welcomes. *Science* gives these novel results a worldwide platform to be presented to the scientific field.

Abstract

Life cycle assessment (LCA) can determine the climate change impact of electricity from tidal turbines compared to fossil energy sources. An LCA model calculated the GHG emissions of electricity from a tidal turbine across its life cycle processes for 23 “hotspot” sites on U.S. coasts, scaled to a functional unit of 1 kWh. Daily peak tidal velocities were used to determine electricity generated over turbines’ lifetimes. The life cycle climate change impacts of electricity from tidal turbines ranged from 43.35 to 4,985 g CO_2eq/kWh. This demonstrates that electricity from tidal turbines can have higher life cycle GHG emissions than electricity from natural gas and coal due to low electricity generation over the turbine lifetime relative to the emissions arising from the life cycle.

1. Introduction

The world is heavily dependent on fossil fuels which contribute to climate change. Mitigating climate change requires moving away from fossil fuels and towards renewable energy. Life cycle assessment (LCA) can be performed to determine if a renewable energy source has a lower climate change impact than fossil energy sources. LCA is a tool to measure the environmental impacts of a product or a system over all the phases of its life cycle. Renewable energy systems do not directly emit greenhouse gas (GHG) emissions during electricity generation, but this only applies to the use phase of the energy system. GHG emissions can occur during the extraction, manufacturing, transportation, maintenance, and end of life phases of the renewable energy system. LCA can determine the environmental impact during all these phases in the life cycle of the renewable energy system to determine if it is a suitable alternative to fossil energy systems from an environmental perspective.

Tidal energy is a renewable energy source that can generate electricity through two methods. The first method is a tidal barrage which uses the potential energy stored in the tidal range (the height difference between low and high tides) to generate electricity. The second method harnesses the kinetic energy in tidal currents, typically using tidal turbines.[1,2] The implementation of tidal turbines avoids some of the challenges of tidal barrages, which require substantial quantities of materials and physically alter the local environment.[3] The first commercial grid-connected tidal turbine was the Seagen (Marine Current Turbines, Emersons Green, England). This 1.2 MW tidal turbine was deployed in May 2008 in Northern Ireland at Strangford Lough. It has two underwater axial flow turbines connected to a steel tower that is visible above the water.[4] In North America, the first commercial tidal project was the 300-kW Cobscook Bay Tidal Project in Maine. Ocean Renewable Power Company (Portland, Maine) used a cross-flow turbine for this project.[5,6] Other projects, such as the Roosevelt Island Tidal Energy (RITE) Project in New York City, are in development in the U.S. Verdant Power (New York City, New York) currently has a commercial license for tidal energy in the East River for the RITE Project and has been testing their tidal turbine technology since 2002.[7] They plan to install 30 Generation 5 axial-flow turbines that will produce 1 MW of power cumulatively each year.[8]

The few published LCAs on electricity from tidal turbines report a life cycle climate change impact between 1.8 and 37 g CO_{2eq}/kWh,[4,9,10,11,12] which is up to 99.65% to 99.82% lower than the climate change impact of electricity from natural gas and from coal, respectively.[13,14] However, these LCAs do not model site-specific electricity generation from tidal turbines. Uihlein (2016) modeled multiple ocean technologies including a horizontal tidal turbine, but did not reference specific geographic locations of those technologies.[10] Douglas *et al.* (2008) modeled the Seagen, a commercial tidal turbine, in Northern Ireland using the flow conditions at the site. The authors did not compare the life cycle climate change impacts of electricity from the tidal turbine in other geographic locations.[4] Rule *et* al. (2009) modeled the proposed project of 200 turbines sited in the Kiapara Harbour in New Zealand to determine its life cycle climate change impact. The authors used a power rating of 77MW across the entire system, or 0.385 MW per turbine, and a capacity factor to calculate the electricity generated by the system over its lifetime, which was set to 100 years.[12] Douziech *et al.* (2016) modeled ocean technologies including three tidal stream devices: The Andritz Hydro Hammerfest HS1000, SeaGen, and the HydraTidal plant. This model also used the expected power rating from each device and a capacity factor, providing a steady rate determined by two measurements alone.[11] However, power output varies based on current’s velocities throughout each day at a given location. Given the absence of published LCAs which account for this variability over time and space, there is a need to model tidal electricity LCA scenarios based on geographically specific conditions at multiple locations. Tidal velocity depends on geography and affects the electricity generated by a tidal turbine; as Figure 1 shows, the maximum velocity of the current reaches different speeds throughout the year and changes depending on the location.

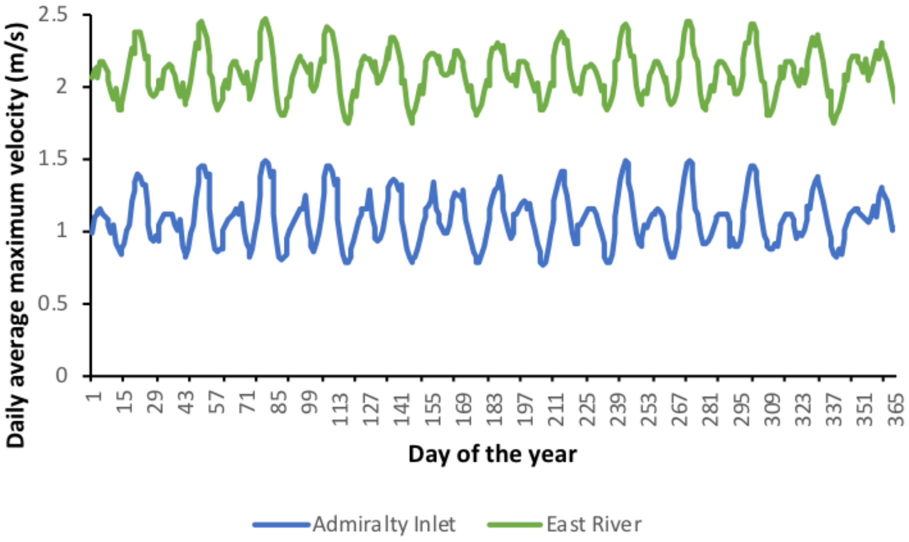

Figure 1. Average maximum velocity of tidal currents in 2015 for the Admiralty Inlet in Washington state and East River in New York state.[18]

This study is the first to investigate how the life cycle climate change impacts of electricity from a tidal turbine vary depending on where the technology is implemented. This cradle-to-grave LCA compares the life cycle GHG emissions of electricity from tidal turbines modeled in 10 coastal U.S. states, incorporating differences in potential power generation across 23 sites. A mathematical model was developed to calculate the GHG emissions of electricity from a standard tidal turbine system across its life cycle processes from cradle to grave. Daily peak tidal velocities were obtained for multiple sites in the United States coastal areas from National Oceanic and Atmospheric Administration (NOAA), and this data was used to determine potential electricity generated over the turbine's lifetime, adapted to the cyclical patterns of tides.

Tidal turbines may use different materials or techniques to construct turbines which can lead to different GHG impacts depending on the design of the technology. To control for the infrastructure-related impacts of the technology, the model used in this study is based on a single type of turbine across all the LCA case studies. Controlling differences in some parameters can isolate the effects of any emergent differences in geographic parameters on the life cycle climate change impacts of electricity from tidal turbines.

2. Methods

2.1 Goal and scope

The goal of this study is to perform an LCA to quantify and compare the cradle-to-grave climate change impacts of electricity generated by a horizontal axis turbine for tidal energy at 23 sites across 10 U.S. states, thus generating and comparing 23 geographically specific LCA scenarios. The primary purpose of this study is to determine whether significant variations in climate change impacts exist for the same tidal turbine based on electricity generation in different regions. The purpose is also to determine: (1) which processes in the life cycle of tidal turbines contribute the highest impacts, (2) to which parameters the life cycle climate change impacts are the most sensitive, and (3) how the life cycle climate change impacts of electricity from tidal turbines compare to those of other electricity sources.

The functional unit for this LCA is 1 kWh. The impact category assessed is climate change, and the life cycle impact assessment method used is the Environmental Protection Agency’s Tool for the Reduction and Assessment of Chemical and other environmental Impacts (EPA TRACI) 2.0. A system of equations with variable input parameters is developed for the

LCA model of electricity from a tidal turbine. The input parameters that are based on distances and tidal current velocities are varied for each site based on geographically-specific data.

The infrastructure of the tidal turbine in this LCA is modeled after the tidal turbine from Verdant Power, Inc. (New York, NY) that is being deployed in their RITE Project.[7] The three blades are made from fiber-reinforced plastic (FRP) composite, and the hub is made from ductile cast iron. The rest of the turbine is mainly made of steel, including the foundation for the turbine. Electrical cables connecting the turbine to the shore are also included in the model, but the onshore electricity network and transmission are outside the scope of this study. Other LCAs completed on tidal turbines also include these cables and exclude additional electricity components in their models.[4,10,11] The length of the cable extends from the turbine to the nearest shore, even for sites where the closest shore is relatively remote (e.g. 0.92 km for Kagalaska Strait). Uihlein (2016) also noted that remote areas would need electricity upgrades in addition to installing tidal turbines, but these processes are not included in their study's scope. The ductile cast iron for the pylon and nacelle connection, the silicone coating, and other smaller amounts of materials for the turbine were excluded from this model because adequate data for these materials were not available. It was also assumed that they made up a minor fraction of the entire turbine mass and potential impacts. The turbine modeled will generate electricity when the velocity of the tidal current has reached at least 1.0 m/s,[7] and it does not generate electricity when the velocity is lower than 1.0 m/s. LCA case studies are performed for installation of the tidal turbine at 23 sites across 10 states on the coastal continental United States and Alaska. The selected sites all originate from a 2011 Georgia Tech Research Corporation report to the Department of Energy which provides an assessment of energy production potential from tidal streams and a list of hotspots for tidal energy on the coasts of the United States.[15] The selection process for this comparative LCA study began by choosing the East River and Admiralty Inlet as case study sites because Verdant Power's tidal turbine is currently being deployed in the East River, and there was a proposal – that was later canceled due to costs – to deploy Verdant Power's turbine in the Admiralty Inlet.[7,16,17] Both sites are listed as hotspots by the Georgia Tech Research Corporation report.[15] The hotspots list was then cross-referenced against the coastal U.S. sites for which the National Oceanic and Atmospheric Administration (NOAA) provides annual velocity data.[18] Only sites for which NOAA data was available, and with a reported mean depth of less than 50 m were selected. This maximum depth was chosen because the tidal turbine modeled is best fitted for depths lower than 40-50 m.[19] Sites that met all criteria were selected as LCA case studies unless they were in a state with more than 2 possible sites. In that case, 50% of the sites that met the criteria were randomly chosen. Table 1 provides a list of each site and its corresponding state. A visual display of where each site is located in their state is shown in the Supplemental Information (Figures S1, S2, S3 and S4).

Table 1. Modeled tidal turbine installation sites.

Site name	**State**
Akutan Pass	AK
Chugach Passage	AK
Chugul Island	AK
Hague Channel	AK
Kagalaska Strait	AK
Little Tanaga Strait	AK
Meares Passage	AK
Sitkinak Strait	AK
Unimak Pass	AK
Carquinez Strait	CA
Humboldt Bay Entrance	CA
St. Marys River	GA/FL
Ogeechee River	GA
Western Passage	ME
Kennebeck River	ME
Delaware Bay	NJ
East River	NY
Coos Bay Entrance	OR
Coosaw River	SC
North Edisto	SC
Admiralty Inlet	WA
Bellingham Channel	WA
Grays Harbor	WA

Sensitivity and uncertainty (Monte Carlo) analyses are also performed for each LCA scenario. To perform these analyses, a minimum and maximum value in addition to the baseline value is defined. The minimum and maximum values chosen for the variable parameters are used for both the sensitivity and uncertainty analyses. The sensitivity analysis changes one of the parameters to the minimum or maximum value while keeping the other parameters at their baseline values in order to isolate the effect of a change in one parameter at a time. The uncertainty analyses are conducted by randomly changing the parameter values within their ranges using uniform distribution for 10,000 simulations of the LCA model. Table 2 provides the values for the variable parameters used in all 23 LCA case studies for the sensitivity and uncertainty analysis. The variable parameters of the distance to the assembly site from manufacturing of the blade and hub, distance to transport the turbine from land to the installation site and vice versa, cable mass, and peak velocities for the year are different among all the case studies and based on site-specific data. The table listing these variable parameters is in the Supplemental Information, Table S1.

Table 2. The non-geographically specific variable parameters used in the tidal turbine LCA model for the 23 LCA case studies.

Parameter name	**Minimum**	**Baseline**	**Maximum**	**Units**
Turbine Efficiency	0.30	0.35	0.40	-
Water Density	1020	1025	1070	kg/m^3
Turbine lifetime	10	20	30	years/turbine
Distance to transport cables	20	60	100	km
Distance to transport steel	20	60	100	km
Distance to transport turbine components to assembly	20	60	100	km
Fraction of ductile cast iron	0.0953	0.1003	0.1053	-
Distance to transport ductile cast iron	20	60	100	km
Fraction of composite fiber-reinforced plastic (FRP)	0.1042	0.1097	0.1152	-
Distance to transport composite FRP	20	60	100	km
Distance to transport turbine to installation by truck	1.06	3.20	4.80	km
Turbine mass	23,847.77	25,102.92	26,358.07	kg/turbine
Distance to transport turbine to landfill	20	60	100	km
Distance to transport turbine to recycling	20	60	100	km
Maintenance trips in lifetime	4	5	6	-
Assembly time	40	50	60	minutes/turbine
Installation time	270	360	540	minutes/turbine
Removal time	270	360	540	minutes/turbine
Fraction of steel recycled	0.5	0.68	0.86	-
Life cycle climate change impact of steel production	1.90	2.28	4.20	kg CO_{2eq}/kg steel

2.2 Processes modeled

The LCA case studies for the 23 different geographic locations consist of the same series of processes along the life cycle of the tidal turbine (Fig. 2), but are modeled with site-specific data. The processes included in the model for the tidal turbine deployed in all the sites begin with the production of cables, the production of steel, and the transportation of these products by truck separately to the production site of the turbine components. The production site of the turbine components for the RITE Project in the East River is in New York. Therefore, it is assumed that the locations for the production of these materials for all the other sites are in their respective surrounding areas.[20] Processes in all the models also include the production of ductile cast iron, the production of FRP composite, and the transport of these materials separately to the manufacturing site of the rotor blades and rotor hub in Grandville, MI. Grandville, MI is where the manufacturing company used by Verdant Power is located, and this company's location was used for the manufacturing of the rotor blades and hub for the tidal turbine deployed in all sites.[21]

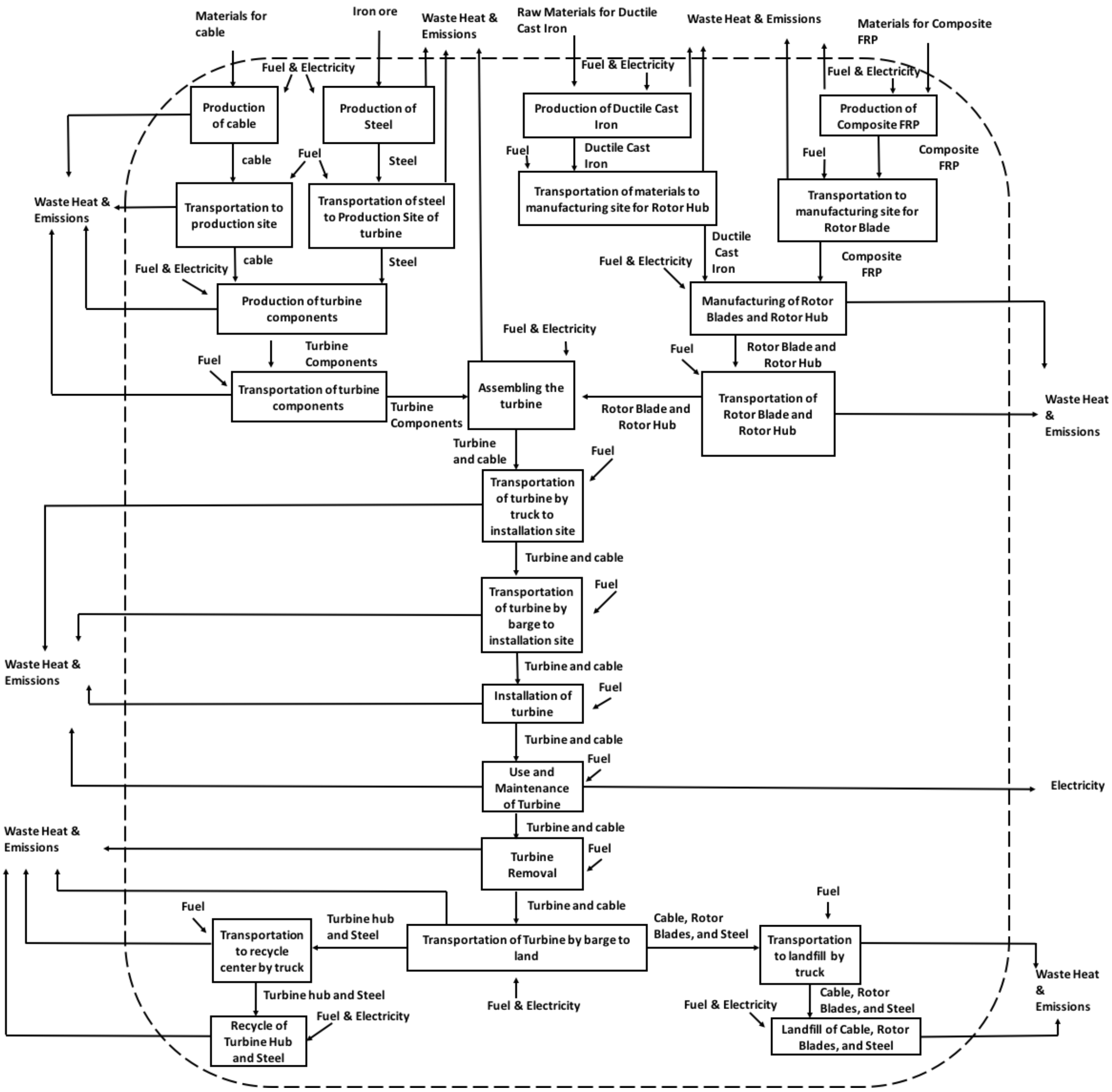

Figure 2. System diagram of the life cycle processes for electricity generation from a tidal turbine.

The next process in the life cycle changes for each case study. For the tidal turbine installed in the East River, the rotor blades, hub, and other turbine components are transported to the assembly site in Bayonne, NJ, which is the site used by Verdant Power for the RITE Project.[20] For the other sites, the rotor blades, hub, and other turbine components are transported to a site that is similar to the assembly site in Bayonne, NJ: close to water and near the final deployment site. The location where the tidal turbine is assembled for each geographic location modeled can be found in the SI (Table S2).

Once the turbine is completely assembled, it is transported by truck to a port where it is then loaded onto a barge. The barge transports the turbine to the final deployment spot where the turbine is installed by machines and divers.[22] The turbines in all modeled geographic locations generate electricity and undergo maintenance repairs throughout their lifetime. Once the turbine has reached the end of its lifetime, it is removed from the water and transported back to land by barge. The hub of the turbine and a fraction of the steel are transported by truck to a recycling center close to each installation site, and another truck transports the rest of the turbine and cables to a nearby landfill. The location for the recycling center and landfill changes for each geographic location because it is assumed that they are disposed in each surrounding area.

Life cycle inventories were obtained from the Ecoinvent 3 and USLCI databases. Information about the structure of the turbine, the mass of the turbine, and maintenance was collected from the Verdant Power website, Verdant Power Pilot License Applications, and a tidal energy workshop paper.[7,8,22,23,24] An article in *The New York Times* on the deployment of the modeled turbine ("In quest for river's power, an underwater test spin") and Verdant Power's final technical reports provided information on transportation, manufacturing, and assembly locations.[20,21,25]

The peak tidal velocities for each case study were collected from NOAA data for the year 2015.[18] Other information on the processes and parameters for the LCA model of tidal turbines was collected from the scientific literature.[1,4,10] More information on the parameters and processes can be found in the SI (Extended Methods section).

2.3 Electrical energy generated calculations

A key component to this study is the modeling of the velocity of the currents, which vary site to site and over time, in order to most accurately quantify the electrical energy generated by a turbine for the LCA case studies. This study used NOAA tidal velocity data for each peak in the ebb and flood cycle of a tide (approximately four peaks per day) in the year 2015 as a parameter to calculate the electricity generated over the turbine's lifetime. This turbine will not generate electricity if the velocity of the tidal current is lower than 1.0 m/s.[7] This technical limitation was incorporated into the model in two ways. First, a conditional statement: if the individual peak velocity was less than 1.0 m/s, then zero electricity generation was modeled for that ebb or flood period. Second, the velocity data provided by NOAA is the individual peak (maximum) velocities of the two ebb and two flood tidal currents each day, which are represented as v_p [m s^{-1}] in Equation 1 and 3. To avoid overestimating the electricity generated, and to appropriately calculate the actual electricity that would be generated at a site, an adjusted average velocity during the time that the turbine generates electricity (e.g. when above 1.0 m/s) for each ebb and flood of the tide was calculated based on the physical cycle of tides. This average velocity v_{avg} [m s^{-1}] during electricity generation, from time t_1 to time t_2 in seconds during an ebb or flood, was calculated as shown in Equations 1, 2, and 3.[26] In these equations, T represents the tidal period of 44,700 seconds. Figure 3 visually displays how the tidal velocity changes over time and the intervals during which the model calculates electricity generation, starting at the cut-in speed of 1.0 m/s.

$$t_1 = \left(\frac{T}{2.0\pi}\right)(\sin^{-1}(1.0/v_p))$$ (Equation 1)

$$t_2 = (T/2.0) - t_1$$ (Equation 2)

$$v_{avg} = (v_p/(t_2\text{-}t_1))^*(T/(2.0\pi))^*(\text{-}cos(2.0\pi t_2/T) + cos(2.0 * \pi^* t_1/T))$$

(Equation 3)

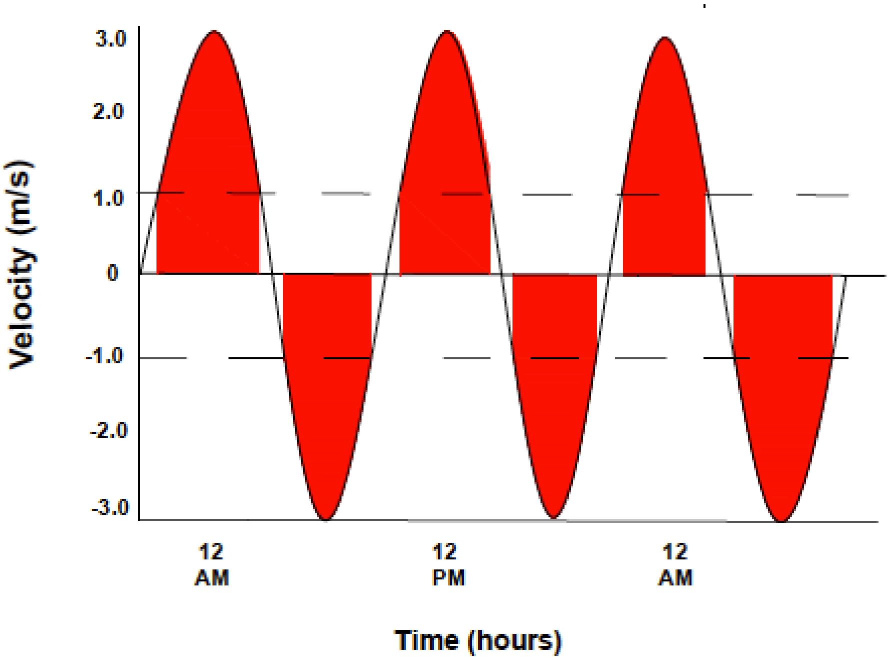

Figure 3. Velocity of the tide over time. The red shaded areas represent the times during which electricity is generated by the turbine above a cut-in speed of 1.0 m/s.

The electricity generated was calculated by multiplying the turbine efficiency, water density, the swept area of the turbine, and the average peak tidal velocity cubed, and dividing by two. This equation originates from Tousif *et al*. (2011).[27] In Equation 4, the turbine efficiency is represented by ε, water density is represented by ρ in units of kg m^{-3}, and *A* represents the swept area of the turbine in m^2. The average peak velocity in m s^{-1} in Equation 4 is represented by v_{avg}. The terms in Equation 4 are multiplied by 1/3,600,000 to convert it to kWh. The equation in this model then converted power to electrical energy generated for each peak period of the ebb and flood current.

$$Energy_{peak} = \varepsilon\rho A(v_{avg})^3\left(\frac{1}{2}\right)(t_2\text{-}t_1)(1\ /\ 3{,}600{,}000) \qquad \text{(Equation 4)}$$

The electricity generated per ebb and flood current is calculated for an entire year, and the only parameter that changes in these calculations for a site is the average peak tidal velocity (v_{avg}). The sum of the electricity generated for each individual peak of the ebb and flood current cycle throughout the year provides the annual electricity generated, which is subsequently multiplied by the lifetime of the turbine in years to calculate the total energy generated over the tidal turbine's lifetime.

During maintenance, the turbine will not generate electricity. The total calculated electricity generation is adjusted to account for zero generation during days of maintenance.

3. Results & Discussion

3.1 Baseline results and discussion

Baseline results for the life cycle climate change impacts of electricity from tidal turbines were obtained by running the LCA model using the baseline input parameter values for all 23 site-specific LCA case studies. The baseline life cycle climate change impacts range from 43.45 to 4,985 g CO_{2eq}/kWh across the sites. Figure 4 depicts the baseline life cycle climate change impacts for all sites based upon geographic region. Stars represent sites for which the baseline life cycle climate change impacts of electricity from tidal turbines are in the same range as the climate change impacts of wind turbines, 1.7 - 81 g CO_2eq/kWh.[28] Squares represent sites for which the baseline life cycle climate change impacts fall in a range higher than those of electricity from wind turbines and up to the climate change impacts of electricity from natural gas, 510 g CO_2eq/kWh.[13] Sites with a life cycle climate change impact that is higher than natural gas and comparable to electricity from coal, 980 g CO_2eq/kWh, are represented as a triangle in

Figure 4, and the sites with a baseline life cycle climate change impact higher than that of electricity from coal are represented as a circle.[14] The life cycle climate change impact varies depending on the location of the tidal turbine (Figure 4). In one area of Alaska, three "hotspot" sites exist on one island, and their baseline life cycle climate change impacts for electricity generated from tidal turbines varies by up to two orders of magnitude, leading to impacts that are comparable to those of electricity from wind, natural gas, and coal (Figure 5). Thus, the life cycle climate change impacts for tidal energy sited at "hotspots" should not be generalized by state.

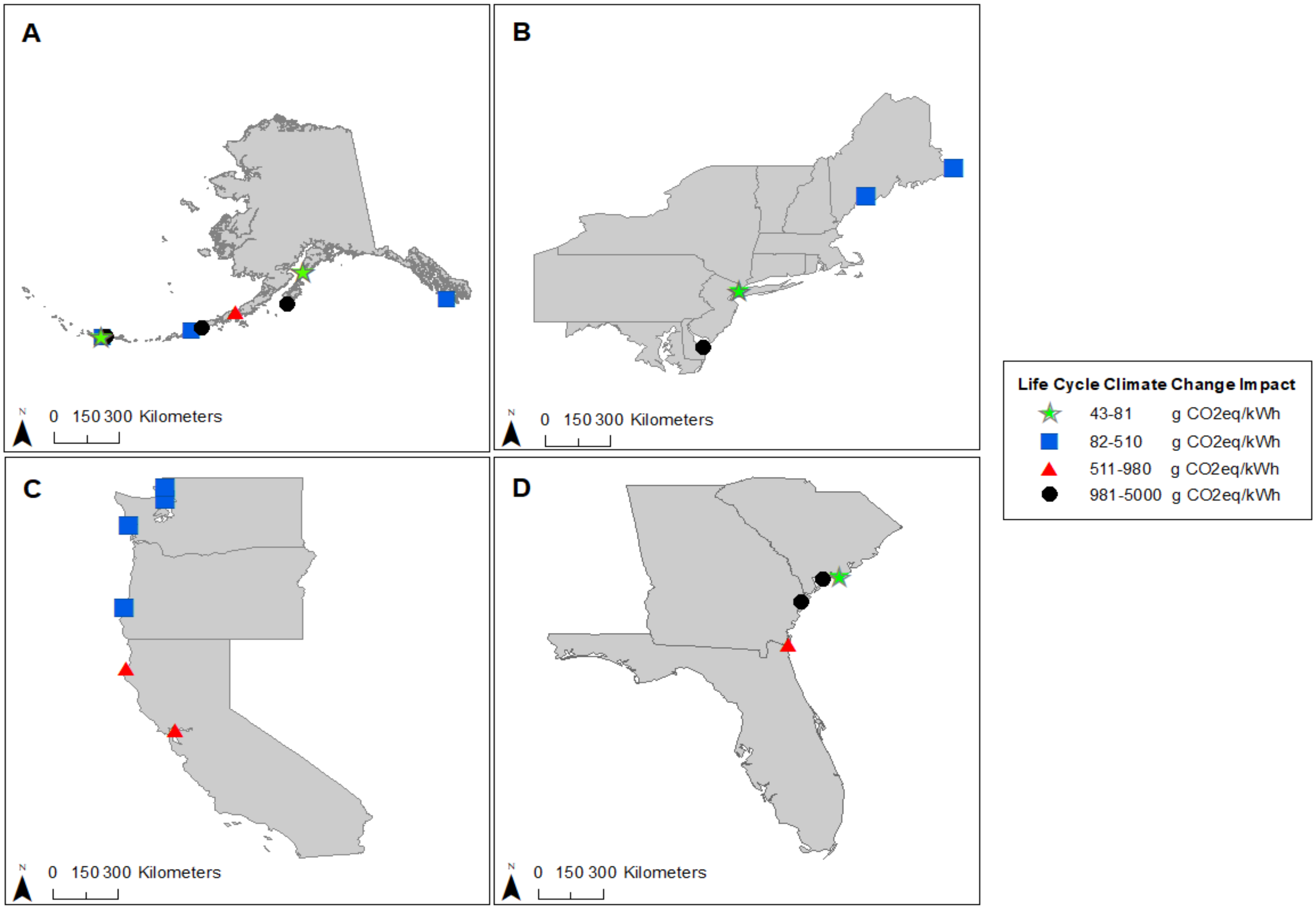

Figure 4. Baseline life cycle climate change impacts of electricity generated from tidal turbines deployed in 23 U.S. coastal sites. Panel A represents the sites in the state of Alaska. Panel B shows the sites in the northeast. Panel C shows the sites on the west coast, and panel D represents the sites in the southeast.

Figure 5. Baseline life cycle climate change impacts of electricity generated from tidal turbines deployed in Kagalaska Strait (star), Little Tanaga Strait (square), and Chugul Island (circle) in Alaska.

It is important to note the total energy produced from the tidal turbine deployed in each site and to investigate its influence on the life cycle climate change impacts of electricity from tidal turbines. The amount of electricity generated over the turbine’s 20-year lifetime ranged from 21,734 - 2,295,087 kWh depending on the installation site (Table 3). Table 3 shows the total baseline life cycle climate change impact, the electricity generated over the turbine’s lifetime, and the corresponding life cycle climate change impact per turbine by site. The differences in electricity generation arise from the unique tidal current speeds at each location. These values correspond to the Coosaw River (SC) and the East River (NY) sites, respectively. While the Coosaw River generated the least amount of electricity it does not have the highest life cycle climate change impact. Sitkinak Strait had the highest life cycle climate change impact even though it generated 3,972 kWh/turbine more than the Coosaw River due to differences in transportation distances and cable mass. Thus, a turbine deployed in the East River would generate 10,460 percent more electricity than a turbine in the Coosaw River with the same lifetime. The GHG emissions released during the life cycle are scaled to the electricity generated at each site, so that the impacts are standardized to the production of the functional unit of 1 kWh, thus providing LCA results in units of g CO_{2eq}/kWh. Subsequently, among the 23 LCA case studies, the higher values of life cycle climate change impacts correlate with lower life cycle electricity generation (Figure 5). Figure 5 shows a logarithmic transformation of the data to depict the relationship between a site's life cycle climate change impact and the amount of electricity generated at that site over the turbine's lifetime. The life cycle climate change impacts are dependent on the life cycle electricity generated from a certain location, resulting in a strong relationship ($R^2 = 0.9874$) between these variables. This relationship also confirms that the electricity generated at a site influences the life cycle climate change impact more substantially than other parameters that vary by site, such as transportation distances.

Table 3. Life cycle climate change impacts and electricity generated, by LCA case study.

Site	Life cycle climate change impact (g CO_{2eq}/kWh)	Total electricity generated over lifetime (kWh/turbine)	Life cycle climate change impact (g CO_{2eq}/turbine)
East River	43.45	2,295,087	9.97×10^7
North Edisto	51.89	1,932,074	1.00×10^8
Kagalaska Strait	60.47	1,830,021	1.11×10^8
Chugach Passage	72.68	1,521,659	1.11×10^8
Western Passage	99.36	1,203,923	1.20×10^8
Akutan Pass	129.70	1,076,475	1.40×10^8
Little Tanaga Strait	152.4	934,712	1.42×10^8
Grays Harbor	207.04	514,088	1.06×10^8
Kennebeck River	272.6	385,608	1.05×10^8
Coos Bay Entrance	291.2	349,044	1.02×10^8
Meares Passage	307.4	365,306	1.12×10^8
Admiralty Inlet	365.4	286,341	1.05×10^8
Bellingham Channel	415.8	274,769	1.14×10^8
Humboldt Bay Entrance	557.2	183,636	1.02×10^8
Hague Channel	588.5	192,533	1.13×10^8
St. Marys River	671.3	175,606	1.18×10^8
Carquinez Strait	696.2	151,374	1.05×10^8
Ogeechee River	1,063	94,172	1.00×10^8
Unimak Pass	1,535	85,793	1.32×10^8
Delaware Bay	3,001	47,036	1.41×10^8
Chugul Island	3,741	54,090	2.02×10^8
Coosaw River	4,603	21,734	1.00×10^8
Sitkinak Strait	4,985	25,706	1.28×10^8

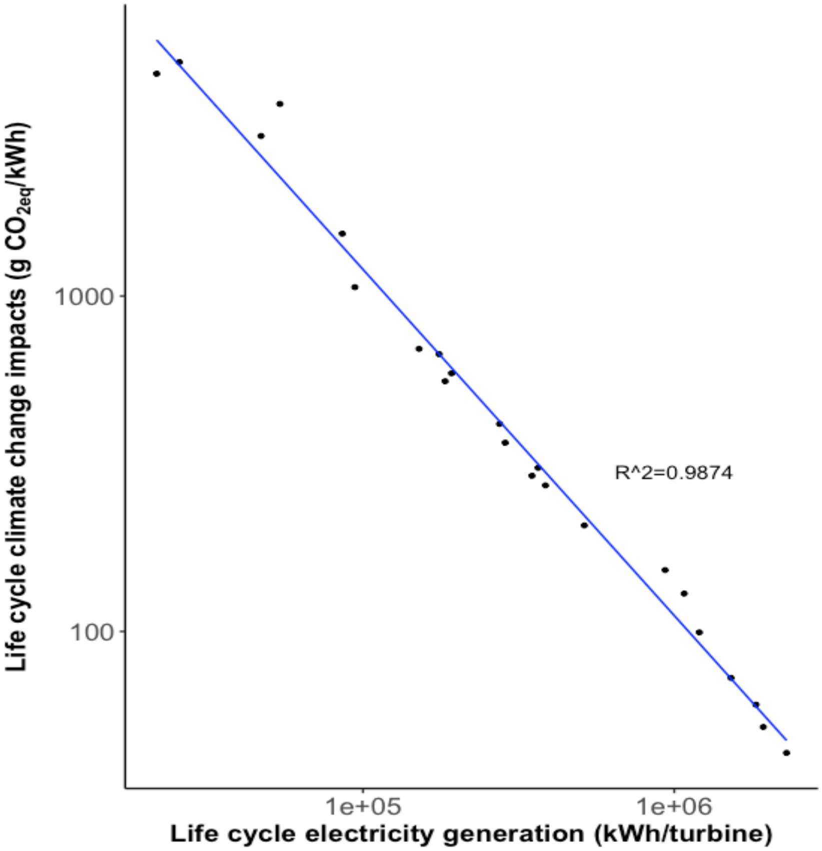

Figure 6. Scatterplot of log-transformed life cycle climate change impacts vs. life cycle electricity generation by LCA case study.

The process that contributed the highest GHG emissions in the life cycle of electricity from tidal turbines across all the LCA case studies was the production of steel. Across the case studies, the process of steel production contributed an average of 39% ± 6% of the baseline life cycle climate change impacts. Another influential process was the production of the turbine components. This process contributed an average of 33% ± 5% of the baseline life cycle climate change impacts. The process that contributed the least to the total baseline life cycle climate change impact is assembling the turbine, which involved approximately 50 minutes of use of a crane. On average, this process contributed nearly 0% to the total impacts. Figure 6 depicts the average percent contribution of each life cycle process in all 23 LCA case studies to the baseline results. Baseline graphs that show the total life cycle climate change impact for each individual site and how much each process in the life cycle of tidal turbines contributed to the impacts are presented in the SI (Figures S5, S6, S7 and S8).

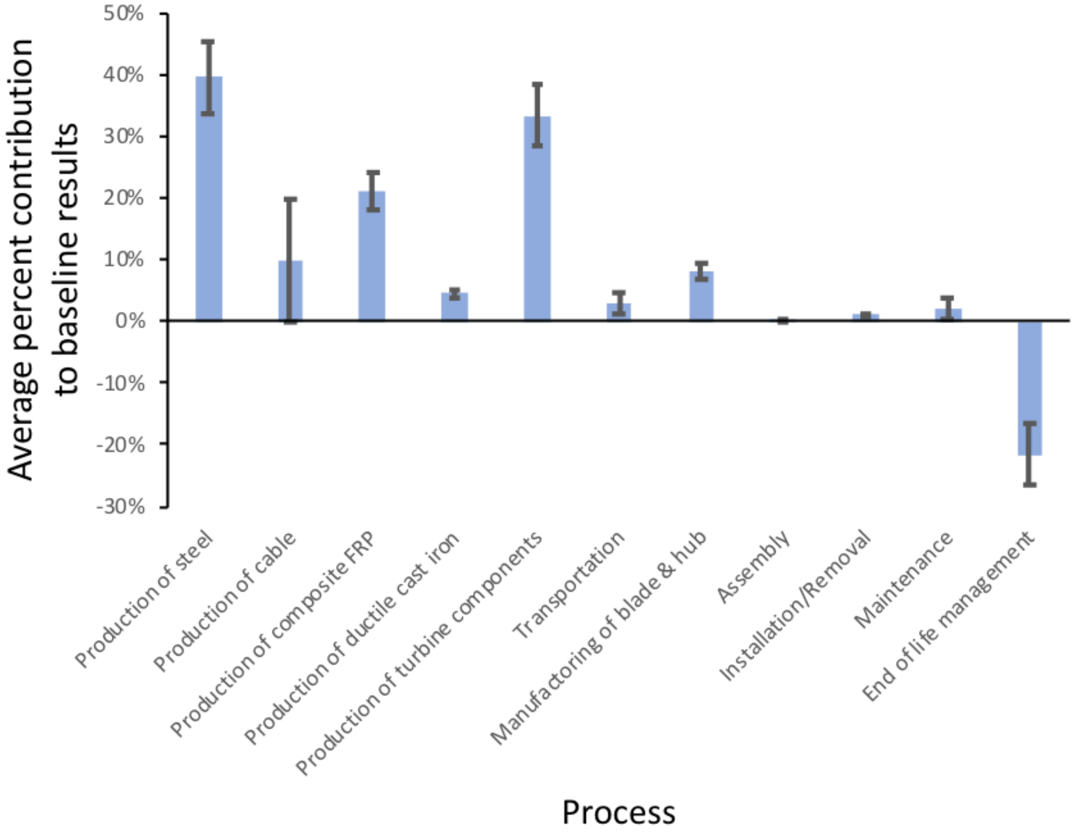

Figure 7. The average percent contribution of each process along the life cycle of electricity from a tidal turbine to the total baseline life cycle climate change impact. The transportation process aggregates all transportation processes along the life cycle. Error bars denote the full range of percent contributions represented across the individual LCA case studies.

3.2 Sensitivity analysis results and discussion

A sensitivity analysis was conducted for each of the 23 LCA case studies to investigate the robustness of the results to changes in input parameter values. For all LCA case studies, the parameter to which the LCA results were the most sensitive was the lifetime of the turbine, followed by the life cycle climate change impact of steel production and the turbine efficiency. When the lifetime is changed to its minimum value of 10 years from its baseline value of 20 years, the life cycle climate change impact increases by 100% from the baseline value. When the lifetime is changed from its baseline value of 20 years to its maximum value of 30 years, the life cycle climate change impact of tidal energy decreases by 33%. This is expected due to the direct influence of the lifetime on the electricity generated by a turbine before it is decommissioned and undergoes end-of-life management. The results indicate that it is crucial for the tidal turbine to have a long lifetime so that it can generate more electricity and therefore, contribute to a lower climate change impact per kWh of electricity generated.

While the LCA results were also sensitive to the life cycle GHG emissions of steel production in all 23 LCA case studies, the effect of this parameter on each site-specific case study varied. When this parameter is changed to its maximum value (4.20 kg CO_{2eq}/kg steel) from its baseline value (2.28 kg CO_{2eq}/kg steel), on average, the life cycle climate change impact increased by 33% ± 5%. The life cycle climate change impact decreased by 7% ± 1% when the parameter is changed from the baseline value to the minimum value of 1.90 kg CO_{2eq}/kg steel. Different types of steel may be used to construct a turbine, causing this variability in life cycle climate change impacts due to structural components. The main material used in most tidal turbines is steel.[4,10,11] Figure 6 shows how steel production contributes a large portion of an LCA case study's baseline life cycle climate change impact. Due to this influence on life cycle climate change impacts, the type of steel used to build the turbine and its associated cradle-to-gate GHG emissions should be considered in the design stage. The sensitivity of the GHG emissions associated with steel production is shown by site in the SI (Figure S9).

The LCA results were also sensitive to the turbine efficiency. The life cycle climate change impact increases by 17% when the turbine efficiency is changed to its minimum value of 0.30 from the baseline value of 0.35 for all LCA case studies. When the turbine efficiency is changed to its maximum value of 0.40, the life cycle climate change impact decreases by 13%. This is expected as the turbine efficiency directly affects the total electricity generation over a turbine’s lifetime.

There was little difference in the life cycle climate change impact when the distance the turbine traveled in different phases of its lifetime or the fraction of ductile cast iron used to build the turbine were changed to their minimum or maximum values. When changed in isolation from other peak tidal current velocities, individual peak velocities did not affect the total life cycle climate change impact of electricity from tidal turbines. This is due to the relative influence of one peak velocity value compared to the cumulative influence of the over 1,400 peak velocity values that define the amount of electricity generated over the turbine’s lifetime.

3.3 Monte Carlo results and discussion

Monte Carlo analysis quantifies the uncertainty in the LCA results from the probability distributions of the input parameters in the LCA model. It allows for the investigation of the range of probability of LCA results based on scenarios representing different combinations of input parameter values. In contrast with sensitivity analysis, more than one input parameter is changed at a time to generate new LCA results in Monte Carlo analysis. Equations were coded into Python to perform the uncertainty analysis using uniform distribution for all variable parameters. Monte Carlo analyses were performed using 10,000 simulations for each geographic LCA case study. The uncertainty analysis results for the LCA case studies on the west coast of the U.S. show 0% probability across 10,000 simulations for each location that the life cycle climate change impact of electricity from tidal turbines would fall within the range of the life cycle climate change impacts of electricity from wind (Figure 7). All the assessed sites on the west coast have a higher probability of being comparable to natural gas and coal, but in some scenarios, Admiralty Inlet, Bellingham Channel, Carquinez Strait, and Humboldt Bay Entrance may be even worse than coal. There is an 89% and 99% cumulative probability of the life cycle climate change impact of electricity from tidal turbines in Coos Bay Entrance and Grays Harbor, respectively, being lower than 510 g CO_{2eq}/kWh (lower than natural gas). For these two sites, there is a 100% probability the electricity generated is lower than 980 g CO_{2eq}/kWh (lower than coal). The cumulative probability the life cycle climate change impact is less than natural gas for the Admiralty Inlet, Bellingham Channel, Carquinez Strait, and Humboldt Bay Entrance is 70%, 62%, 8%, and 29%, respectively. The cumulative probability for those four sites on the west coast to have a life cycle climate change impact less than coal is 99%, 99%, 71%, and 87%. The 10,000 simulations of life cycle climate change impacts for the Admiralty Inlet, Bellingham Channel, Coos Bay Entrance, and Grays Harbor resulted in a mean value lower than the life cycle climate change impact of electricity generated from natural gas, 448.5 g CO_{2eq}/kWh, 492.1 g CO_{2eq}/kWh, 340.5 g CO_{2eq}/kWh, and 256.5 g CO_{2eq}/kWh, respectively. The mean life cycle climate change impact for electricity generated from a tidal turbine deployed in the Carquinez Strait is 852.5 g CO_{2eq}/kWh and is 681 g CO_{2eq}/kWh for electricity generated in the Humboldt Bay Entrance, which are both higher than the life cycle climate change impact of electricity from coal. All the site’s mean values are higher than their respective baseline values. The percent change between these two values ranges from 14%-19%.

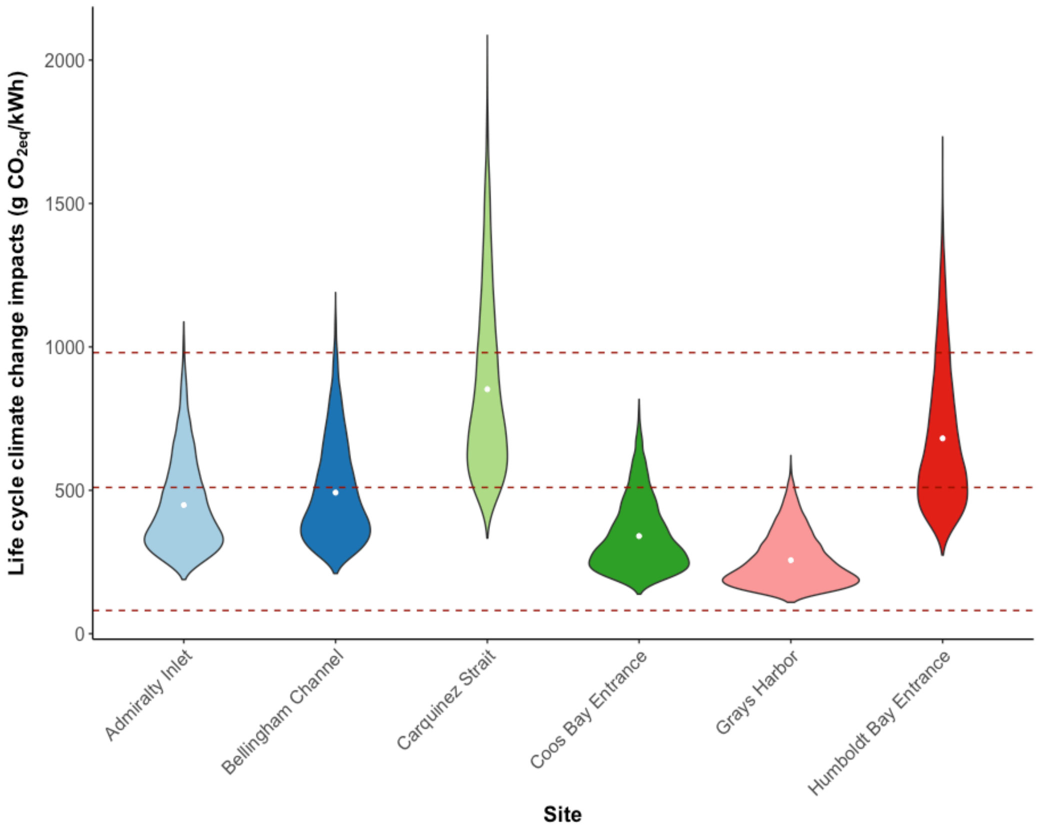

Figure 8. Probability plot of the distribution of life cycle climate change impacts of generating electricity from tidal turbines at six assessed sites located on the west coast of the U.S. The red dashed line at 81 g CO_2/kWh represents the highest value of published life cycle climate change impacts of electricity from wind turbines.[28] The red dashed line at 510 g CO_2/kWh represents the mean harmonized value of the life cycle climate change impacts of electricity from natural gas. The red dashed line at 980 g CO_2/kWh represents the mean harmonized value of the life cycle climate change impacts of electricity from coal.[13,14]

In Alaska, there is a 49%, and 66% cumulative probability that electricity generated from tidal turbines at the Chugach Passage and Kagalaska Strait sites, respectively, would have life cycle climate change impacts lower than 81 g CO_{2eq}/kWh and thus comparable to those of electricity from wind turbines (Figure 8). On the other side of the spectrum, the probability of electricity from tidal turbines situated on Chugul Island and Sitkinak Strait having life cycle climate change impacts lower than coal is zero. The uncertainty analysis results for the LCA case studies for Unimak Pass shows 0% probability for the life cycle climate change impact of electricity from a tidal turbine would fall below that of natural gas, and there is only a 2.1%

probability it would fall below coal. Therefore, whether electricity from tidal turbines that are deployed at "hotspots" in Alaska shows a lower life cycle climate change impact relative to fossil fuel sources of electricity depends on the site and cannot be generalized across the state. Kagalaska Strait is the only site with a mean value below the life cycle climate change impact of electricity from wind turbines, 75 g CO_{2eq}/kWh. Akutan Pass, Chugach Passage, Little Tanaga Strait, and Meares Passsage have a mean value of 157 g CO_{2eq}/kWh, 90 g CO_{2eq}/kWh, 180 g CO_{2eq}/kWh, and 364.4 g CO_{2eq}/kWh, respectively, which signifies a value lower than natural gas. The mean value of 643 g CO_{2eq}/kWh for Hague Channel is less than the life cycle climate change impact of coal, and Chugul Island, Sitkinak Strait, and Unimak Pass have mean values that are worse than coal, 3,245 g CO_{2eq}/kWh, 5704 g CO_{2eq}/kWh, and 1,806 g CO_{2eq}/kWh, respectively. The percent change between the mean value and the sites respective baseline values ranges from as little as 8% to 19%. The Hague Channel is the site with a difference of only 8%. Having a low difference shows that this mean value can be expected and that the baseline life cycle climate change impact represents the mean of the 10,000 LCA simulations well.

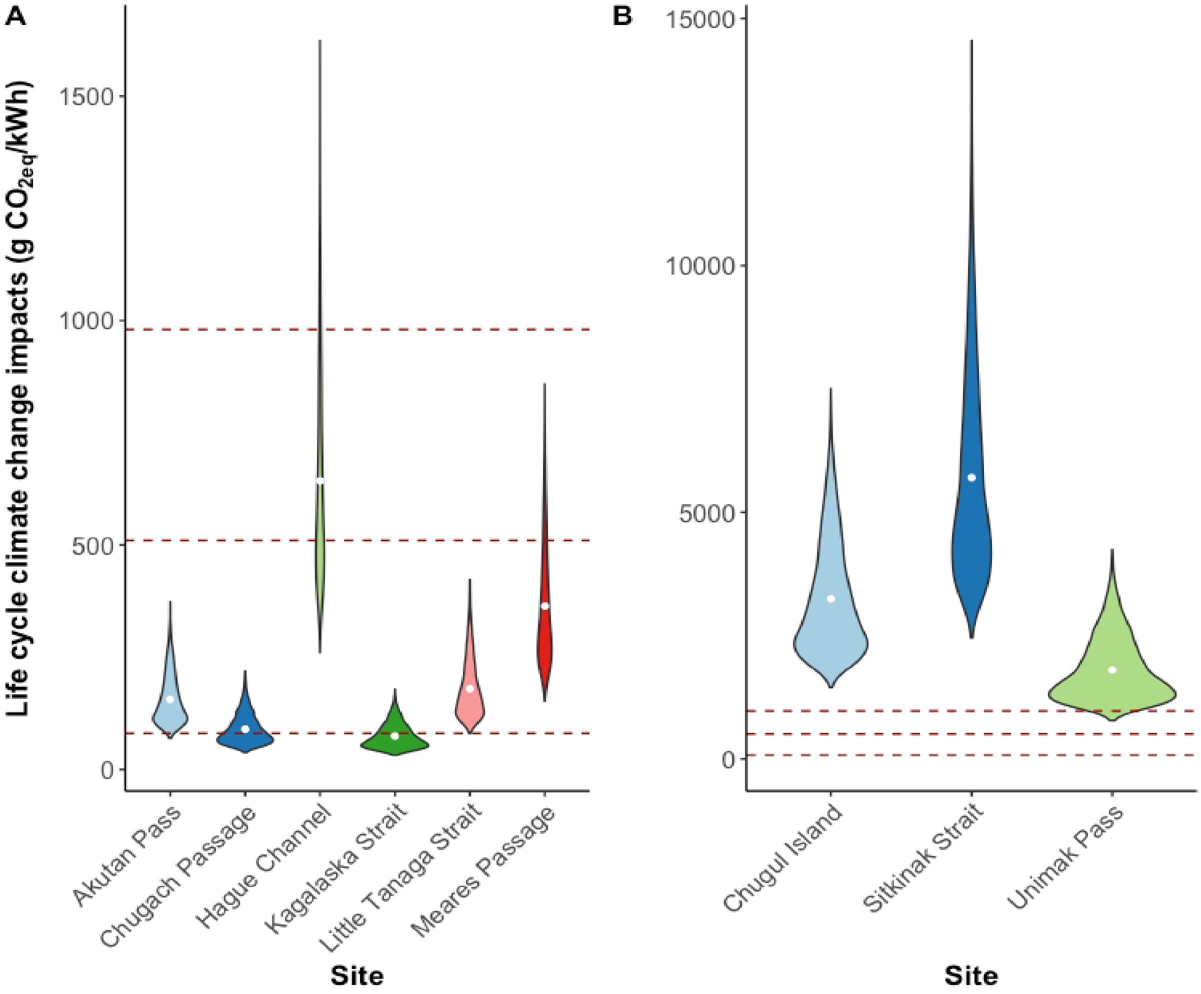

Figure 9. Probability plot of the distribution of life cycle climate change impacts of generating electricity from tidal turbines in the nine assessed sites in Alaska. The red dashed line at 81 g CO_2/kWh represents the highest value of published life cycle climate change impacts of electricity from wind turbines.[28] The red dashed line at 510 g CO_2/kWh represents the mean harmonized value of the life cycle climate change impacts of electricity from natural gas. The red dashed line at 980 g CO_2/kWh represents the mean harmonized value of the life cycle climate change impacts of electricity from coal.[13,14] Panel A shows sites that have a nonzero probability of Monte Carlo results that are comparable to electricity from natural gas or renewable sources. Panel B shows sites that have no probability of being comparable to natural gas.

The life cycle climate change impacts of electricity generated from tidal turbines installed in the East River, North Edisto, and Western Passage on the east coast of the U.S. show a cumulative probability of being lower than 81 g CO_{2eq}/kWh of 88%, 77%, and 17%, respectively. The five other assessed sites on the east coast have a much larger range of uncertainty for the life cycle climate change impacts compared to those three sites. The range for the Coosaw River is 7,867 g CO_{2eq}/kWh and the range for Delaware Bay range is 7,149 g CO_{2eq}/kWh. The Ogeechee River has a range of 2,248 g CO_{2eq}/kWh which is still thousands of g CO_{2eq}/kWh more than the range of uncertainty for the life cycle climate change impacts for the site East River yet also thousands of g CO_{2eq}/kWh less than the Coosaw River and Delaware Bay. This shows how the range varies among sites and by different magnitudes. The LCA case studies for electricity from tidal turbines deployed at the Kennebeck River, Ogeechee River, and St. Marys River sites show probability ranges of impacts that are comparable to those of electricity from natural gas and coal. The Monte Carlo results for the Ogeechee River and St. Marys River case studies also have a 50% and 79% cumulative probability of being higher than the impacts of electricity from coal, respectively. All 10,000 Monte Carlo simulations for the Coosaw River and Delaware Bay case studies show a life cycle climate change impact above that of electricity from coal. The baseline value of Ogeechee River site is very comparable to the mean value with a difference of only 1%. The percent change from the mean Monte Carlo value to the baseline value for sites on the East Coast ranges from 1%-20%.

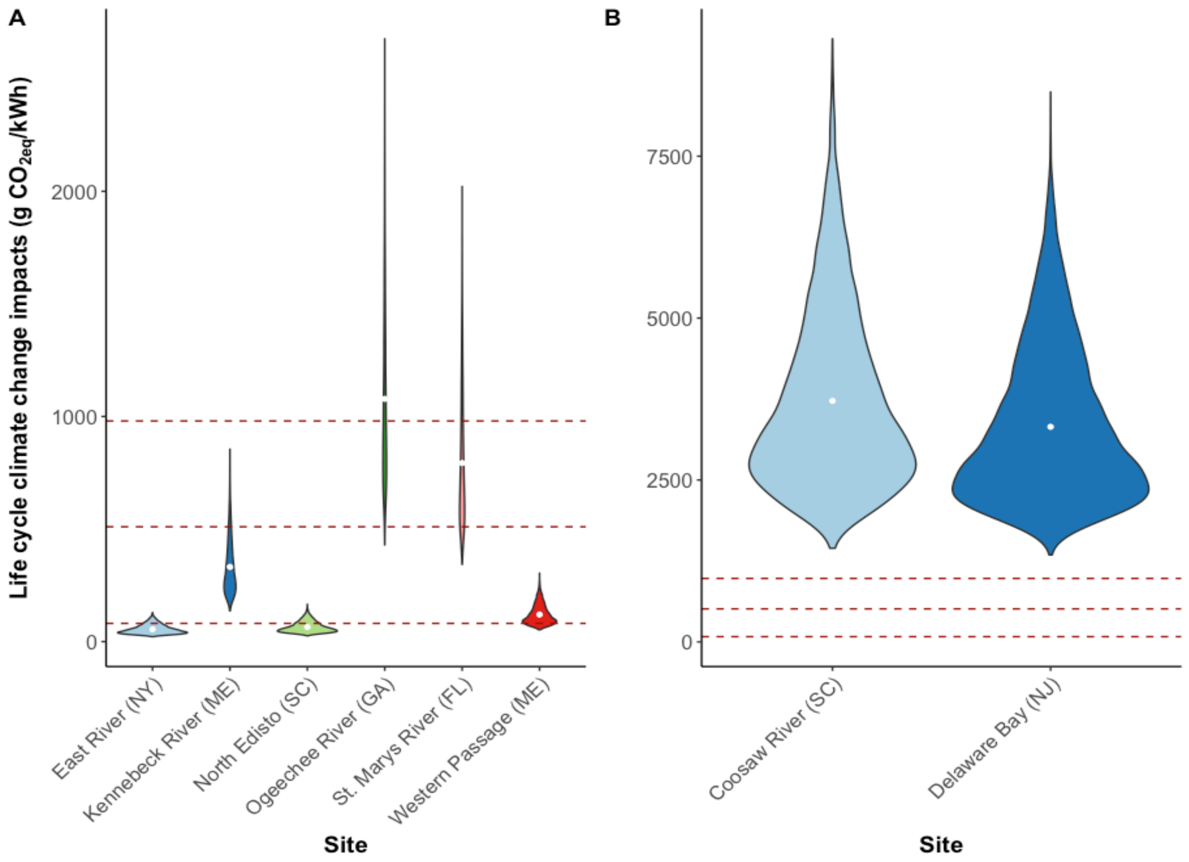

Figure 10. Probability plot of the distribution of life cycle climate change impacts of generating electricity from tidal turbines at eight assessed sites on the east coast of the U.S. The red dashed line at 81 g CO_2/kWh represents the highest value of published life cycle climate change impacts of electricity from wind turbines.[28] The red dashed line at 510 g CO_2/kWh represents the mean harmonized value of the life cycle climate change impacts of electricity from natural gas. The red dashed line at 980 g CO_2/kWh represents the mean harmonized value of the life cycle climate change impacts of electricity from coal.[13,14] Panel A shows sites that have a nonzero probability of Monte Carlo results that are comparable to natural gas or renewable sources of electricity. Panel B shows sites that have no probability of being comparable to natural gas.

The Monte Carlo analysis results show that the life cycle climate change impact of electricity from tidal turbines varies geographically and also within the same state. There are only five sites among the 23 “hotspot” sites assessed that show high probability of life cycle climate change impacts that are comparable to those of wind. For four sites, the range of LCA results is always higher than coal. As a result, these sites have zero probability of being a suitable site for tidal energy to be a more sustainable alternative to fossil fuels even though they are considered a “hotspot” because these sites would not generate enough electricity to lower their life cycle climate change impacts.

3.4 Comparison to other tidal turbine LCA studies

The life cycle climate change impacts of electricity from tidal turbines in this study differ from the results of similar tidal energy systems LCAs. Previous LCAs state that the life cycle climate change impacts of electricity from tidal turbines range between 1.8 and 37 g CO_{2eq}/kWh.[4,9,10,11,12] The lowest baseline value from this study is 43.45 g CO_{2eq}/kWh. The geographic LCA case studies with the lowest life cycle climate change impacts, which are the East River, North Edisto, and Kagalaska Strait, have a cumulative probability of a life cycle climate change impact of 37 g CO_{2eq}/kWh or below of 19%, 6%, and 0.8%, respectively.

This study’s results reveal a much wider range compared to previous LCAs, due to it being the first study to accurately model the resource availability as it changes over time and by location. Other tidal energy LCA studies used the power rating along with the capacity factor of a turbine to determine the electricity generation at a site, and none of those studies extended their analysis to more than one location. This study models how the available resource of the tidal current changes over time by taking into account the duration of time during which the turbine will generate electricity based on the cut-in speed, and by utilizing site-specific tidal current velocity measurements. Some previous LCA studies modeled a tidal turbine that has more rotors than just one. This may help lower life cycle climate change impacts because the total swept area is increased by adding rotors, but a turbine with more rotors requires more infrastructure. If the rotors share some of the same infrastructure, this would help offset the additional GHG emissions from the added materials. Previous LCAs have lower GHG emissions over the turbine's lifetime in large part due to their assumptions. Uihlein (2016) assumed no materials were replaced during the maintenance process. He also did not account for any emissions during the removal process.[10] Each of these processes contributed to the total life cycle climate change impacts in this study. The maintenance process accounted for an average of 2% of the life cycle climate change impact, but the contribution to the impacts from this process reached a maximum of 9%. The removal process accounted for an average of 1% of the total impacts. The low result from Rule *et al*. (2009), 1.8 g CO_{2eq}/kWh, was also due to some of their assumptions, such as assuming a 100-year lifespan for a technology that is completely submerged in water and subject to corrosion and weathering.[12] Even if this study was adjusted to a 100-year lifetime, the results would still not account for all the differences and range of results from this study and from the literature. Rule *et al.* (2009) also did not include the construction and assembly processes of materials. The construction of the turbine blade and hub and fabrication of the turbine components contributed 8% ± 1.2% and 33% ± 4.9% to the total life cycle climate change impacts in this study, respectively. These low life cycle climate change impacts from Rule et al. (2009) and others have been cited and used to represent the life cycle climate change impacts of ocean energy in general in reports by the IPCC, NREL, and others.[12, 29]

3.5 Comparison to alternative LCA studies

The LCA literature on wind turbines reports that the life cycle climate change impact of electricity from wind turbines ranges from 1.7-81 g CO_{2eq}/kWh.[28] The tidal electricity LCA case studies for the East River, North Edisto, Kagalaska Strait, and Chugach Passage sites fit within this range of impacts. These sites are in three different states: New York, Alaska, and South Carolina. A harmonized LCA on electricity generated from natural gas technologies reports a mean climate change impact of 510 g CO_{2eq}/kWh.[13] Tidal energy LCA case studies in four different states – Western Passage (ME), Akutan Pass (AK), Little Tangaga Strait (AK), Grays Harbor (WA), Kennebeck River (ME), Coos Bay Entrance (OR), Meares Passage (AK), Admiralty Inlet (WA), and Bellingham Channel (WA) – show life cycle climate change impacts higher than those of electricity from wind turbines and just under the mean value of that of electricity from natural gas. Tidal electricity from turbines installed at the Humboldt Bay Entrance (CA), Hague Channel (AK), St. Marys River (GA/FL), and Carquinez Strait (CA) sites would have life cycle GHG emissions that fall between the harmonized LCA results on electricity natural gas and the mean harmonized LCA result of electricity from coal, 980 g CO_{2eq}/kWh.[14] This category also consists of sites in three different states. The case studies for Ogeechee River (GA), Unimak Pass (AK), Delaware Bay (NJ), Chugual Island (AK), Coosaw River (SC), and Sitkinak Strait (AK), which are tidal energy "hotspots" located in four different states, show climate change impacts worse than those of electricity from coal. The life cycle climate change impacts of the sites chosen as "hotspots" varies between being a suitable alternative to conventional energy sources and being comparative or even worse than fossil fuels. Differentiating between these categories requires consideration of the exact location of the tidal turbine. Determining if electricity from tidal turbines can lead to lower life cycle GHG emissions when replacing fossil fuels depends on the geographic location.

3.6 Implications for sustainable implementation of tidal turbines

Previous LCAs of tidal turbines have reported steel as the material used in the largest quantities in the infrastructure of the technology.[4,10,11] This study highlights how the production of steel is the leading contributor among the life cycle processes of a turbine to the life cycle climate change impacts and the need to choose a type of steel that emits fewer GHG emissions during production. The results of this LCA study indicate that processes in the beginning of a tidal turbine's lifetime, e.g. the production of its materials and components, contribute more to the climate change impacts than later processes, which include maintenance and end-of-life management. To reduce climate change impacts, changes in the production process of these materials or different choices in materials could lead to more significant reductions than changing the end-of-life management or installation and maintenance procedures. However, recycling materials helps offset some of the GHG emissions from earlier processes. This stresses the need to recycle as much material as possible during the end of life stage.

Unlike other LCA studies on tidal turbines, this LCA analyzed 23 sites reported as "hotspots" for tidal energy on U.S. coasts to investigate the effects of geographic specific parameters on life cycle climate change impacts. Previous studies only modeled the turbine in one location and did not consider how the carbon footprint of the technology changes based on the location installed. Site-specific parameters were determined to be influential, not due to transportation distances, but because of the unique current speeds in each location leading to differences in total electricity generation over the lifetime of a tidal turbine. The electricity generated affects the life cycle climate change impacts because the aggregated GHG emissions throughout the life cycle of the system are scaled to the amount of electricity generated. The tidal current characteristics are unique to each location and velocities cannot be extrapolated to nearby locations. The velocities of tidal currents differ among geographic locations and the topography in an area can amplify the speed. The optimal conditions for a fast current include areas with hydrodynamic resource characteristics of a restricted channel, tidal resonance, and differences in surface elevation.[31] The first commercial tidal project in the United States, the Cobscook Bay

Tidal Project, will be removed in 2022. The site's energy developer states that the current velocities are too low to feasibly continue with the project, which was installed in 2012.[32] With only a 10-year lifespan and inadequate velocities, these conditions substantially raise the life cycle GHG emissions of the electricity generated by a tidal energy project. If tidal turbines are to serve as an alternative to fossil fuels, the geographic location of the technology must be considered before a commercial scale project is deployed.

LCAs on bioenergy have become more geographically specific. Conditions such as the directional orientation of crops, precipitation rates, frost risk, and humidity differentiate among regions and impact the development of crops.[33] Transportation differences have also been found to affect the life cycle climate change impact of bioenergy.[34] While geographic specificity of LCAs for bioenergy is common, this is the first study for ocean energy that incorporates geographic factors to accurately model the resource available and that compares the life cycle climate change impacts by geographic region that an ocean energy technology would be deployed. The use of site-specific parameters in bioenergy LCAs improved the accuracy of results.[34] This study's results suggest the need for governments to set LCA standards that include site specific LCA analysis requirements for tidal energy projects. Without this, tidal energy could be deployed in an area to promote renewable energy and emit more GHG emissions than a coal power plant. Ocean energy has the potential to sustainably replace fossil fuels, but the life cycle climate change impacts of this mechanical energy source should not be extrapolated to different sites as they can significantly vary by location of installation. The message from this study not only applies to the United States, but also to the global resource potential of ocean energy. Once it is recognized that the carbon footprint of ocean energy changes based on the location, countries can plan to implement this technology in areas that would in practice show reduced life cycle GHG emissions compared to electricity from fossil fuels.

3.7 Limitations and opportunities for future development

The results of the sensitivity analysis show that the LCA results for all site-specific case studies are highly sensitive to the cradle-to-gate GHG emissions of steel production. The type of steel used throughout the construction of the tidal turbine may be different from the types represented in life cycle inventories, and there exists a range of values for the life cycle climate change impact associated with steel production.[35, 36, 4] The impact of steel production was thus modeled as a variable input parameter for sensitivity and uncertainty analyses. In practice, there may be differences in the maintenance and assembly processes, which were modeled in this study with informed assumptions. However, the maintenance and assembly processes together only contributed 2% ± 1.7% of the total life cycle climate change impacts of electricity from a tidal turbine. The hub of the turbine is also made of ductile cast iron, but a life cycle inventory for production of ductile cast iron was not available in the USLCI or Ecoinvent 3 databases. As a result, the model used the Ecoinvent 3 life cycle impact inventory for cast iron production as a proxy.

The peak velocity data used in this model is based on tidal current predictions from NOAA. Tidal current stations are characterized as either harmonic or subordinate stations. Harmonic stations use harmonic constants from that station to predict the current.[18] Harmonic constants are created from water level readings from that location and provide information on the amplitude for the equation used by NOAA for the tide-producing force.[37] NOAA can provide more services on the predictions of this station due to this information. Subordinate stations do not have tidal harmonic constants available. Predictions are then made from the timing and amplitude of high and low water from a reference station (a harmonic station) with similar tidal characteristics and adjusted to different times, heights, and qualities unique to that subordinate station. These stations can only accurately predict the speeds at times of maximum and slack currents.[18] Even though some information from a reference station is used to help predict the tidal currents at a subordinate station, the average error of these predictions which are provided by NOAA are taken into account with the minimum and maximum values used for the peak velocities in the sensitivity and Monte Carlo analysis.

The NOAA tidal current predictions also only account for changes in currents due to normal tidal changes. Predictions can also change based on meteorological forces.[30] This model does not include meteorological data such as wind speeds throughout the year and a more complex model would be needed to determine this in future work.

The siting of where NOAA deploys their instruments to assist in predictions depends on many factors besides the velocity of the current in that area. Deployment of survey stations are based on navigational requirements, communication and coordination with navigational community and local agencies, modeling and academic community, requests from tidal current prediction users, and availability or lack of historic predictions.[30] Data collected for Historic Prediction stations is determined by the location of a specific project. Some of these stations are chosen based on the current of a specific point such as a river entrance while other projects could be focused more on a region to understand the differences of the currents throughout that area. This requires multiple stations across the river or bay.[18,30] Due to the variety of selection processes, sites may have areas where the tidal current velocity is higher than the specific spot where NOAA measured the current velocity. Velocities at the installation location within that hotspot will make a difference to the total life cycle climate change impact. With this study, it’s even more important to properly site tidal turbines for their sustainability, even within the same hotspot if the velocities change in that area. These LCA case studies examine the associated GHG emissions of electricity from tidal turbines between point locations. Future research can extend it to an aerial analysis by examining the life cycle GHG emissions of electricity from tidal turbines within a site.

4. Conclusion

Tidal turbines are a viable technology to assist society in transitioning away from fossil fuels and towards renewable energy. However, it is important to consider the impacts of different geographic locations before this technology is implemented. This study demonstrated that conditions that vary geographically can substantially affect the overall life cycle climate change impact of electricity from tidal turbines. The East River (NY) shows the lowest baseline life cycle climate change impact from the 23 sites assessed. The carbon footprint of electricity generated at the Sitkinak Strait (AK), which shows the highest baseline life cycle climate change impact from the study, is 115 times that of electricity generated at the East River site. Even though the 23 assessed sites are considered optimal locations for tidal energy in the United States, electricity from tidal turbines can have life cycle climate change impacts that range from being comparable to those of renewable energy sources to being higher than those of electricity from fossil fuel sources, depending on their geographic location. Sites with a higher life cycle climate change impact do not generate enough electricity to scale the aggregated GHG emissions throughout a turbine’s life cycle sufficiently to produce LCA results within the range of those for other renewable electricity sources. Steel production contributed the most to the life cycle climate change impacts for each site, and the LCA results were particularly sensitive to the cradle-to-gate GHG emissions of steel production, followed by the turbine lifetime and turbine efficiency. The results of this study emphasize the need to use geographic specific parameters in ocean energy LCAs and provide information to optimize sustainable siting decisions for tidal turbines so that this technology may be a suitable alternative to conventional energy systems.

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Supplemental Information

1. Determination of geographically-specific LCA parameters

The variable input parameters in the model which changed based on geographic location are listed in the first column of Table S1. The values in Table SI are based on the life cycle assessment (LCA) case study for electricity from a tidal turbine in Akutan Pass, Alaska, and it is to serve as an example for the geographically specific variable parameters varied for each of the 23 case studies. There are approximately 1,411 individual peak velocity variables for each site (not shown in full in Table S1).

Table S1. Geographically specific variable parameters for Akutan Pass, including the first 10 peak velocities out of 1411 modeled.

Parameter name	**Minimum**	**Baseline**	**Maximum**	**Unit**
Cable mass	4492.8	5140.8	6156.0	kg cable/turbine
Distance to transport the rotor blade & hub to assemble site	5829.0	5887.3	5945.6	km
Distance to transport the turbine from land to installation by barge	1329.7	1343.0	1356.3	km
Peak Velocity 0001	1.8777049	2.006316	2.1349271	m/s
Peak Velocity 0002	0.4887169	0.617328	0.7459391	m/s
Peak Velocity 0003	1.5690409	1.697652	1.8262631	m/s
Peak Velocity 0004	1.4661529	1.594764	1.7233751	m/s
Peak Velocity 0005	2.0320369	2.160648	2.2892591	m/s
Peak Velocity 0006	0.5401609	0.668772	0.7973831	m/s
Peak Velocity 0007	1.4661529	1.594764	1.7233751	m/s
Peak Velocity 0008	1.5175969	1.646208	1.7748191	m/s
Peak Velocity 0009	2.1863689	2.31498	2.4435911	m/s
Peak Velocity 0010	0.5916049	0.720216	0.8488271	m/s

2. Extended methods

Methods and associated calculations for the processes modeled in this LCA of electricity from tidal turbines are described in further detail below.

2.1. Tidal turbine

The turbine in this study is modeled after the Verdant Power's Gen5 tidal turbine (Verdant Power, New York City, United States). This tidal turbine will be used in their Roosevelt Island Tidal Energy Project located in the East River in New York.[1] This tidal turbine was chosen because it is a horizontal-axial turbine, the most prominent tidal turbine design at the time.[2] This project also received a pilot commercial license from the Federal Energy Regulatory Commission, which means this turbine will be functioning at a commercial project.[1] Verdant Power plans to deploy a total of 30 turbines in the East River and had previous plans to expand in Washington state.[3] The Verdant Power Gen5 tidal turbine thus can represent the type of tidal turbine that would be considered for new installations in the United States. Therefore, it is important to know where to sustainably deploy this technology and to calculate the site-specific life cycle greenhouse gas emissions associated with the electricity that these turbines would produce.

2.2. Site selection

The 23 sites studied across 10 coastal U.S. states are displayed in Figures S1, Figure S2, Figure S3, and Figure S4.

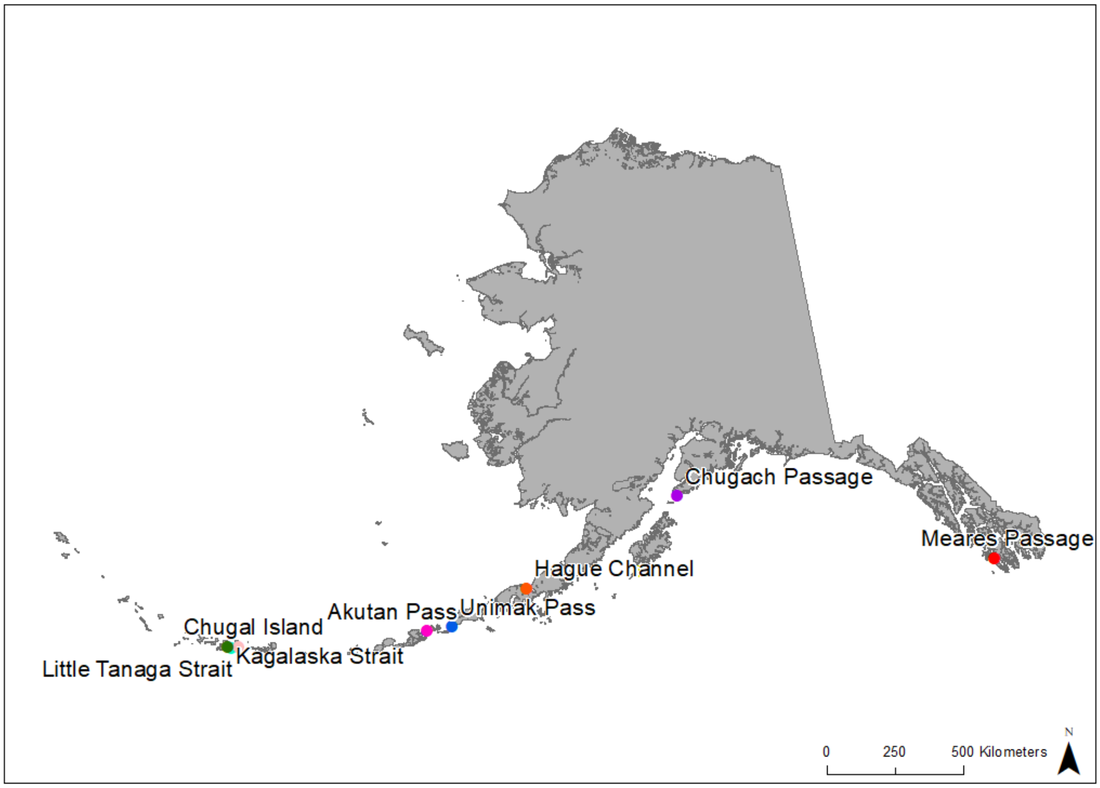

Figure S1: Hotspot sites chosen for this study in Alaska.

Figure S2: Hotspot sites chosen for this study on the West coast of the United States.

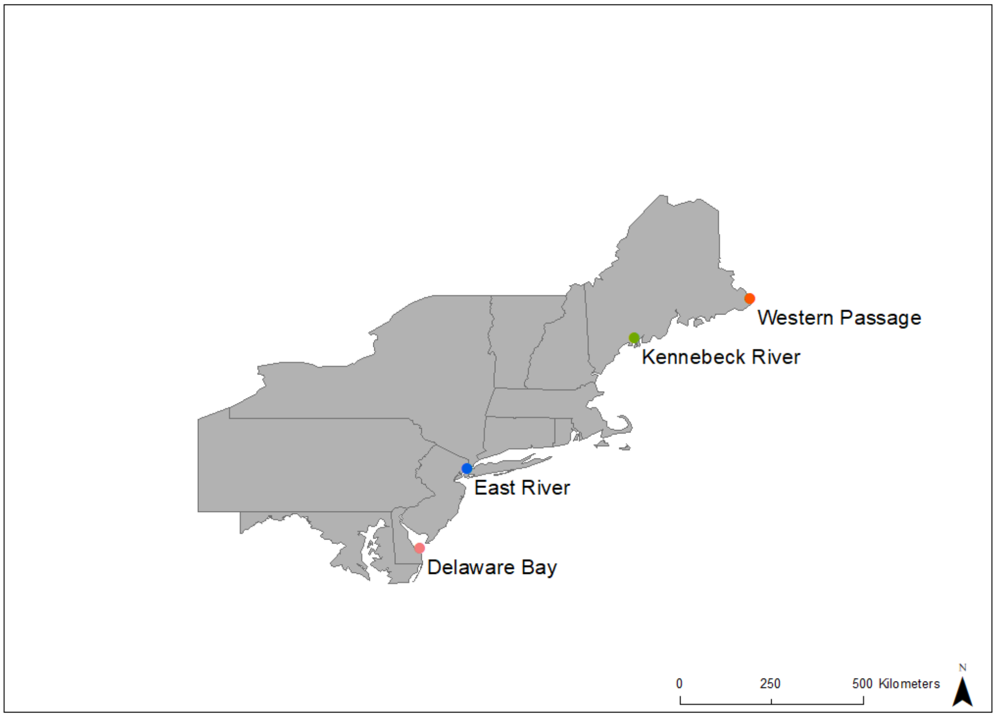

Figure S3: Hotspot sites chosen for this study in the North East of the United States.

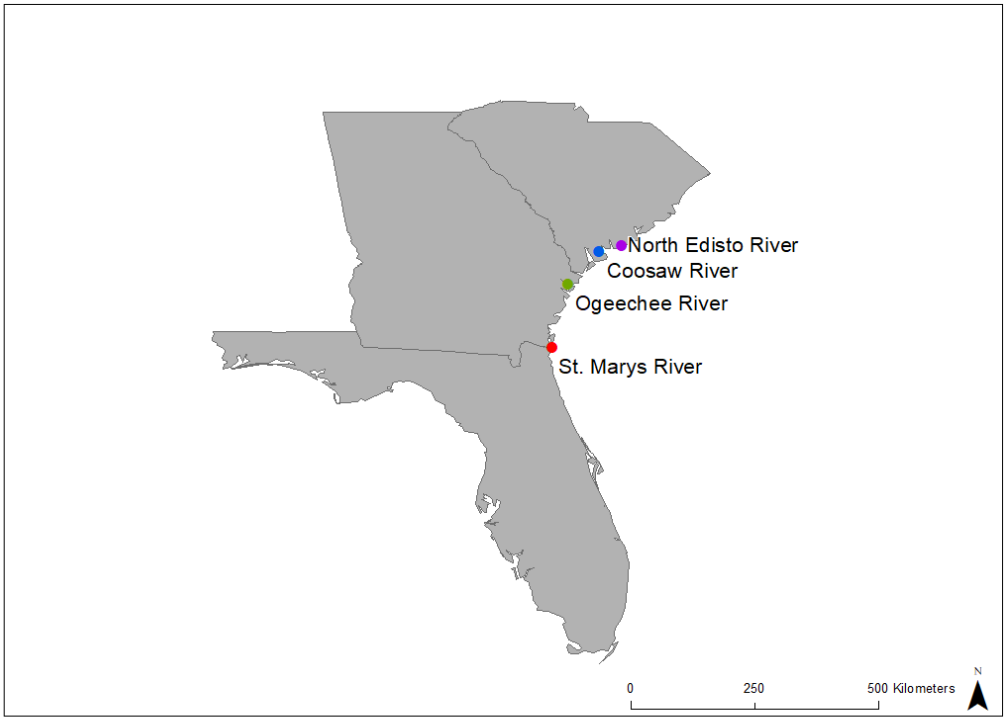

Figure S4: Hotspot sites chosen for this study in the South East of the United States.

2.3 Mass of the tidal turbine

2.3.1. Mass of cables

Electrical cables are included in the model, but the onshore electricity network is outside the scope of this research. LCAs completed on tidal turbines also include cables but do not include additional electricity components inside their system boundary.[7,8]The weight of 780-V power cables produced by Hydro Group (Aberdeen, United Kingdom), which designs cables for tidal turbines, is used. This is the closet cable produced by the company to the cable Verdant Power uses in the RITE Project, 480 V.[9] The weight is provided in kg/km; thus, it is multiplied by the distance of a modeled turbine to the closest land area at each site.

The distances are calculated by using the distance tool in ArcMap 10.5 and some are estimated using the scale bar on the NOAA Tides & Currents map.

2.3.2. Mass of the turbine foundation

Verdant Power plans to use a steel tri-frame as the foundation for the turbines.[10] The company provides a scale to measure the dimensions of the tri-frame and supporting base.[10] The measurement is provided in units of m^3 and multiplied by the density of steel, 7,850 kg/m^3.[11] This mass of the turbine foundation is added to the total mass of the tidal turbine.

2.3.3. Mass of individual materials

The materials modeled for the tidal turbine are steel, ductile cast iron, and composite fiber-reinforced plastic (FRP). These materials comprise the majority of the tidal turbine.[9] Uihlein (2016) provided percentages of each material that comprise the horizontal axial tidal turbine modeled in their study, thus this study used the same percentages of materials to represent the Verdant Power tidal turbine. As the given percentages of steel, plastics, and ductile cast iron summed to 63.6%,[8] the relative percentages of the composite FRP and ductile cast iron to this total are modeled for their composition in the entire turbine (6.98%/63.6% or 10.97% for the baseline percentage of composite FRP and 6.38%/63.6% or 10.03% for the baseline percentage of ductile cast iron). Steel is subsequently modeled for the remaining composition of the turbine, dependent on the fractions of composite FRP and ductile cast iron, which are varied for sensitivity and uncertainty analyses. The minimum and maximum values are selected by decreasing and increasing the value by 5%. The mass of each individual material is calculated in the LCA model by multiplying the total mass of the turbine including the foundation by the fraction of each material.[12]

2.4. Production of materials

The impacts from producing the materials are provided from life cycle inventories from Ecoinvent 3 and USLCI databases and using the life cycle impact assessment method EPA TRACI 2.0. For steel production, a range of impacts are used because there is a large difference between the values provided by different inventories in the Ecoinvent 3 and USLCI databases. Some LCAs on tidal turbines do not specify which type of steel they use, while the Seagen (Marine Current Turbine, Emersons Green, England) uses stainless steel. The climate change impact of stainless steel production used in the model for the Seagen LCA is 6.15 kg CO_2/kg.[7] This is a larger value than found in the databases which reinforces the need for a range of this value to account for the variation. Ecoinvent 3 provided all the values for the life cycle climate change impact of steel production. The minimum value modeled in this study is 1.89 kg CO_2/kg, which represents low-alloyed steel that has been hot-rolled in the Ecoinvent 3 database, and is in agreement with the World Steel Association's reporting that, on average, 1.8 kg of CO_2 is emitted per kg of steel.[13] The baseline value for the model is 2.27 kg CO_2/kg. This was chosen because it also represents the impact of producing low-alloyed steel from an Ecoinvent 3 inventory. This type of steel has resistance properties to atmospheric conditions which is needed for a turbine submerged in water.[14] The Department of Energy's Advanced Research Projects Agency's (ARPA-E) Metal Program Overview also states that the emissions rate of steel is 2.3 kg CO_2/kg.[15] The maximum value modeled is 4.2 kg CO_2/kg, which represents a chromium steel. Chromium makes stainless steel which provides corrosion resistance and is a type of steel used in manufacturing turbines.[16]

2.5. Transportation of materials to the manufacturing sites of the tidal turbine

It is assumed that the production of the materials and manufacturing would be located within the surrounding area, thus the following distances are used: 20 km, 60 km, and 100 km (Table 2). Transportation by truck was chosen as the most appropriate mode of transportation due to the materials being transported and the distances traveled.

2.6. Production of the turbine components

This modeled process represents the construction of parts such as the pylon and nacelle by steel metal working.[7,17]

2.7 Production of the rotor blades and hub

The rotor hub is comprised of ductile cast iron and the rotor blades are comprised of composite FRP.[9] The blades are formed through plastic molding.[18] It is assumed that the hub is formed by metal working.

2.8 Transportation to the assembly site

2.8.1. Transportation of turbine components

Besides the rotor blades and hub, the turbine components for the Verdant Power's RITE Project are produced in New York state.[19] It is thus assumed that these parts are also produced in the surrounding area of each installation site.

2.8.2. Transportation of rotor hub and blade

Verdant Power has a contract with Composite Builders in Grandville, MI to manufacture the rotor blades and hub.[20] This study uses this location for the manufacturing of the blades and hub for each site. Google Maps determined the distances from Grandville, MI to each assembly site. Google Maps provides three routes which are subsequently used to define the minimum, baseline, and maximum values for the distances in each case study.

2.9 Assembling the tidal turbine

In each LCA case study, the tidal turbine is assembled in a different location. The assembly site for each geographic location modeled is shown in Table S2.

Table S2. Location for assembling the tidal turbine.

Site name	**Land Assembly**
Akutan Pass	Anchorage, AK
Chugach Passage	Anchorage, AK
Chugul Island	Anchorage, AK
Hague Channel	Anchorage, AK
Kagalaska Strait	Anchorage, AK
Little Tanaga Strait	Anchorage, AK
Meares Passage	Seaward, AK
Sitkinak Strait	Anchorage, AK
Unimak Pass	Anchorage, AK
Carquinez Strait	Crockett, CA
Humboldt Bay Entrance	Loleta, CA
St. Marys River	Fernandina Beach, FL
Ogeechee River	Richmond Hill, GA
Western Passage	Perry, ME
Kennebeck River	Woolwich, ME
Delaware Bay	West Cape May, NJ
East River	Bayonne, NJ
Coos Bay Entrance	Coos Bay, OR
Coosaw River	Coosaw Island, SC
North Edisto	Seabrook Island, SC
Admiralty Inlet	Freeland, WA
Bellingham Channel	Bellingham, WA
Grays Harbor	Ocean Shores, WA

It is assumed that assembly of the tidal turbine would involve hand tools used by workers and cranes to move the parts of the turbine so that they could be attached. The crane is used to lift parts from a truck and move a part close to another component to which it is then attached.[21] It is also assumed that a crane will be used to put the entire turbine on a truck so that it can be transported to the barge. This study assumed that these actions require 10 minutes each. The baseline value for the time of use of the crane is then based on taking the turbine components off the truck, the hub and blades off the truck, attaching the nacelle to the pylon, attaching the blades and hub to the turbine, and picking the completed turbine up and into a truck. This results in a total of 50 minutes. The maximum and minimum values were defined by increasing and decreasing the baseline value by 10 minutes, respectively.

2.10 Transportation to the installation site

2.10.1 Transportation by truck

Once the turbine is assembled, it is transported by truck. From the assembly site at Bayonne, NJ for the tidal turbine being deployed in the East River, Verdant Power recorded that it traveled 2 miles (3.2 km).[18,19] This value is used as the baseline value. The minimum and maximum values are found by subtracting and adding half of the distance of the baseline value (1.6 km), respectively. These values are used for the transportation to the installation site by truck for each site because each assembly site is located near the coast just like the assembly location for the East River.

2.10.2 Transportation by barge

From the land, the tidal turbine is transported to the installation site by barge.[18]

2.11 Installation of the tidal turbine

Divers perform most of the installation process. The other portion is done by a crane.[18] It takes 2 days to install a turbine.[9] The entire installation will not involve a crane, thus the assumed baseline value for the time that a crane is utilized in installation is 6 hours (360 minutes). The assumed minimum value is 4 hours and 30 minutes (270 minutes), and the assumed maximum value is 9 hours (540 minutes).

2.12 Use and maintenance of the tidal turbine

2.12.1 Use of tidal turbine

During the use phase of the tidal turbine, it will generate electricity. This study used NOAA velocity data of the individual peak velocities throughout the year 2015 as input parameters to calculate the electricity generated over the turbine's lifetime based on the electricity generated during each ebb and flood of the tide by site. The year 2015 was chosen because when this study was conducted, NOAA provided past data for only the years 2016 and 2015. The year 2016 was a leap year, thus 2015 data represents a more typical year in the turbine's lifetime. Some sites had days with five to seven values for peak velocities instead of four. These additional values were removed from the raw data so that each day only included at the most four peak velocity values representing the two high and two low tides in a day. For the sensitivity and uncertainty analyses, a minimum and maximum peak velocity is defined for each entry. On average the NOAA tidal currents predictions have an error of ± 0.25 knots for harmonic stations and ± 0.5 knots for subordinate stations.[22] These errors are used to define the minimum and maximum peak velocities, depending on the type of station that NOAA labels on their website for each site.

2.12.2 Maintenance of tidal turbine

During maintenance, the turbine will not generate electricity; the total electricity generation during the lifetime of the turbine accounts for these maintenance intervals. The only information provided by Verdant Power on their maintenance process is that in its lifetime of 20 years, the maintenance interval is 3-5 years.[12] Therefore with a 3 year interval in 20 years, it is assumed there were 6 maintenance trips. With a 4 year interval, 5 maintenance trips occurred in the lifetime and 4 maintenance trips occurred when there is a 5 year interval.

To maintain the quality of the turbine, Verdant Power removes an entire turbine unit and replaces it with another one during maintenance.[3] The foundation and cables are not removed. The new turbine is taken by barge to the installation site. A crane is used to remove it and replace it. All services are performed off site, and the original tidal turbine is taken back to land by barge to be fixed.[3]

2.13 Removing the tidal turbine for disposal

It is assumed that the turbine is removed using similar methods to the installation process. The turbine is lifted out of the water by a crane.

2.14 Transportation of tidal turbine from the installation site to land for disposal

The tidal turbine is transported by barge to land for its final disposal.[18]

2.15 Transportation to disposal

2.15.1 Transportation to a recycling center

The hub of the tidal turbine and a fraction of the steel are transported by truck to the recycling center. Google Maps obtained the exact distances from a site to a nearby recycling center; these distances range from 13 to 100 km. The LCA results are not sensitive to this variable input parameter. The life cycle climate change impact increased by 0.013% when the distance to a recycling center was changed to its maximum value from the baseline value. When the distance to the recycling center changed to its minimum value, the life cycle climate change impact decreased by 0.0018% from the baseline result. Due to these results, this model assumed that the recycling center would be in the surrounding area. The minimum variable parameter value is set at 20 km, 60 km as the baseline value, and 100 km as the maximum value for all the sites.

2.15.2 Transportation to the landfill

The rotor blades, other turbine components, and cables are transported by truck to the landfill. Google Maps obtained the exact distances from a site to a nearby landfill; these distances range from 20 to 100 km. The LCA results are not sensitive to this variable input parameter. The life cycle climate change impact increased by 0.08% when the distance to a landfill was changed to its maximum value from the baseline value. When the distance to the recycling center was changed to its minimum value, the life cycle climate change impact decreased by 0.039% from the baseline result. Due to these results, this model assumed that the landfill would be in the surrounding area. The minimum variable parameter value is set at 20 km, 60 km as the baseline value, and 100 km as the maximum value for all the sites.

2.16 Recycling

The hub of the turbine is recycled. This information is provided from life cycle inventories from Ecoinvent 3, and using the EPA TRACI impact assessment method. Steel is also a recycled material in the model because a large portion of steel is recycled. There are varying accounts on the percentage of new steel that originates from recycling, thus a range was modeled for the percentage of the steel that is from recycled material. The U.S. Geological Survey (USGS) states that in 2014, 50% of steel was recycled.[23] The Steel Institute states that the recycling rate was 86%.[24] The baseline for the variable parameter for the fraction of steel recycled is the average between these two percentages, 68%.

2.17 Landfilling

The remaining parts of the turbine are landfilled. This information was provided from life cycle inventories from Ecoinvent 3.

3. Additional Baseline Results

Baseline life cycle climate change impacts for each LCA case study are shown in Figures S5, S6, S7, and S8. These graphs depict how much each process in the life cycle of electricity from a tidal turbine contributes to the total life cycle climate change impact.

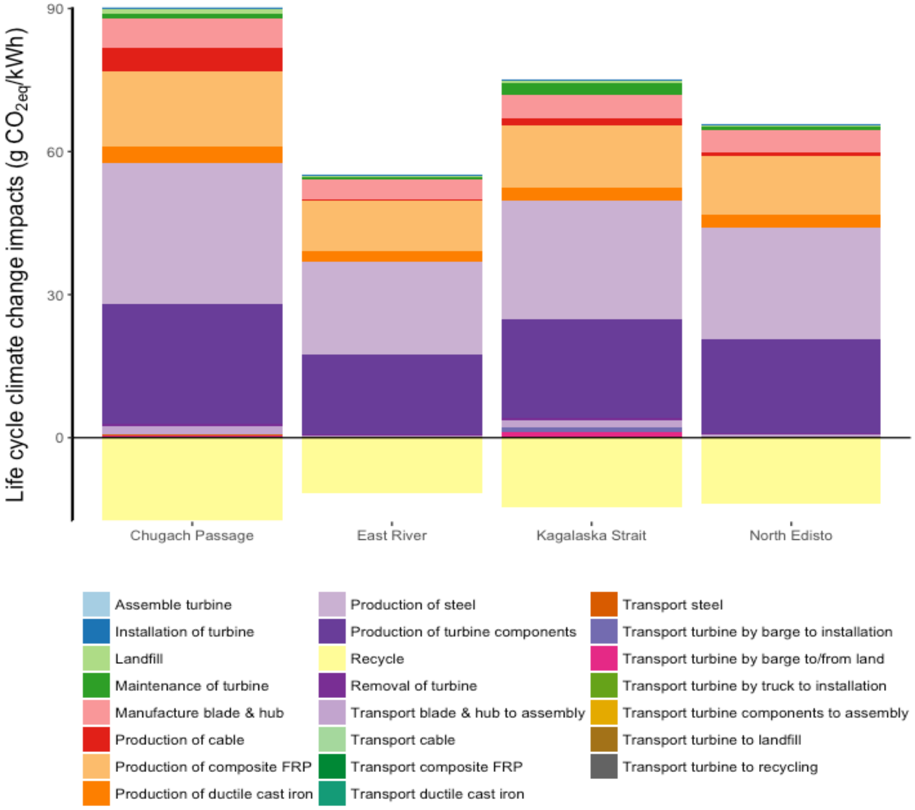

Figure S5. Baseline LCA results depicting the life cycle climate change impacts of electricity generated from tidal turbines for the site-specific case studies whose results are comparable to the life cycle climate change impacts of wind turbines (1.7 – 81 g CO_2/kWh).[25]

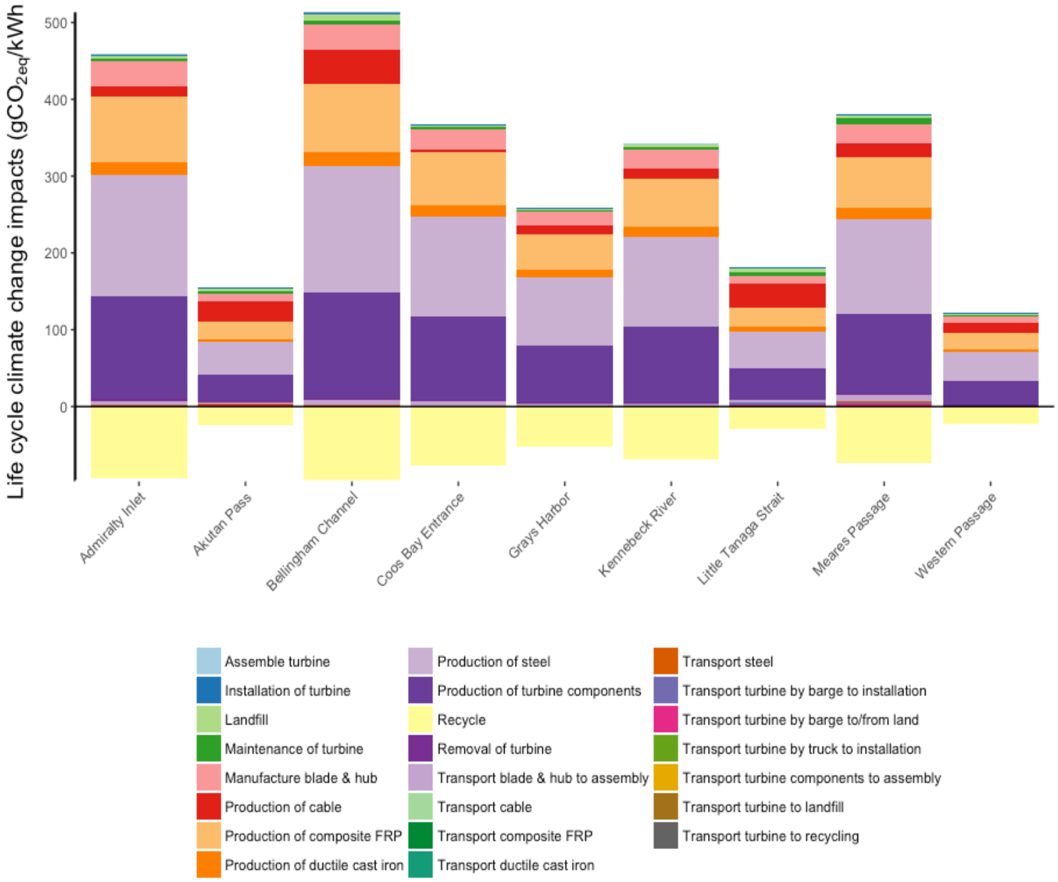

Figure S6. Baseline LCA results depicting the life cycle climate change impacts of electricity generated from tidal turbines for the site-specific case studies whose results are higher than those of wind turbines and/or comparable to the climate change impacts of natural gas (510 g CO_2/kWh).[26]

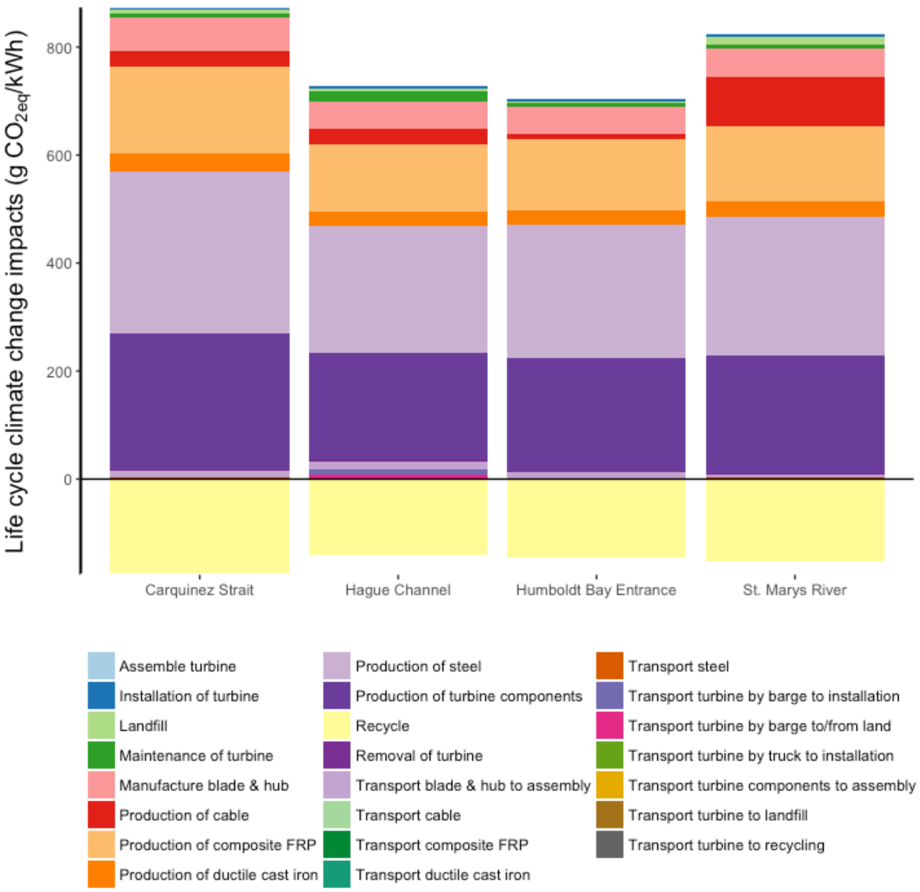

Figure S7. Baseline LCA results depicting the life cycle climate change impacts of electricity generated from tidal turbines for the site-specific case studies whose results are higher than those of natural gas and comparable to the climate change impacts of coal power plants (980 g CO_2/kWh).[27]

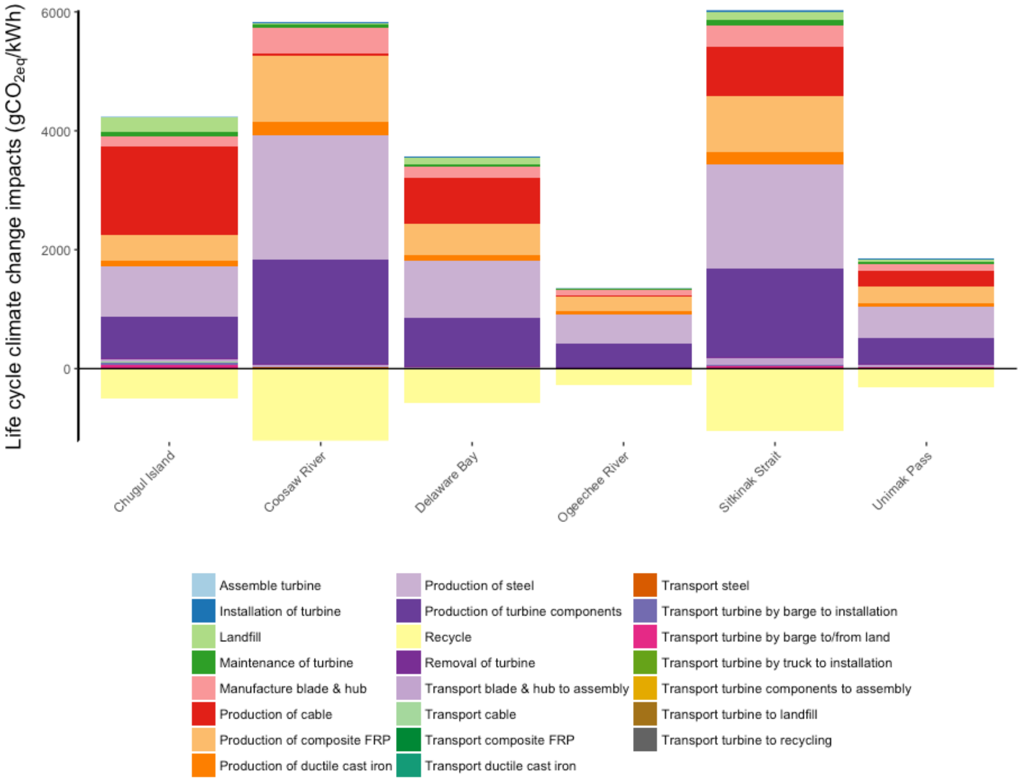

Figure S8. Baseline LCA results depicting the life cycle climate change impacts of electricity generated from tidal turbines for the site-specific case studies whose results are higher than the climate change impacts of coal power plants (980 g CO_2/kWh).[27]

4. Additional Sensitivity Results

The life cycle climate change impact of steel production is one of the most sensitive parameters for all the LCA case studies. The sensitivity of this parameter for each individual site is shown in Figure S9.

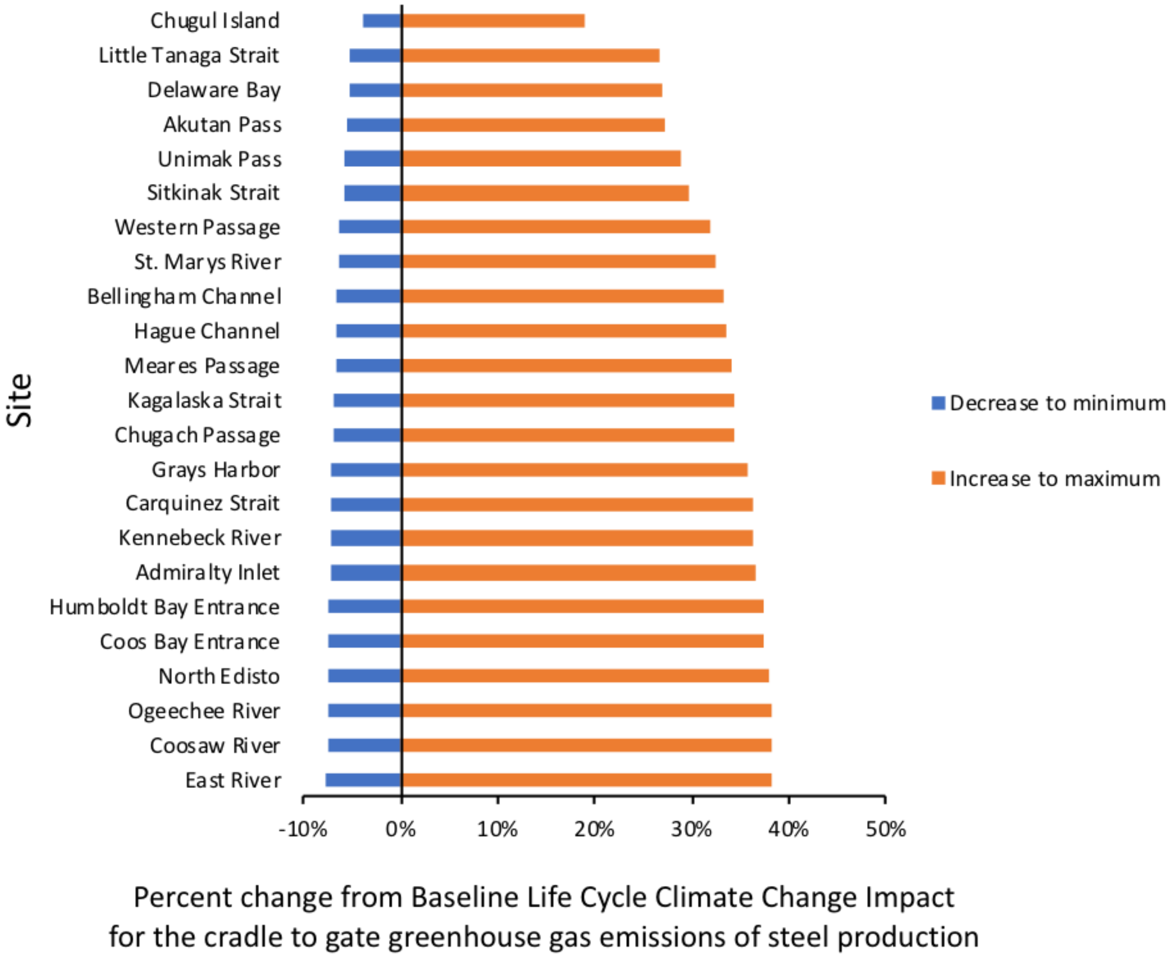

Figure S9. Sensitivity analysis graph on the influence of the life cycle climate change impact of producing steel.

Supplemental Information References

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Thesis Conclusion

Tidal turbines are a viable technology to assist society in transitioning away from fossil fuels and towards renewable energy. However, it is important to consider how the impacts may vary by different geographic location before this technology is implemented. The results of life cycle assessments (LCAs) of electricity from tidal turbines cannot be extrapolated from one site to another due to conditions that vary geographically. This study highlights the need to model site-specific parameters in LCAs of ocean energy technologies and provides information to optimize sustainable siting decisions for tidal turbines so that this technology may be a suitable alternative to conventional energy systems. This technology is still in the development stage, thus the results of this study can influence where the industry of ocean energy sites new installations. Developers may begin commercial installments in the United States in areas that have a lower life cycle impact to help minimize the climate change impact of ocean energy technology using these results.

Depending on the installation site, the life cycle climate change impacts of generating electricity from tidal turbines in “hotspots” could be higher than those of natural gas and coal. Determining if electricity from a tidal turbine would be associated with these high life cycle impacts depends on the location of the turbine due to the unique velocities at each site. The velocities of the tidal currents influence the amount of electricity generated over the lifetime of a turbine, and a high amount of electricity generation is needed to counterbalance the greenhouse gas emissions from the turbines’ infrastructure. The importance of differences in location does not apply to just a region but also within a state. One state can have a site with life cycle climate change impacts for tidal electricity that are comparable to a renewable energy source, natural gas, and a fossil fuel energy source, based on the exact location within the coast of the state. The processes earlier in the tidal turbine’s life cycle, including steel production and turbine component production, contributed the most to the aggregated greenhouse gas emissions. The life cycle climate change impact of steel production was a sensitive parameter for all sites. The large contribution of steel production to the total impact and the sensitivity of the results to the cradle-to-gate greenhouse gas emissions of steel indicate that variation in the amount of steel used to build the technology strongly affects the life cycle climate change impact of the tidal turbine. To reduce the life cycle climate change impact of electricity from tidal turbines, a longer lifetime and turbine higher efficiency of converting mechanical energy into electrical energy through this technology are also necessary. The probability distributions of LCA results obtained by site through Monte Carlo analyses show large ranges and that the distributions for some sites do not overlap across 10,000 simulations. Tidal turbines may serve as an alternative to conventional energy systems, as four out of the 23 sites assessed showed life cycle climate change impacts that are comparable to electricity from wind and solar sources and nine additional sites showed life cycle climate change impacts that are lower than those of electricity from natural gas. However, this is highly dependent on the location installed. Geographic factors have a large effect on these LCA results, which highlights the need to develop methodology that improves the geographic specificity of energy system LCAs.

Appendix A:

Literature Review

Climate change is a wicked problem. Greenhouse gases (GHGs) are a major contributor. From 1970 to 2011, 78% of the GHGs emitted were from carbon dioxide emissions due to fossil fuel combustion and industrial processes.[10] To reduce CO_2 emissions and mitigate climate change, a transition away from fossil fuels and towards renewable energy is required. Tidal energy is a renewable energy source that can help in this transition. Tidal energy generates electricity from two methods. The first method uses the rise and fall of the tides to generate electricity. This method was first deployed in 1966 as a tidal barrage in France. The second method uses the kinetic energy in tidal currents. A technology used to harness this kinetic energy is a tidal turbine.[11,12] Tidal barrages have a high capital cost and may cause environmental impacts associated with altering the flow regime in an area. The high capital cost is due to the large quantity of materials used in its construction and the length of a tidal barrage.[12] A barrage blocks the natural flow of the tide, causing erosion, nutrient built up, and increased sedimentation.[13] Tidal barrages need specific site characteristics such as a large basin which limits the global development of this technology.[1] Due to their massive size, they can also take years to install.[3] Therefore, there is more widespread potential for harnessing ocean energy through tidal turbines than tidal barrages.

Tidal energy is also a predictable and reliable form of renewable energy. The tides are caused by the movement of planets. The gravitational force of the Sun and moon on the Earth cause the tides to rise and fall. The gravitational and centrifugal forces of the moon-earth system create bulges of water on either side the earth. As a result, a high tide forms around land in line with the moon and Earth. A low tide forms around land that is at 90 degrees of the moon-earth system.[12] The angle of the Sun and moon aids in changing the intensity of the tide. When the Sun and moon are in line with the Earth, spring tides are caused, which show an increase in average tidal range. This happens during a new moon and full moon. Neap tides are created when the Sun and moon are 90 degrees from each other. During the third and fourth quarters of the moon cycle, neap tides cause a slight decrease in high tides and slight increase in low tides.[14] These forces make a cyclical pattern.

While the tides move up and down, they cause tidal currents. Tidal currents move the water back and forth from the shore. The horizontal movement of currents provides a moving fluid from which renewable energy technology extracts energy.[15] The current moving towards the shore is called the flood current, and ebb current is the current moving away from the shore. The period between the ebb and flood current when there is no movement of the water is called the slack period. The current happens in regular patterns and the tides occur every 12 hours and 25 minutes. During the day, there are approximately two high tides and two low tides, making the tides and currents very predictable.[14] A problem that most renewable energy sources face is that they are intermittent. The frequency of the wind changes irregularly and the sun can be blocked by clouds or smog. The characteristics of tidal currents allow the currents in the future to be predicted with data from past currents.[14] Therefore, the consistent cyclical pattern of tidal currents make tidal energy more predictable compared to other renewable energy sources.

While tidal currents are driven by gravity, the topography at a site can amplify the tidal current. The hydrodynamic conditions that are optimal for tidal energy extraction include restricted channels, tidal resonance, and differences in surface elevation. Restricted channels increase the speed of the tidal flow by funneling the water through a narrow section to a wider area.[16] Tidal resonance works best when one section is open where the water enters and the other is closed, pushing it back out the mouth of the river or bay. It occurs when a wave moves from the opening to the shoreline and then back out at the same time that the high and low tides are transitioning.[16] This occurrence amplifies the push of the wave and tides. An example of a tidal resonance is the Bay of Fundy in Canada. A hydraulic current is created in regions with different tidal ranges because of the pressure gradient from the drop in surface elevation.[16] These three conditions assist in accelerating the tidal current and increasing the suitability of harvesting energy from a site.

There are two main types of tidal turbines that generate energy from tidal currents. These tidal turbine technologies are axial-flow and cross-flow turbines. The most widely used tidal turbine is the axial-flow turbine. An axial-flow turbine rotates on an axis parallel to the flow of water. The device requires a yawning mechanism.[11] This allows the turbine to rotate and generate electricity from the incoming and outgoing tides. A cross-flow turbine can be vertical or horizontal. It rotates on an axis perpendicular to the flow of water. The vertical type of cross-flow turbine does not need a yawning device because it can generate electricity from flowing water in all directions.[11] This makes it a very suitable tidal energy technology. However, axial-flow turbines are widely used by developers and the most promising tidal current energy technologies.[1]

The tidal turbine technologies were influenced by the design of a wind turbine. They both function around the same concept by converting kinetic energy into mechanical energy, which is subsequently converted into electrical energy. A tidal turbine uses the kinetic energy from the movement of water to rotate the blades of the turbine to spin a generator to generate electrical power.[15] The variables for calculating the power of these renewable energy sources are also very similar. The density of water and velocity of the current is used for tidal power whereas the density of air and velocity of the wind is used for wind power. The most important variable for both calculations is still the velocity variable. The power generated is proportional to the velocity cubed.[17] Therefore, it is essential to take into account the velocity of the current for where the turbine is deployed.

Unlike a wind turbine, the fluid that spins a tidal turbine is much denser. The density of water is almost 1000 times more than the density of air.[11] As a result, the size of the tidal turbine is normally smaller than the size of a wind turbine and still has a comparable output. This technology can also be completely submerged in the water. This eliminates the problem of "not in my backyard" that wind turbines face.[11] Tidal turbines are out of sight which can help the implementation of this renewable energy technology.

Due to the environment in which tidal turbines are deployed, the infrastructure of the technology encounters many challenges. The materials used for tidal turbines need to be strong enough to withstand the force of water and not corrode. Steel is often used for tidal turbines. Its thickness is increased to help prevent corrosion.[18] The installation and some maintenance of the tidal turbine is under water, creating difficult working conditions. These steps must be completed during the short slack periods and require the use of boats to get to the deployment site.[12] These are some technical challenges, but the development of tidal turbines is advancing.

The first commercial prototype of a tidal turbine was the Seagen (Marine Current Turbines, Emersons Green, England). This 1.2-MW tidal turbine was deployed in May 2008 in Northern Ireland at Strangford Lough.[12] It consists of two axial flow turbines submerged in water connected to a steel tower structure above water that is connected to the seabed. The tidal current speed where the Seagen is deployed can reach above 3.5 m/s and has an average spring peak velocity of 2.5 m/s.[9] Taking into account maintenance schedules, the potential electrical energy generation of the tidal turbine is 4736 MWh/year.[9] The success of this technology promotes deployment of more tidal turbines in the United Kingdom.

In 2011, HS1000, a prototype horizontal axis tidal turbine, was installed at The European Marine Energy Centre testing site in Scotland waters.[12] The success of this device clinched the deployment of a project in the Sound of Islay on the west coast of Scotland. The project will consist of ten 1-MW HS1000 tidal turbines and generate approximately 30 GWh annually.[19] This project will assist Scotland in reaching their renewable energy generation target.

In the U.S., Verdant Power has been testing their tidal turbine technology since 2002, and from 2006-2009, the company tested six turbines in the East River in New York for their Roosevelt Island Tidal Energy Project. They are connected to the grid to power a nearby supermarket and parking garage. This project was for demonstration purposes only and not for commercial scale, but it delivered a total of 70 MWh of energy.[20] One reason for choosing the East River as the location was because of its average current speed of approximately 2.5 m/s.[14,20] These speeds make the East River a very appealing site for using tidal turbines.

In 2012, Verdant Power received a commercial license for tidal energy in the East River. There will be a total of 30 horizontal axis turbines that will collectively produce 1 MW of power. Verdant Power recently received funding to manufacture full-scale TriFrames, which mounts three tidal turbines on one platform.[22] The company is following through with the RITE Project while also looking to other areas to develop tidal energy projects, and other companies such as Atlantis Resources, EDF, and Marine Current Turbines, currently have pilot projects that will be in operation in the near future.[1]

While few tidal turbines have been implemented, this technology has a high potential. A report completed by the Georgia Tech Research Corporation and funded by the Office of Energy

Efficiency and Renewable Energy of the U.S. Department of Energy provides a list of suitable locations in the United States to deploy tidal turbines. These locations were considered suitable if they met the following criteria: a mean kinetic power density of 500 W/m^2, the surface area of the hotspot region is larger than 0.5 km^2, and a depth larger than 5 m. The mean kinetic power density is nearly a velocity of 1.0 m/s. This is necessary because most turbines have a cut-in speed to start generating electricity.[4] Throughout the United States, many states are suitable for this technology and have multiple areas along their coasts to deploy tidal turbines. The state with the highest number of suitable sites identified by this report is Alaska. Other states that have reported hotspots are Maine, Washington, Oregon, California, New Hampshire, Massachusetts, New York, New Jersey, North Carolina, South Carolina, Georgia, and Florida.[4]

As a renewable energy technology, tidal turbines produce no direct emissions of pollutants while generating electricity. However, this is only based on the use phase of the tidal turbine and not its entire life cycle. It is important to know the life cycle climate change impact of generating electricity from a tidal turbine to determine the relative benefit or harm of a transition away from fossil fuels and towards renewables. The life cycle climate change impact of electricity from a tidal turbine must be less than that of electricity from fossil fuels if it is to serve as a suitable alternative. Life cycle assessment (LCA) is a tool to quantify these impacts. LCA mathematically models all the phases of a product’s life cycle to measure the environmental impact of the product because even if the product does not directly emit GHGs or release waste during its use, the manufacturing, transportation, disposal, and other phases of its life can contribute environmental emissions. Each LCA contains four parts that meets the International Organization for Standardization (ISO) 14040 and 14044 standards: goal and scope definition, inventory analysis, impact assessment, and interpretation.[23] This framework provides all LCAs with a standard methodology to complete the study. LCAs with the same functional unit, which is a quantitative measure that describes the primary function of the product, are comparable, meaning that the life cycle climate change impacts of one product can be directly compared to the life cycle climate change impacts of another source, as they are quantified with the same units.[23] For example, product systems that produce electricity can be compared with other alternative product systems that produce electricity because both have the same function. An appropriate functional unit for these electricity LCAs is 1 kWh. In a LCA, all environmental impacts are scaled to the functional unit.[24] As a result, the environmental impacts of a tidal turbine are greatly influenced by the amount of electricity generated from the renewable energy source.

Published LCAs on electricity from tidal turbines report that the life cycle climate change impact ranges from 1.8 to 37 CO_{2eq}/kWh.[6,7,8,9] Douglas *et al.* modeled the Seagen in the Strangford Narrows in Northern Ireland. This cradle-to-grave LCA models a steel tower with two 16 m diameter axial flow rotors attached to it under the water. Steel is used for 88.8% of the device, mainly the tower, and the rotor blades are made of composite material. This turbine starts generating electricity when the velocity of the current is 0.7 m/s, and the rated speed for the area is 2.25 m/s.[9] The low cut-in speed and high current velocities allow for the turbine to generate electricity multiple hours a day. The functional unit used in this study is 1 kWh. The annual electrical energy produced from the turbine was calculated by using the flow conditions of the site and the Seagen’s power curve. This led to a total of 5038 MWh/year, or 4736 MWh/year when accounting for maintenance (reducing the time that the turbine can generate power by 6%). The Seagen has the capability to lift the rotors above the water for inspection and maintenance, which is done on a 6-month basis. Then, every 5 years during its 20-year lifetime, parts of the turbine are removed and serviced.[9] Thus, there is a long stretch between refurbishments, limiting the number of trips with added mass from the land to the installation site and vice versa, and lowering the number of times that maintenance is performed. In the installation process, a cargo ship and crane are used to install the turbine and a machine is used to drill a hole in the seabed for the tower to sit. During the removal process, 51% of the tower mass is left in the seabed. The top part of the tower and all other parts of the device are returned to the land for disposal.[9] However, the installed Seagen is still in operation and has not yet officially been disposed. The model assumes that 90% of steel parts (except for the bottom half of the tower), 95% of copper, 90% iron, and the cables are recycled. The plastics and composites are sent to the landfill. The total life cycle climate change impact of the Seagen is 15 g CO_2/kWh, with steel use as the main life cycle climate change impact factor.[9] The study also performs a sensitivity analysis by changing the values of some variables including recycling rate, manufacturing process, and material's cradle-to-gate GHG emissions. The life cycle climate change impact values from this analysis range from 10.1 g CO_2/kWh to 19.8 g CO_2/kWh, which is within 33% of the original value.[9] With these results, the Seagen has lower life cycle climate change impacts than some renewable energy sources and is comparable to other renewable energy sources.

Uihlein (2016) modeled multiple ocean technologies including a horizontal axis tidal turbine. The cradle-to-grave LCA aggregates the information of all 49 turbines studied in the model to define input parameter values rather than using the data from one particular device in an exact location. The functional unit is 1kWh of electricity delivered to the grid. The study calculated the electricity generated by using the power rating with a capacity factor of 34%. Steel is the material most used to construct the turbine. The model assumed stainless steel is used for all steel parts. The blades are made from composites. The lifetime of the turbine is 20 years.

During the installation process, the model used vessels and barges. If information was not provided, only 100 hours of maintenance a year was allocated to this process, and it was assumed that no parts were ever replaced during the lifetime of the turbine, in spite of the harsh underwater conditions.[6] The study also does not include any environmental impacts of the removal process before the end of life phase. In the disposal stage, 90% of steel and 95% of non-ferrous metals are recycled. The rest of the materials are sent to the landfill. The composite material is incinerated. With these assumptions, the total life cycle climate change impact is 23.1 g CO_{2eq}/kWh. The moorings and foundation contributed the most to the life cycle GHG emissions. The study performed a sensitivity analysis to show improvements in the climate change impact by using cold-rolled coil steel, increasing the lifetime to 30 years, increasing the capacity factor to 45%, and moving the device further offshore. All changes except for the transportation distance lowered the life cycle climate change impact.[6] This study already has a low environmental impact that makes electricity from tidal turbines a suitable alternative to electricity from fossil fuel sources, and using their best-case scenarios, the impact is better than other studied renewable energy sources.

Douziech *et al.* (2016) modeled cradle-to-grave LCAs of ocean technologies including three tidal turbines: the Seagen (Ireland), HS1000 (Scotland), and Hydra Tidal (Norway). The study stated that the power output for the Seagen, HS1000, and Hydra Tidal is 1200 kW, 1000 kW, and1500 kW, respectively. The power rating for each device is used to calculate the electricity generated over the tidal turbine’s lifetime with efficiencies of 44%, 40%, and 38%, respectively. The materials used for all the turbines are similar. Steel is the most used material and all anchoring structures are made from it. The two types of steel used are unalloyed steel and low alloyed steel. The Seagen is the only device that used low alloyed steel. The biggest difference between the turbines is the material comprising the rotor blades; the Seagen and HS1000 use composite while the eight blades of the Hydra Tidal are comprised of wood. Maintenance occurs every 5 years for each device in their 25-year lifetime.[8] Each maintenance process differs slightly by tidal turbine, but no process requires complete removal for service. The HS1000 maintenance requires removal of the nacelle and the Hydra Tidal maintenance requires removal of all eight blades. After their lifetime, the devices are removed by a barge and taken to land. For the end of life stage, 90% of steel is recycled but environmental impact benefits are only incurred for the unalloyed steel recycling. Also, 90% of cast iron and aluminum, and 95% of brass is recycled. Only 10% of composites are landfilled, and 90% enter municipal solid waste incineration. Other materials such as nylon, synthetic rubber, and plastics are also incinerated. The life cycle climate change impact resulted in 25.5 g CO_{2eq}/kWh, 37 g CO_{2eq}/kWh, and 20.1 g CO_{2eq}/kWh for the Seagen, HS1000, and Hydra Tidal, respectively. The study assumed a lower lifetime, power output, and recycling rate in their sensitivity analysis. They assumed a higher transport distance and material input to the steel and metal product manufacturing process. Another scenario switched the electricity used throughout the study to the Union for the Coordination of Transmission of Electricity.[8] There was also a set of scenarios performed only on the Hydra Tidal model which analyzed the influence of wooden blades. One LCA scenario called for half of the blades to be replaced. Another scenario switched the blades with composites. The results show that tidal energy devices should aim for a longer lifetime, higher power output, and more recycling. The transportation difference was insignificant but the electricity mix was influential. Finally, wooden blades should be considered when designing the turbine because it can help lower the climate change impact.

Rule *et al*. (2009) completed a comparative cradle-to-grave LCA by modeling a wind turbine, hydroelectric dam, geothermal power station, and tidal turbine. The tidal turbine model is for a proposed project of 200 turbines in the Kalpara Harbour in New Zealand. The predicted power rating of the entire project is 77 MW with a capacity factor of 37%. It is assumed that the turbine will generate electricity 16 hours per day. The tidal turbine is composed of materials such as steel, aluminum, and copper. The manufacturing of materials is included in the model, but the assembly and construction processes for parts of the turbine such as welding are not included. During a 100-year lifetime, maintenance is planned to only occur for one week every four years. The entire turbine is modeled to be removed for service.[7] Compared to the assumptions of other tidal electricity LCA models, this assumes relatively low maintenance needs for a turbine with an expected lifetime of 100 years under harsh conditions. For the disposal phase, 50% of steel is recycled and 100% of the other materials are sent to the landfill. There was no sensitivity analysis performed. The life cycle climate change impact resulted in 1.8 g CO_{2eq}/kWh. This is the lowest impact value in literature, and this value is cited for the life cycle climate change impact of ocean energy by the NREL and IPCC.[25] If the impacts are scaled to a lifetime of 25 years instead of 100 years, this total life cycle climate change impact is still lower than those calculated in other tidal electricity LCAs.

Expanding from previous LCAs on electricity from tidal turbines, this is the first study to examine how the life cycle climate change impacts of electricity from a tidal turbine change between different sites where the technology is deployed. This cradle-to-grave LCA analyzes 23 sites considered hotspots for tidal energy in 10 coastal U.S. states. A model was developed to compare the GHG emissions of electricity from a horizontal axis tidal turbine using modeled tidal velocities based on the physics of tides and velocities of each peak in the ebb and flood in the year 2015 from NOAA for each site. This data assists in calculating the electricity generated from the turbine and determining differences in power generation across sites. This geographically specific LCA is novel for LCAs of mechanical energy systems. Previous ocean energy LCAs are not geographically specific and do not model resource availability as it changes over time. Tidal turbines are being deployed and geographic specific LCAs are needed to inform where to sustainably install the technology.

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Appendix B:

Additional Graphs

1. Additional sensitivity graphs

A sensitivity analysis was performed on each LCA case study. The top three most sensitive parameters are the same for every site (lifetime of the turbine, life cycle climate change impact of steel production, turbine efficiency), but then the relative sensitivity of parameters varies between sites. The sensitivity of the parameters for each site are shown in the graphs below, but the approximate 1,411 peak velocity parameters are excluded. They are not a sensitive parameter at any site because the sensitivity analysis only changes one peak velocity parameter at a time. The percent change in life cycle climate change impacts when the peak velocity parameters are individually changed from their baseline to their maximum or minimum values was miniscule and in some cases 0%. This is due to the turbine’s cut-in-speed of 1.0 m/s and the conditional statements included in the model. The LCI impact of steel production labeled in Figure B1-B23 refers to the varied life cycle inventories selected to represent the life cycle climate change impact values for steel production in the model.

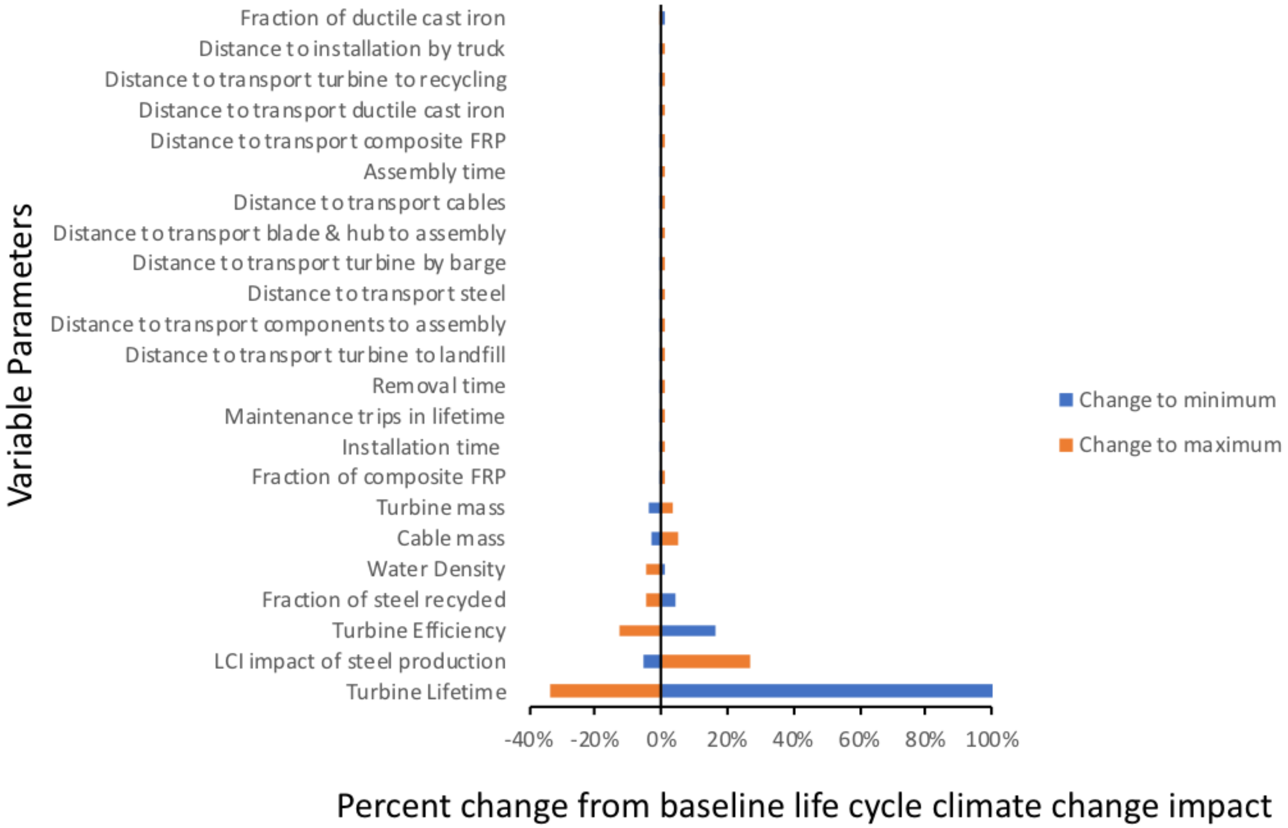

Figure B1. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Akutan Pass.

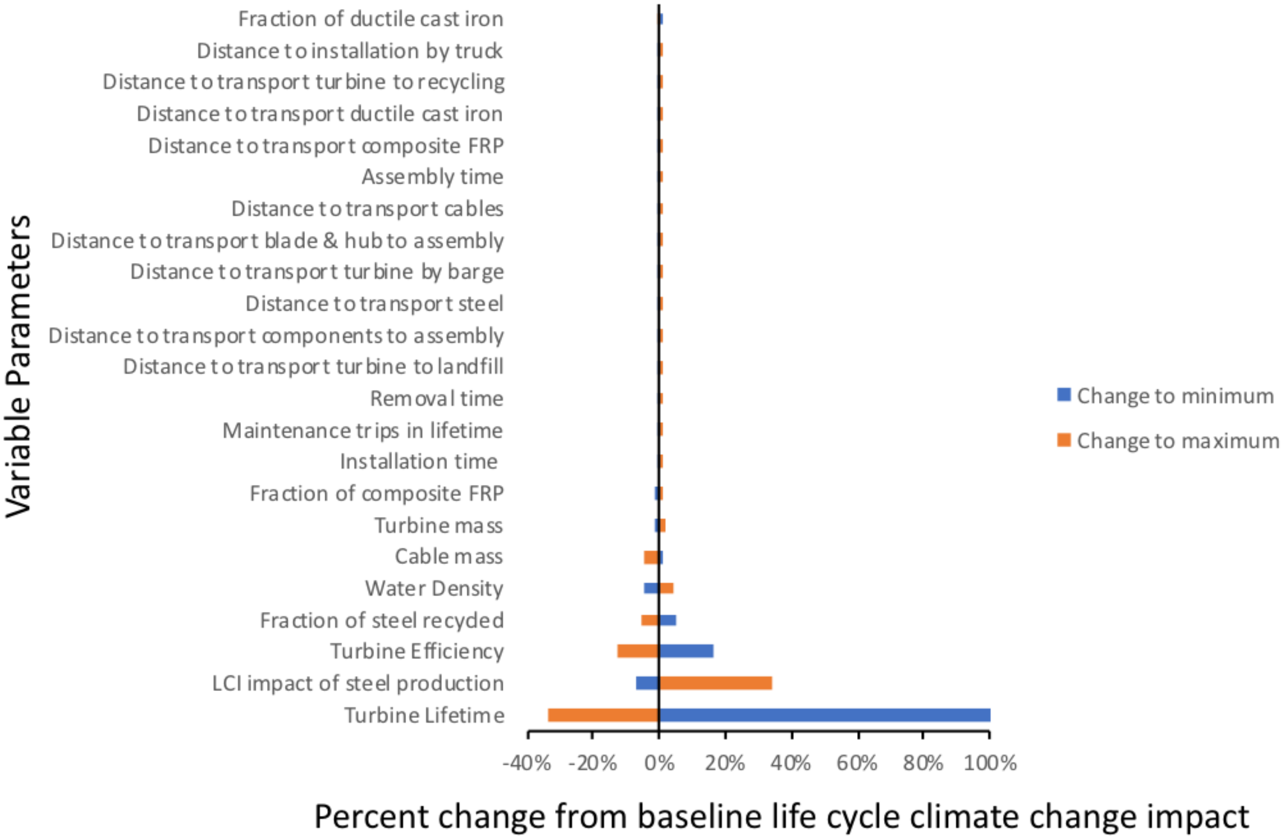

Figure B2. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Chugach Passage.

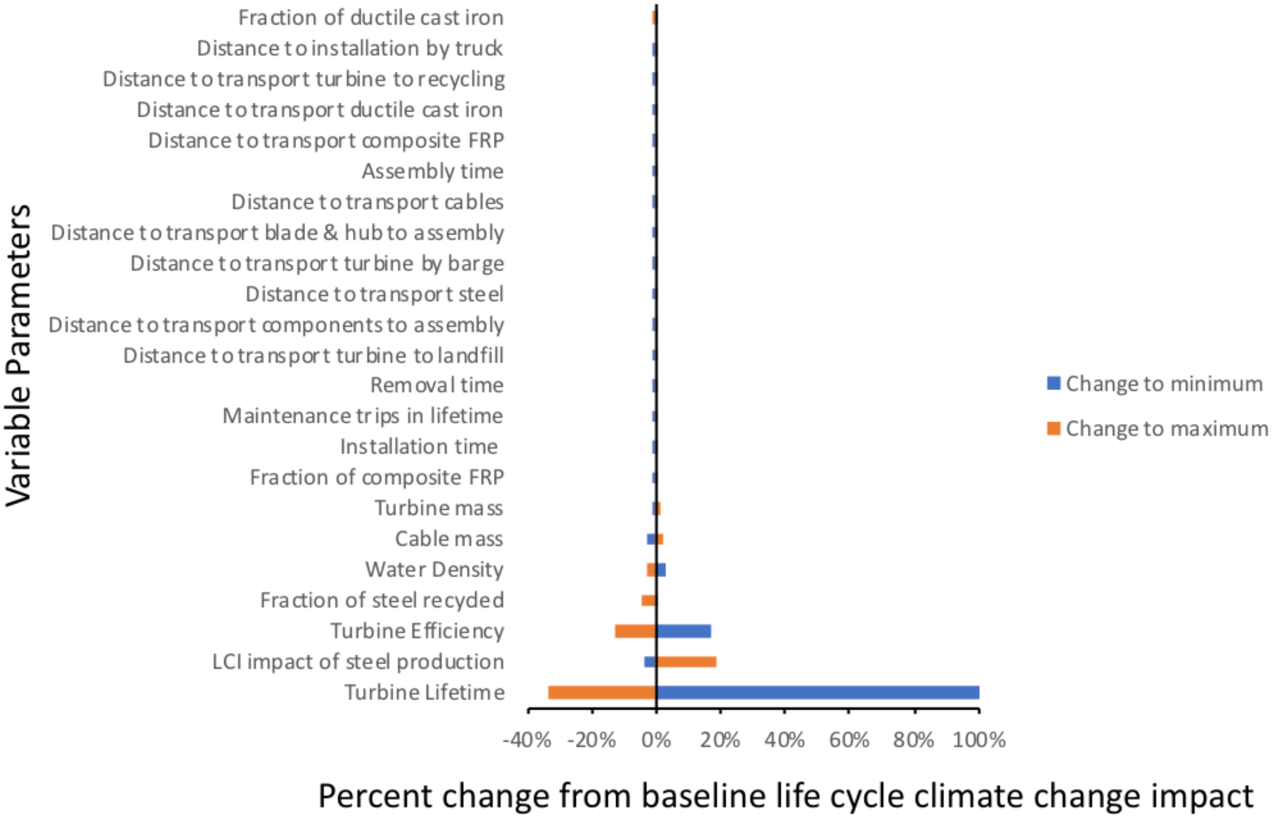

Figure B3. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Chugul Island.

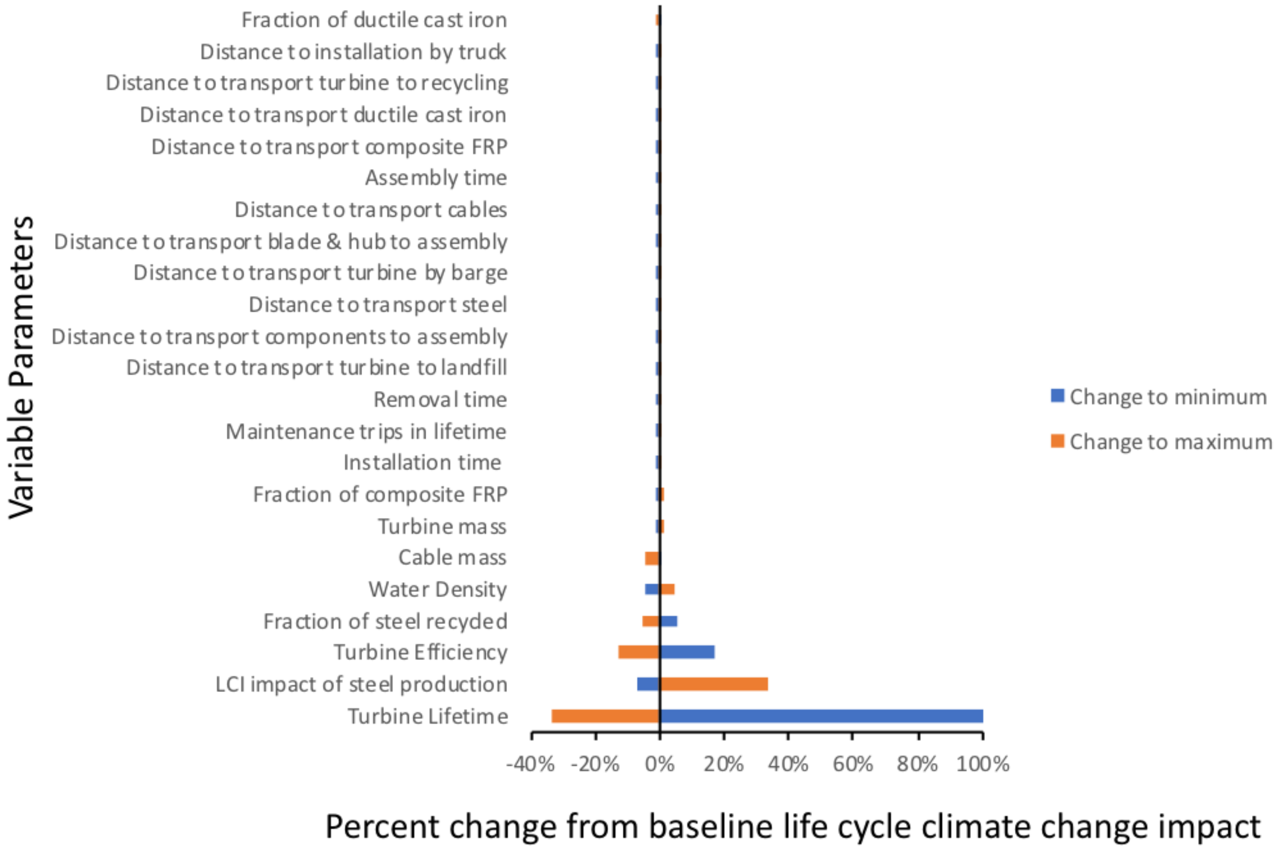

Figure B4. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Hague Channel.

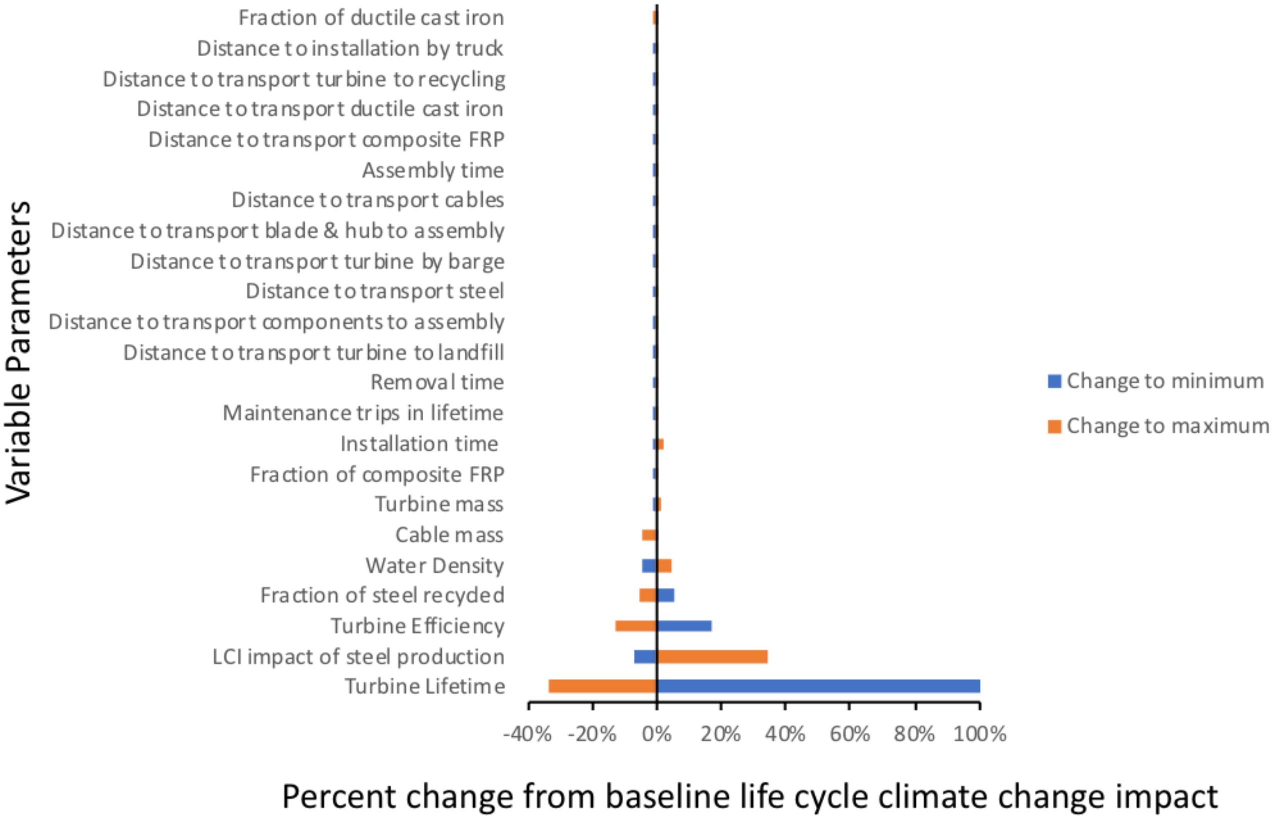

Figure B5. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Kagalaska Strait.

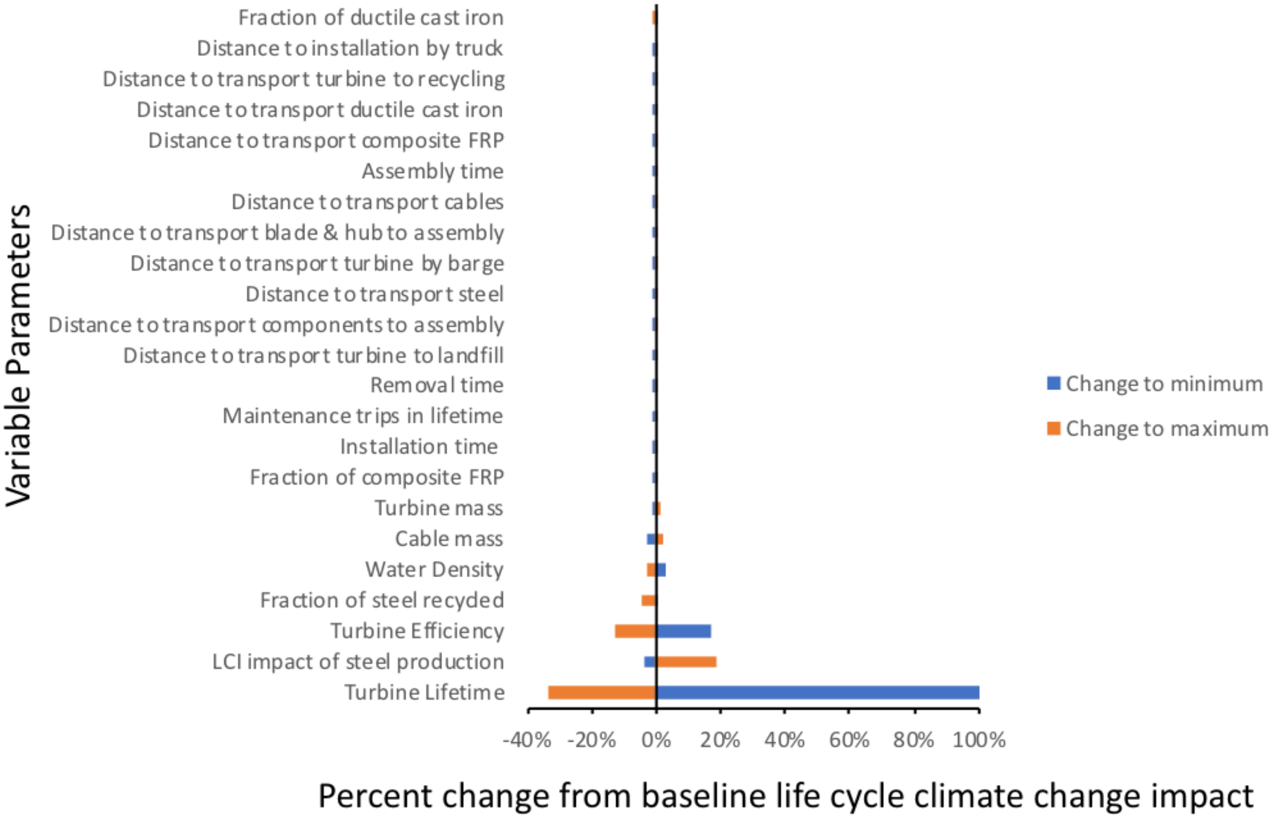

Figure B6. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Little Tanaga Strait.

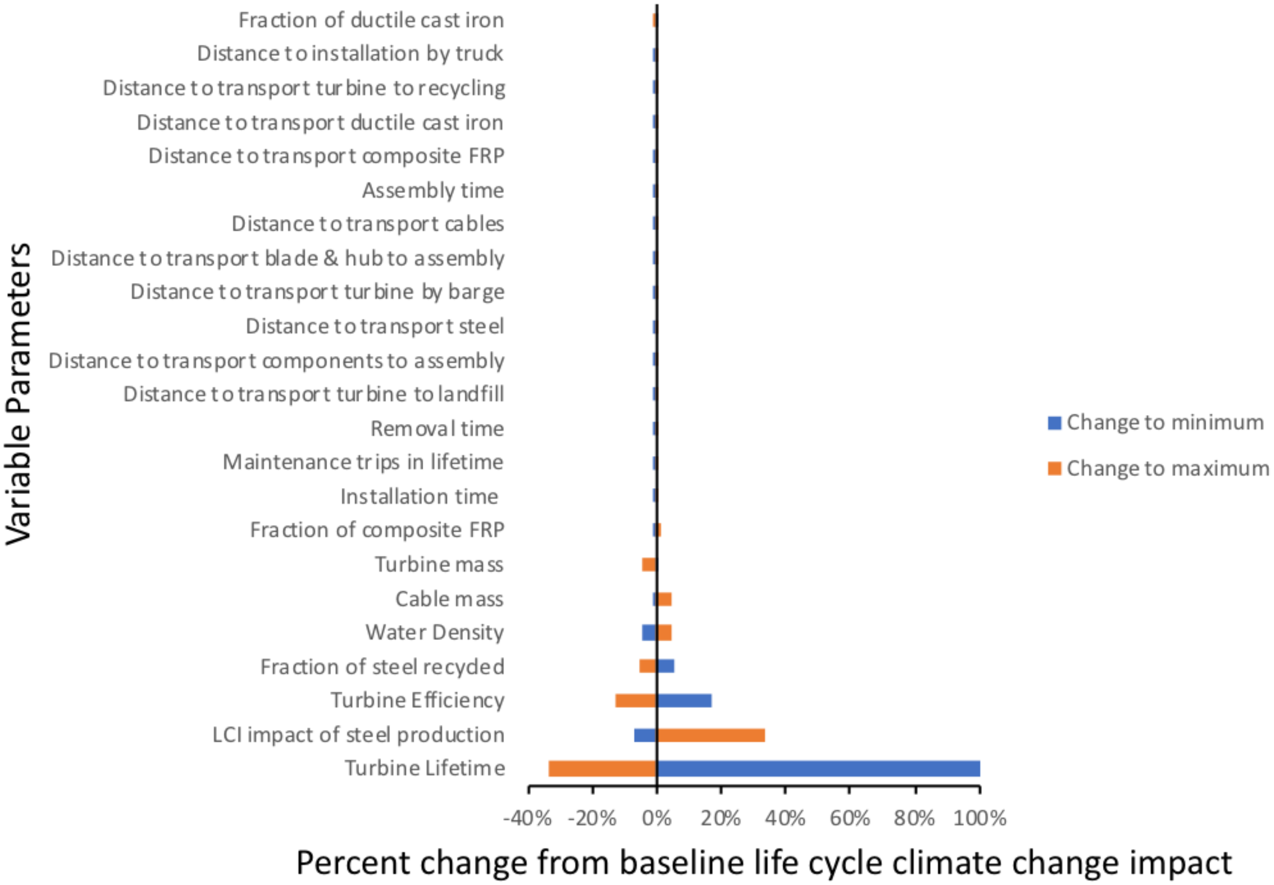

Figure B7. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Meares Passage.

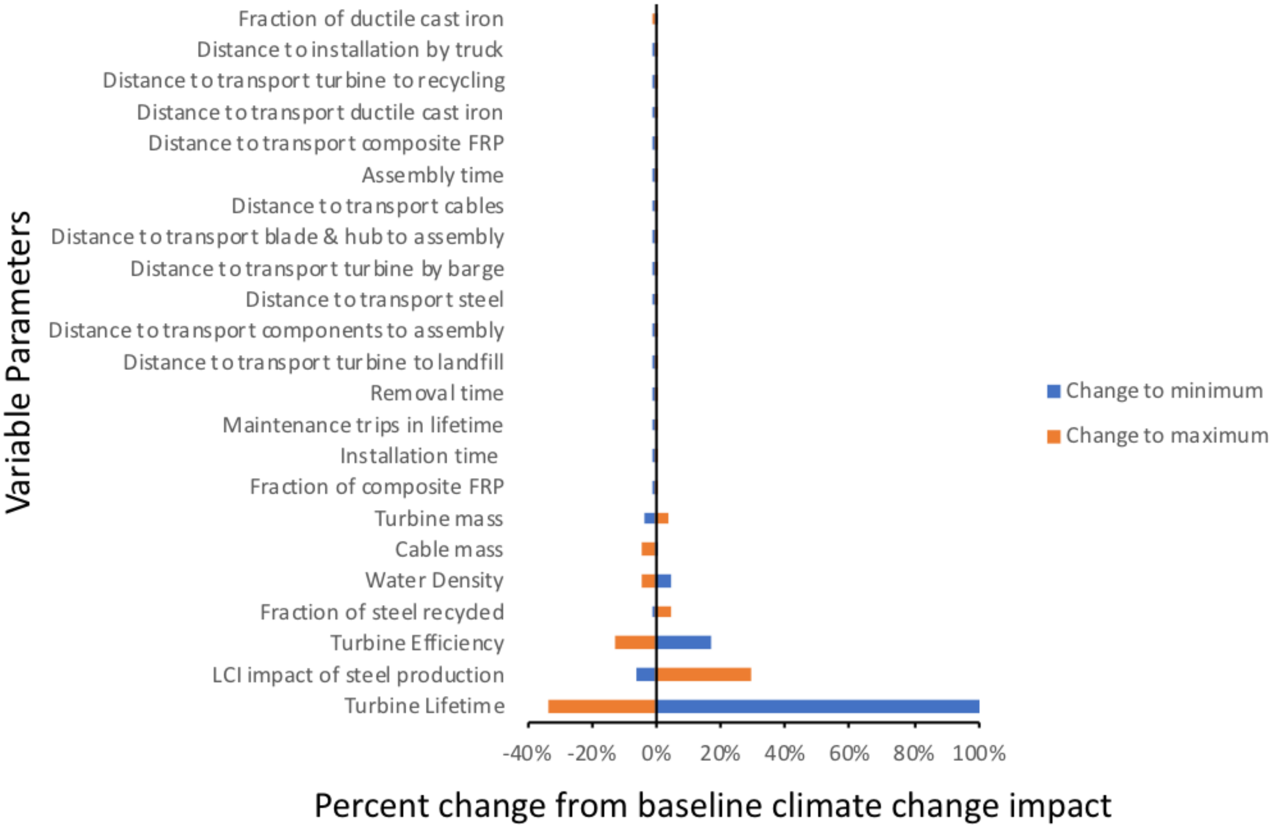

Figure B8. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Sitkinak Strait.

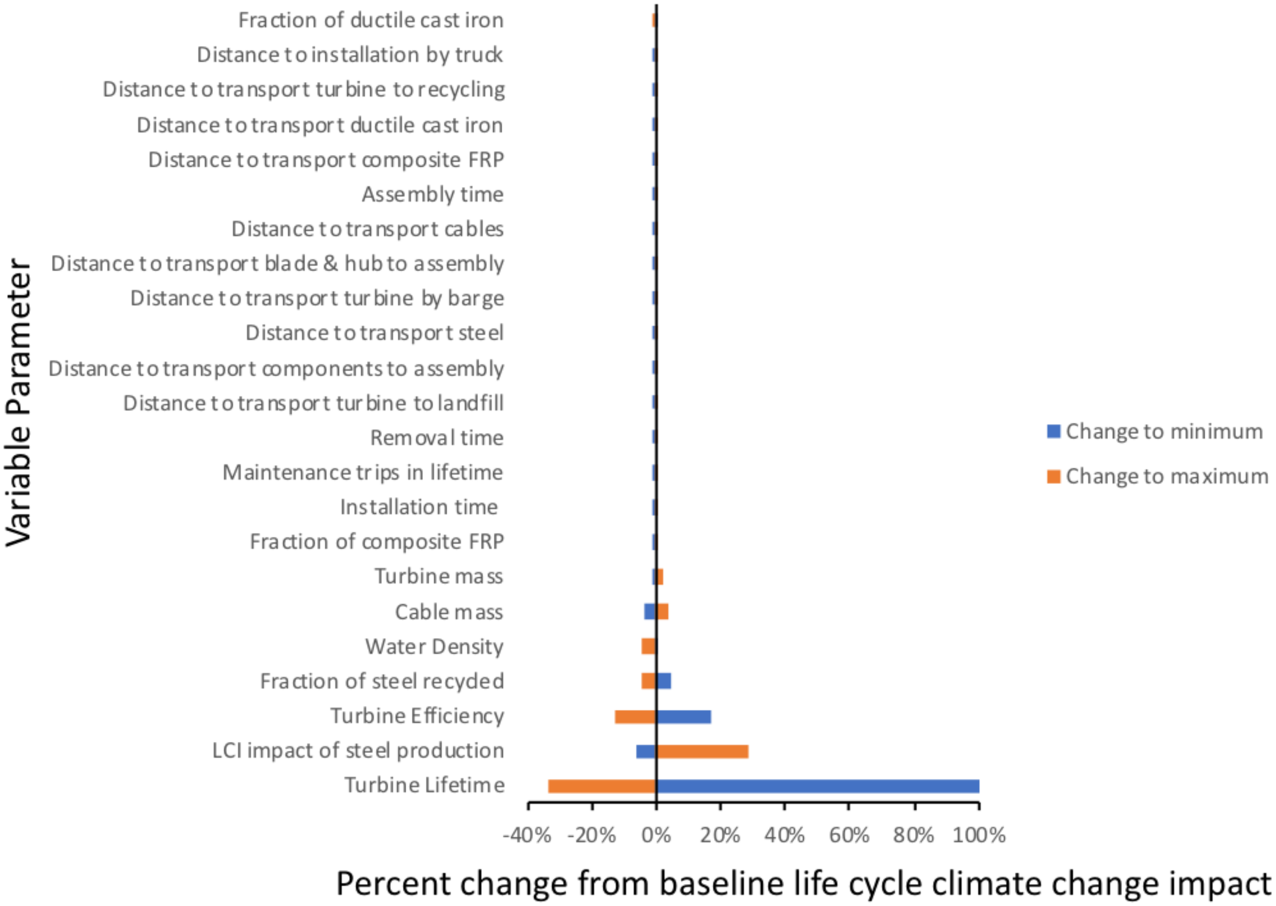

Figure B9. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Unimak Pass.

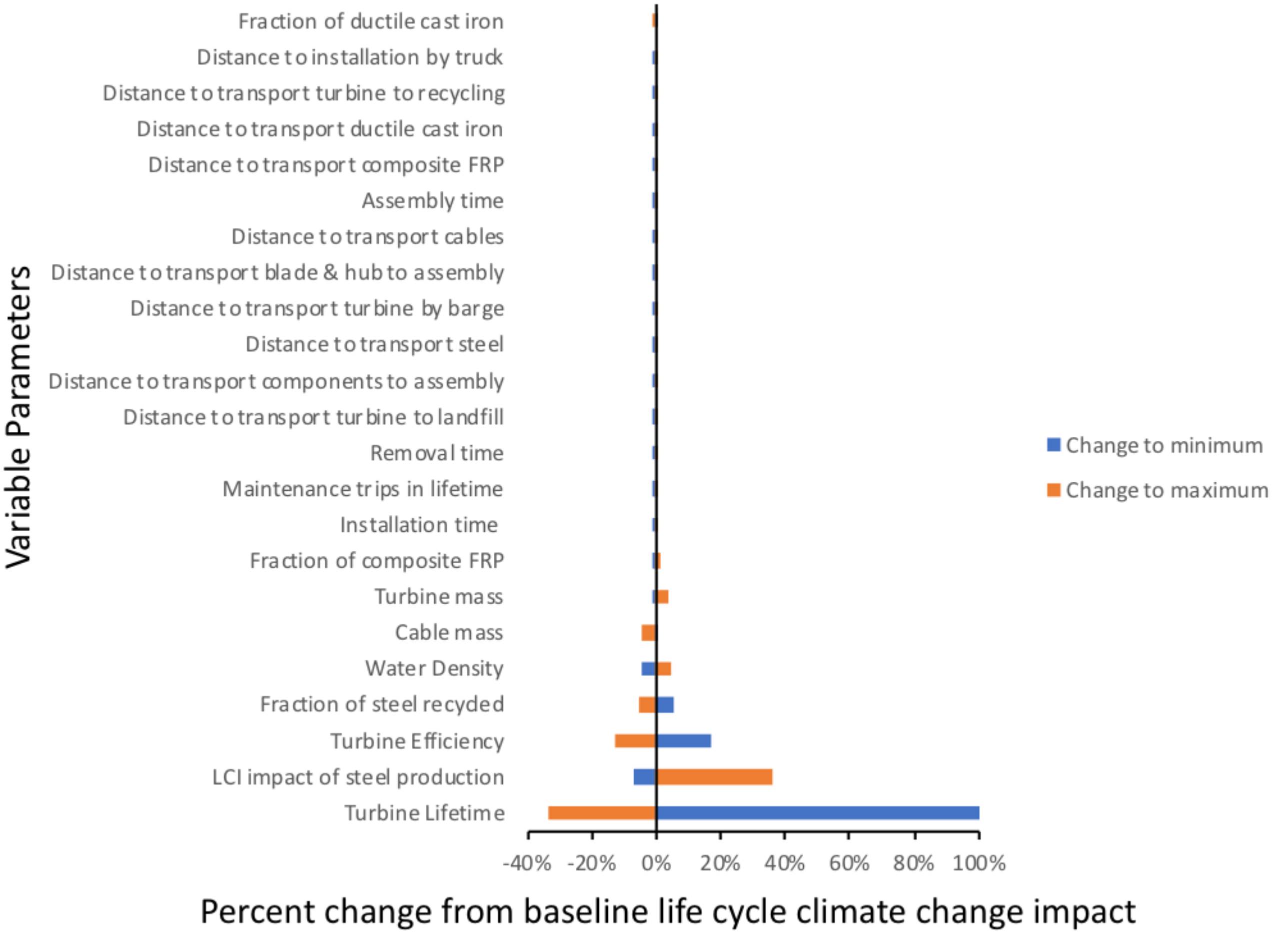

Figure B10. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Carquinez Strait.

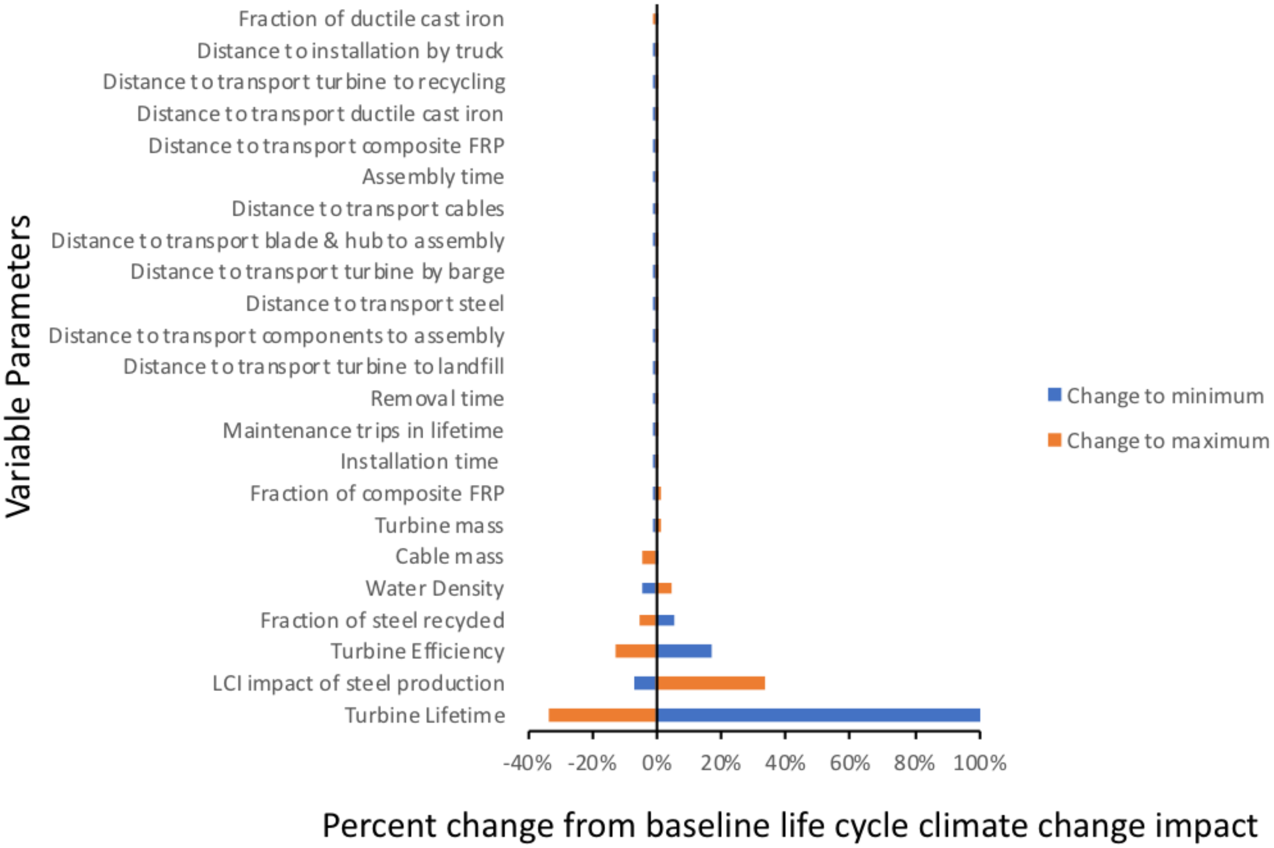

Figure B11. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Humboldt Bay Entrance.

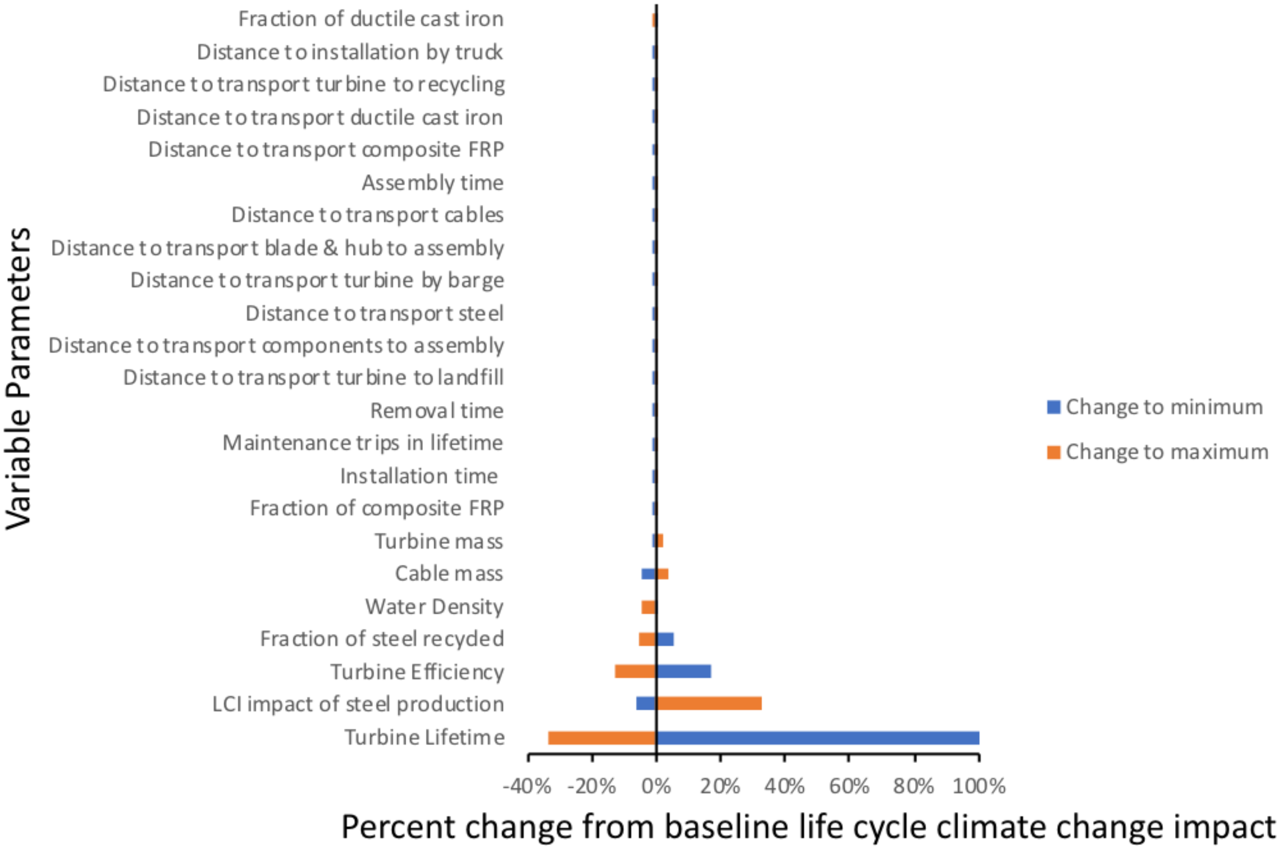

Figure B12. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the St. Marys River.

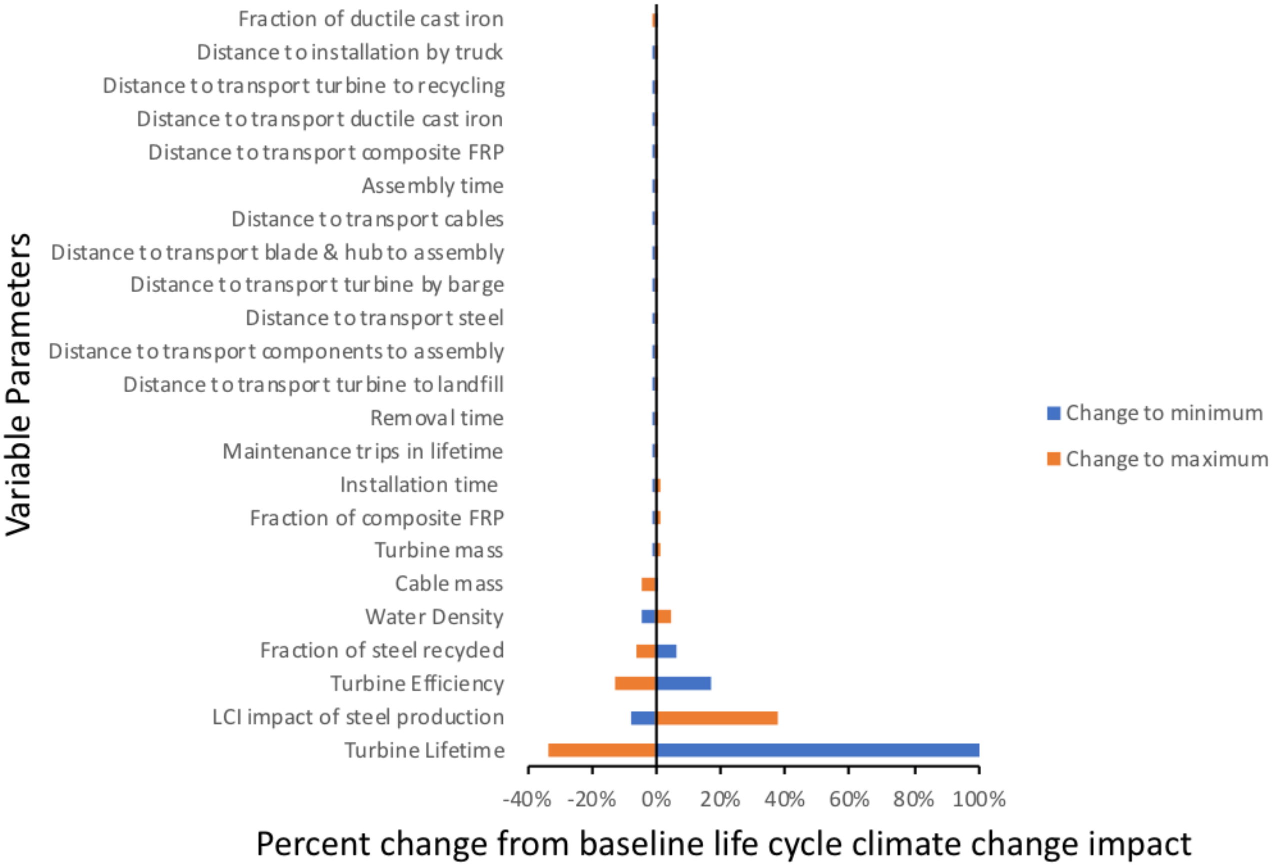

Figure B13. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Ogeechee River.

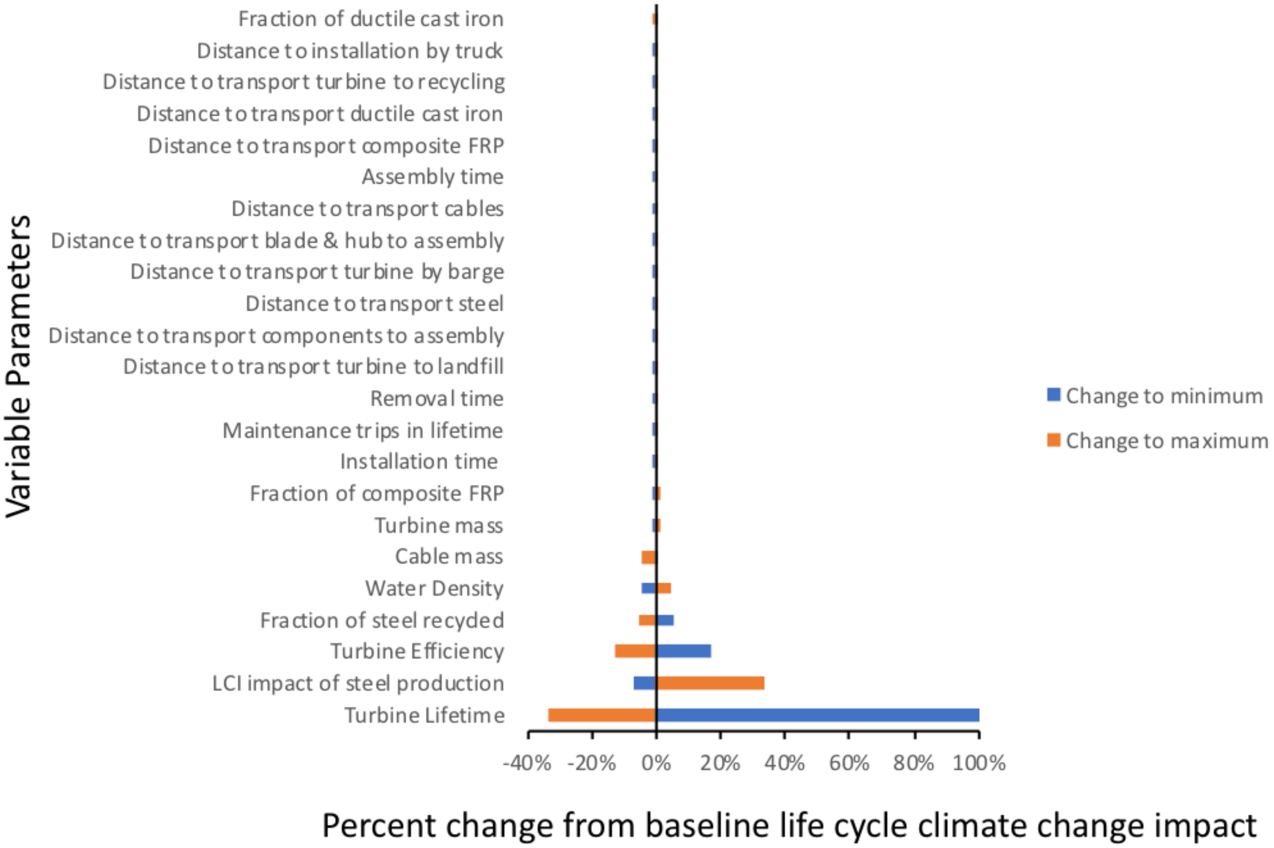

Figure B14. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Kennebeck River.

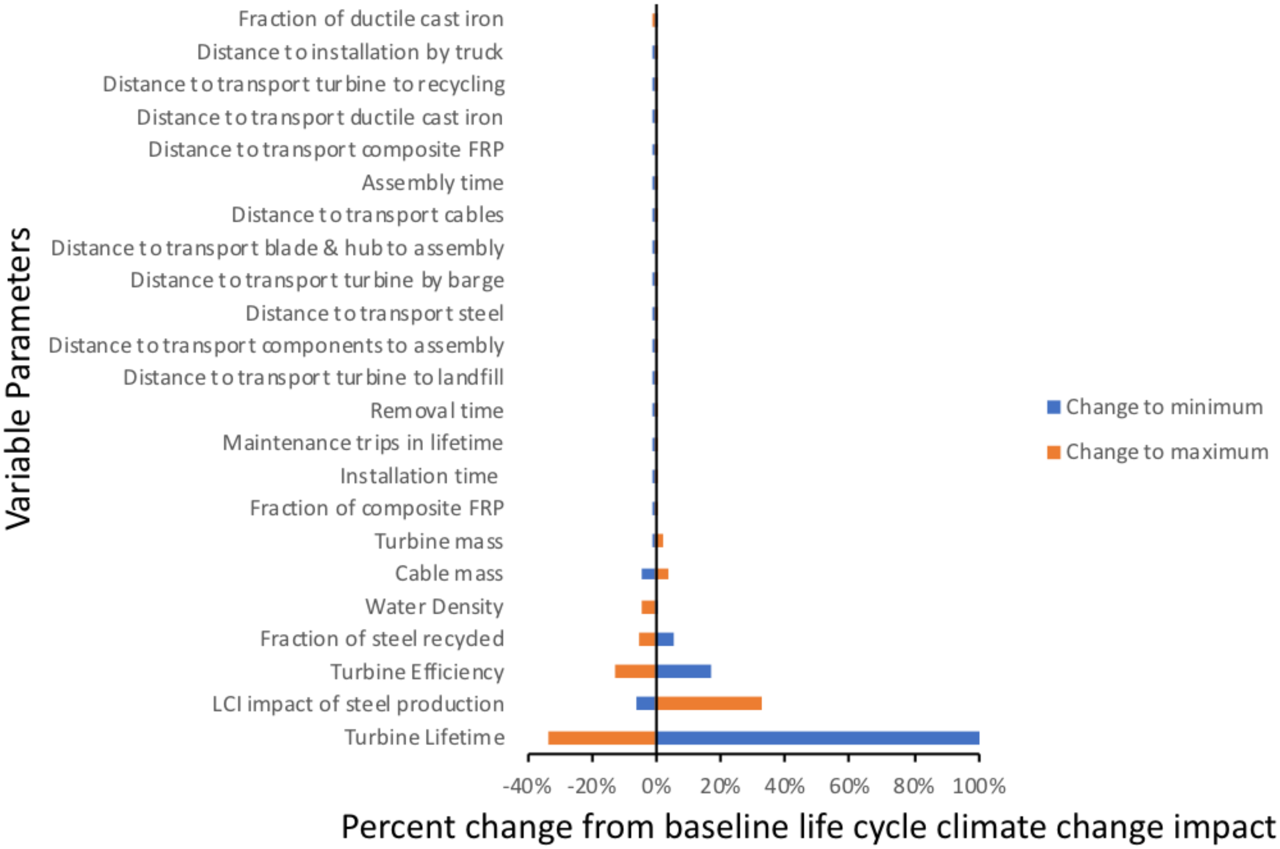

Figure B15. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Western Passage.

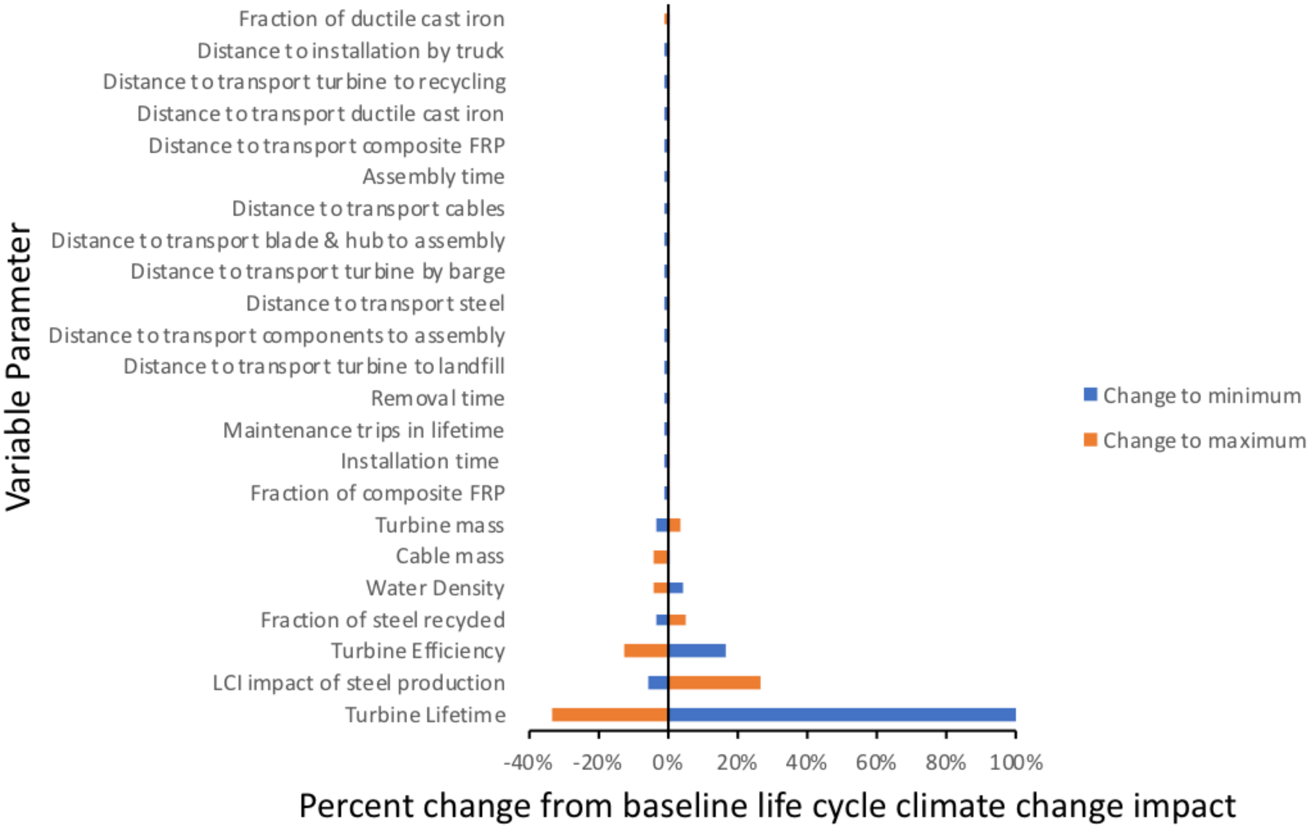

Figure B16. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Delaware Bay.

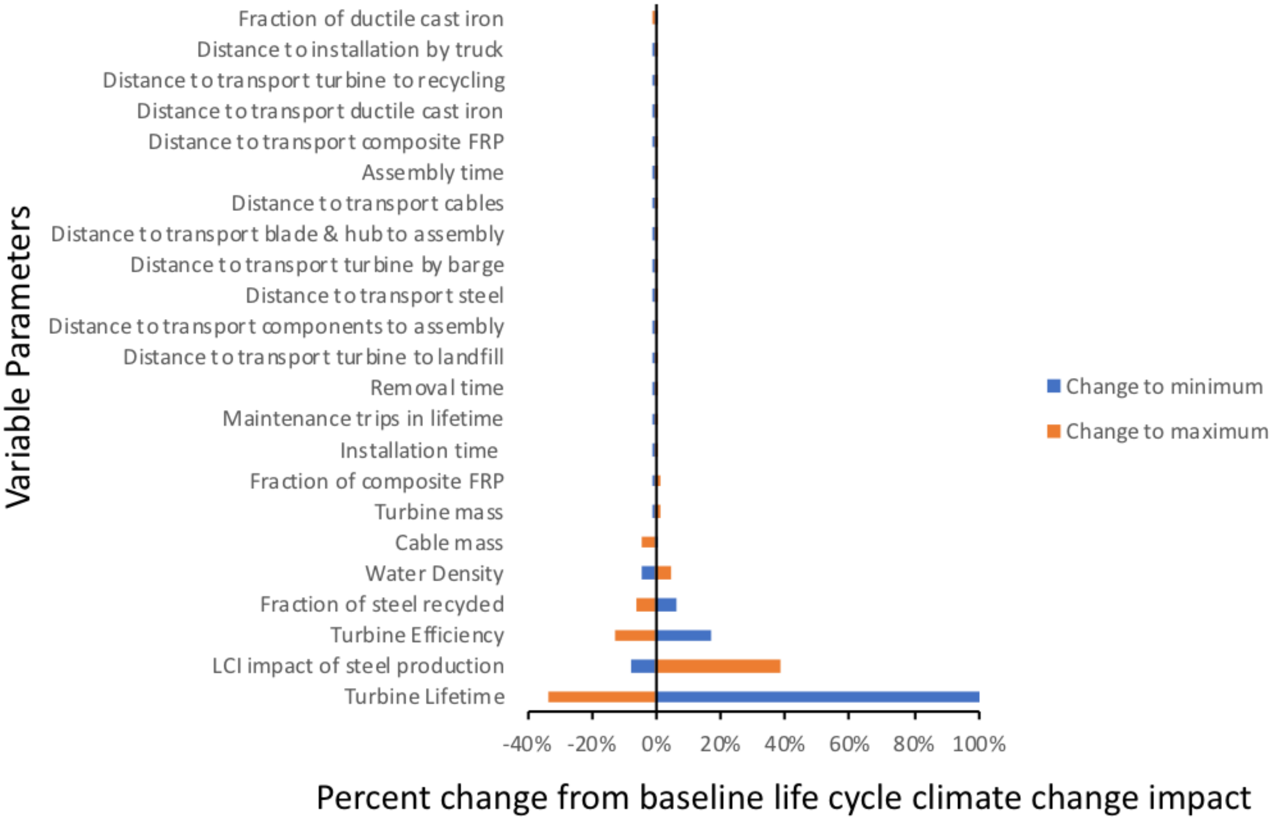

Figure B17. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the East River.

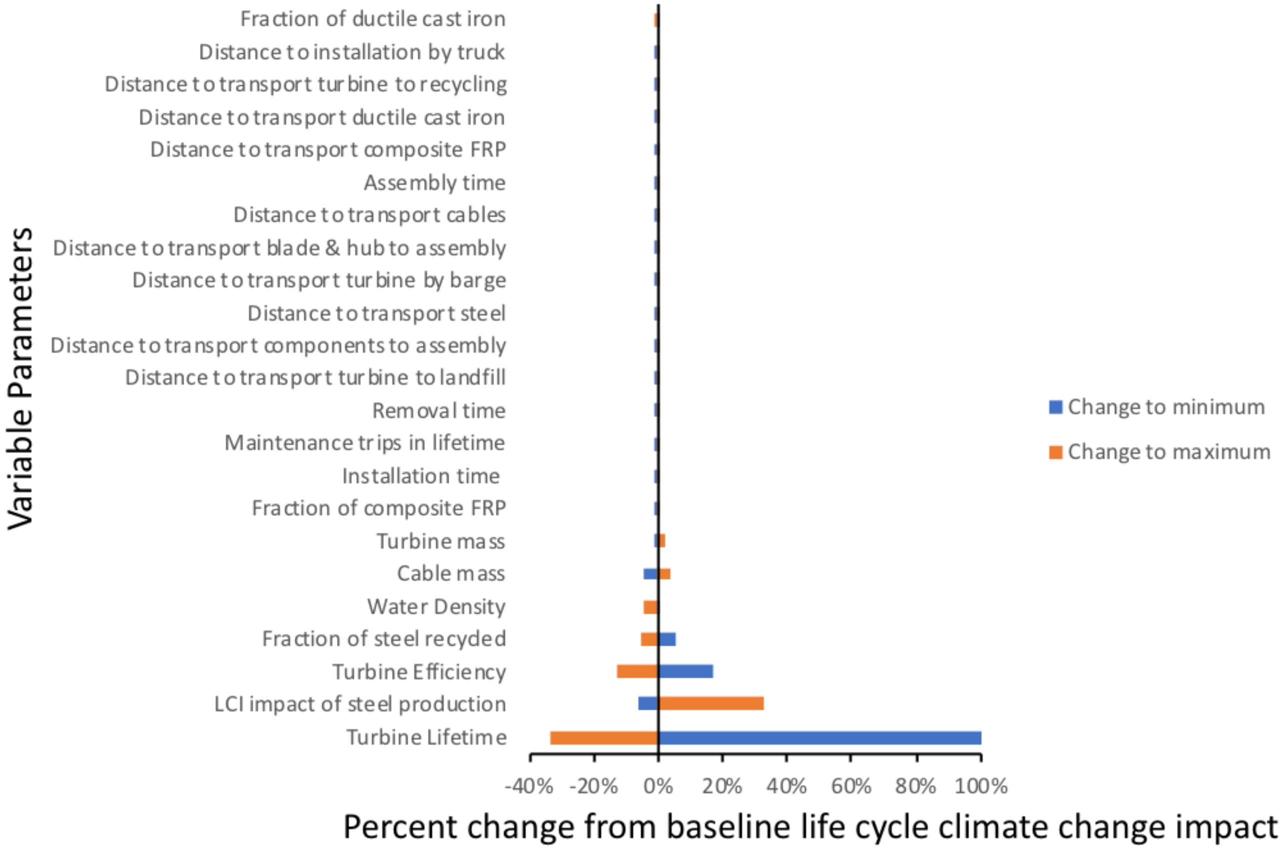

Figure B18. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Coos Bay Entrance.

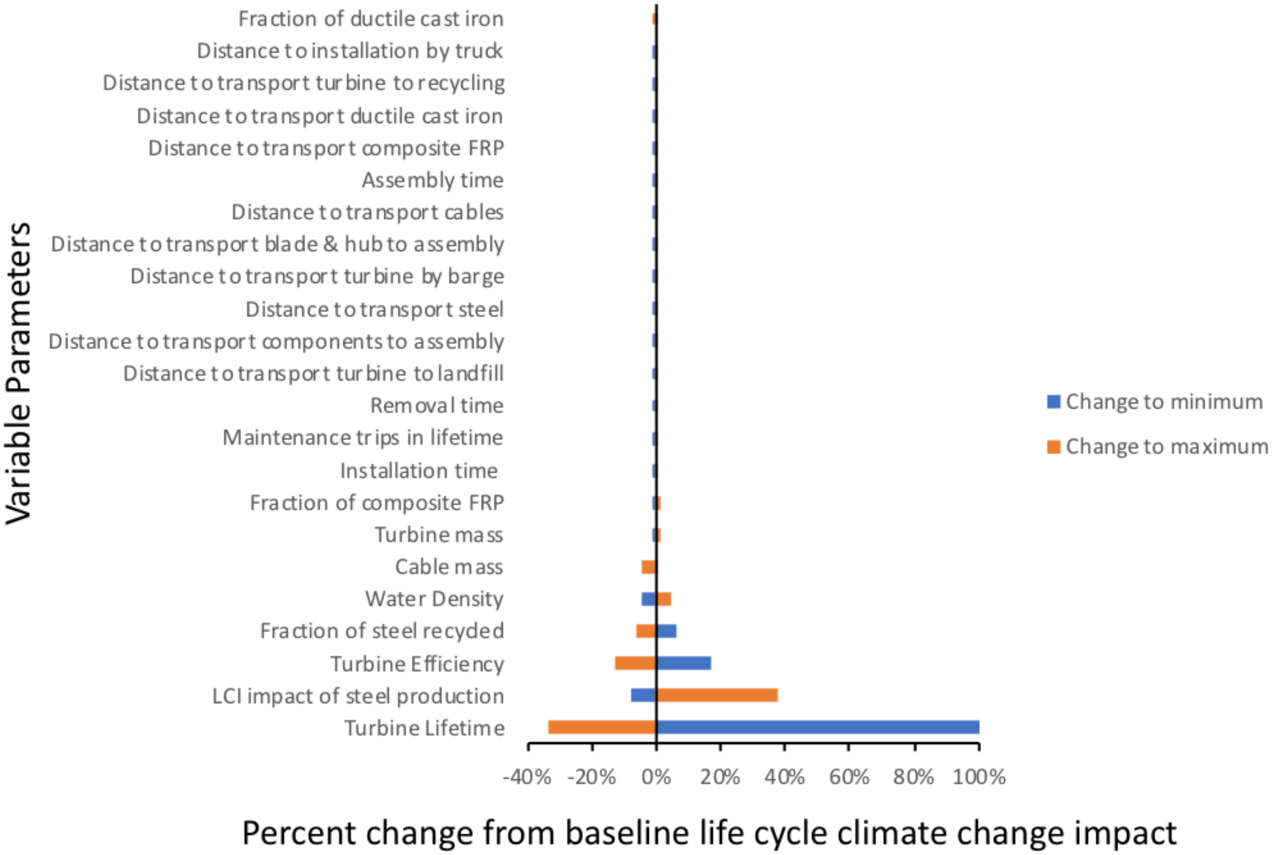

Figure B19. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Coosaw River.

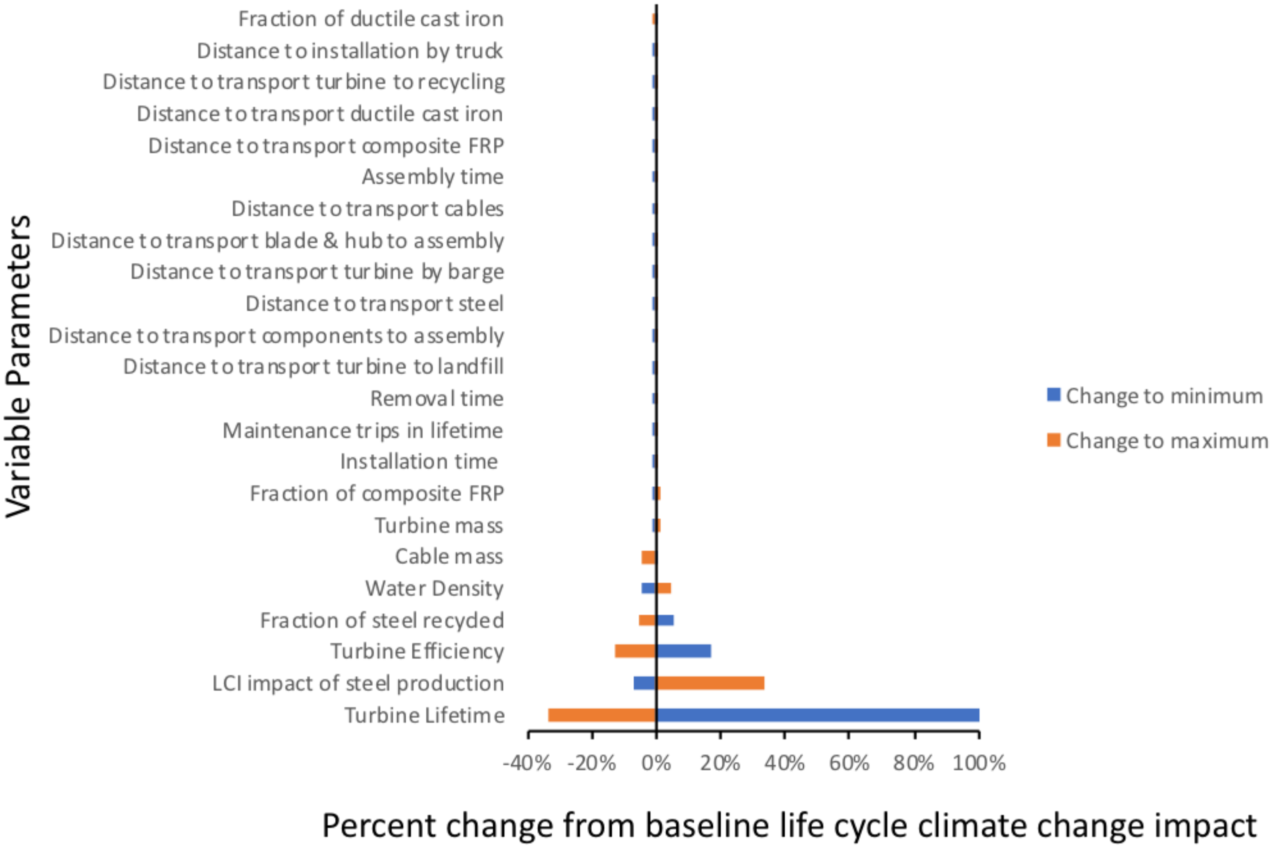

Figure B20. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the North Edisto.

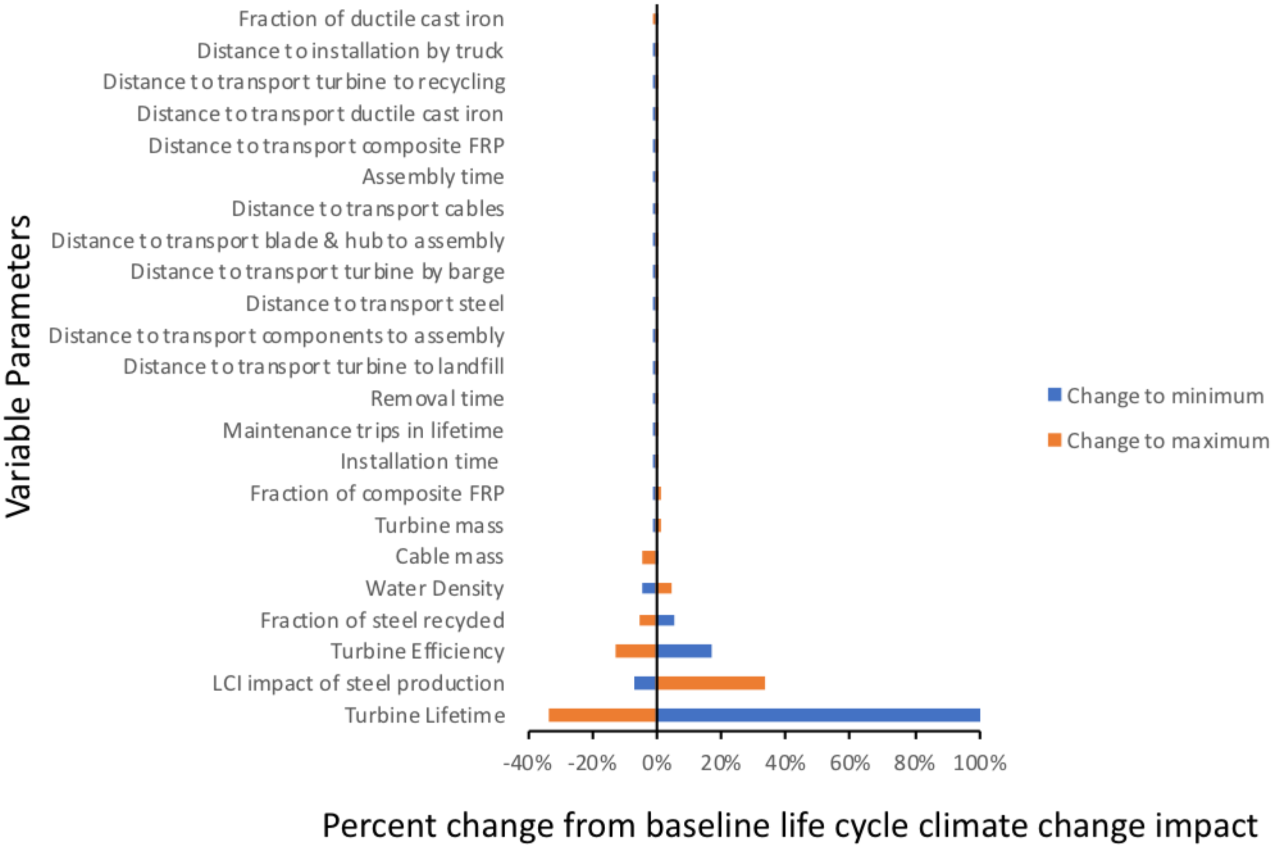

Figure B21. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Admiralty Inlet.

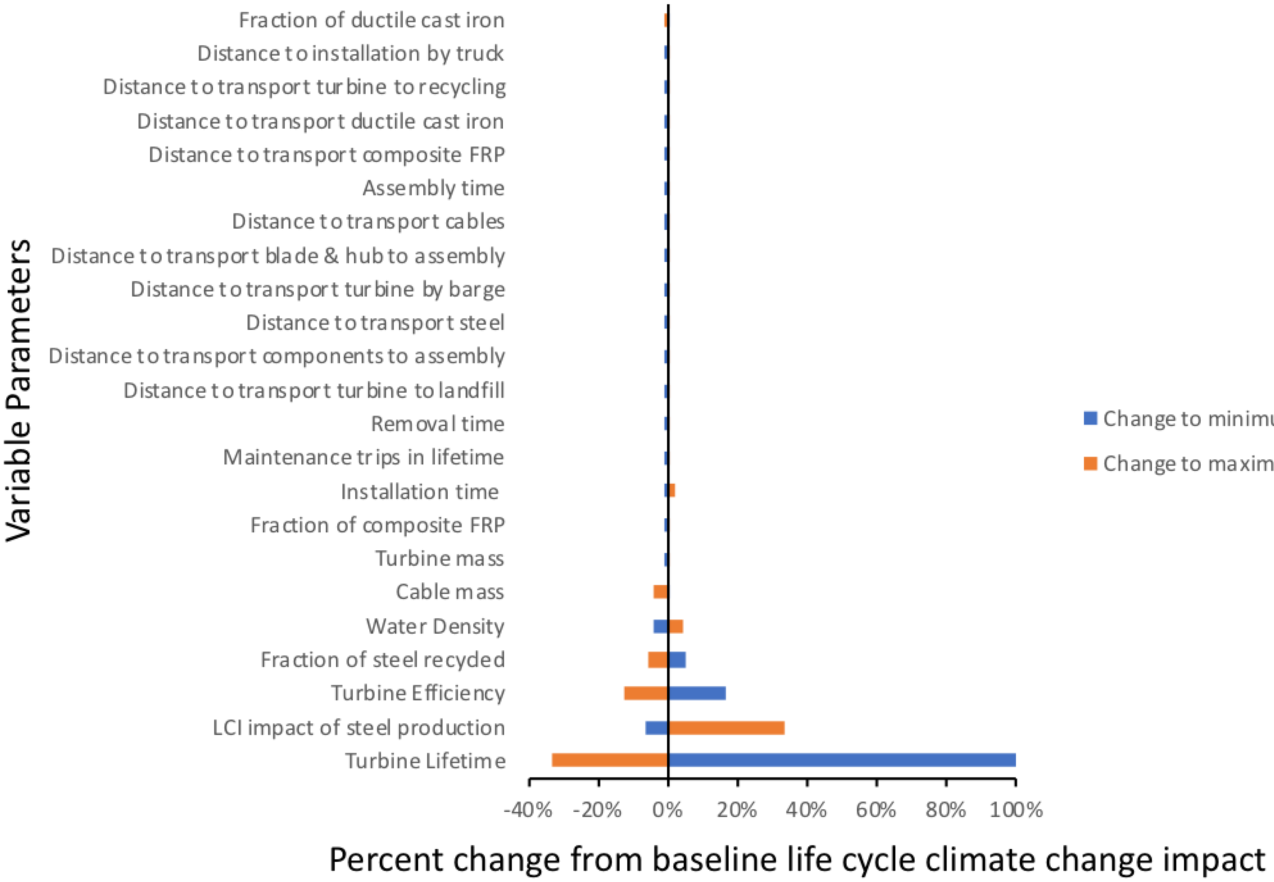

Figure B22. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Bellingham Channel.

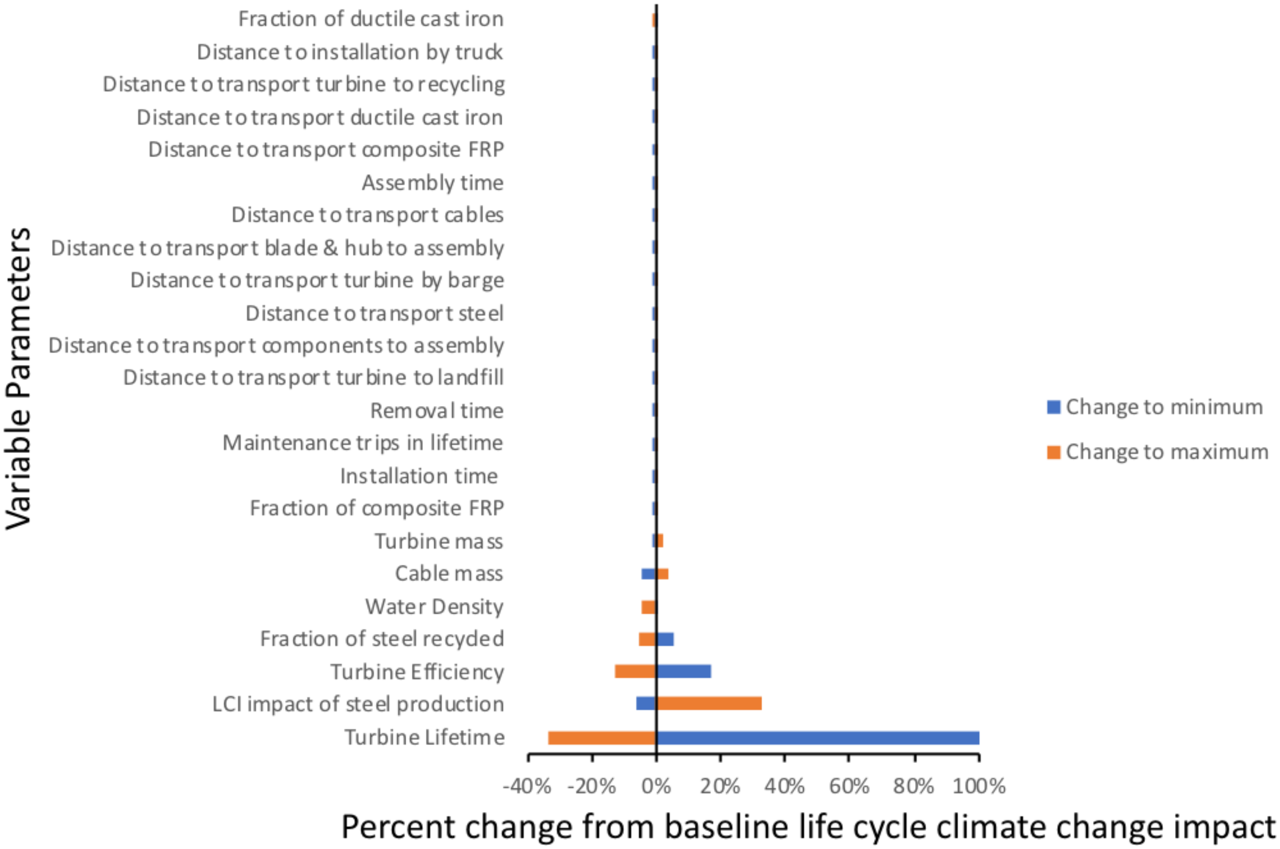

Figure B23. Sensitivity analysis of the variable parameters modeled for the electricity generation from a tidal turbine in the Grays Harbor.

CURRICULUM VITAE
BRECK SULLIVAN

Permanent Address:
600 Ulster Street
Syracuse, NY 13204
Mobile: (443) 783-6656

breck.sullivan@gmail.com

School Address:
1 Forestry Drive
Syracuse, NY 13210

EDUCATION

Salisbury University, Salisbury, MD
B.A. in Environmental Studies, Minor in Mathematics
GPA: 3.96
Graduation- May 2016

SUNY College of Environmental Science & Forestry (ESF), Syracuse, NY
MS in Environmental Science, Major in Environmental Monitoring and Modeling
GPA: 3.959
Anticipated Graduation- May 2018

HONORS AND AWARDS

EPA Greater Research Opportunity Fellowship, Environmental Protection Agency
August 2014- May 2016
- 1 of 34 students in the U.S. chosen to receive support during their undergraduate junior and senior year and an internship at an EPA facility to enhance and support environmental education

Outstanding Master's Degree Scholar Award, SUNY-ESF
2017-2018
- Graduate Program of Environmental Science

3rd Place Poster for SUNY-ESF Spotlight on Student Research
2018

President's Scholarship, Salisbury University
2013 – 2016

Mary L. Nock Scholarship, Salisbury University
2013 – 2016

Dean's List, Salisbury University
2012 – 2016

Phi Eta Sigma, Salisbury University
2013 – Present
- Freshman Honor Society with inductees meeting the requirement of a cumulative GPA of at least 3.5 at the end of their freshman year

Chi Alpha Sigma, Salisbury University
March 2015 – Present
- College Student Athletes recognized for earning a varsity letter in at least one sport while maintaining at least 3.4 or higher cumulative GPA throughout their junior and senior years

Phi Kappa Phi, Salisbury University
2016 – Present

- National Honor Society that recognizes scholarship in all academic fields
- members are in the top 10% of their class

Phi Mu Epsilon
2016 – Present

- National Mathematics Honorary Society

Summa Cum Laude, Salisbury University
2016

Environmental Studies Award for Excellence in Scholarship
2016

- Recognizes a graduating senior for outstanding academic achievement inside and outside of the environmental studies classroom

Guerrieri University Center Scholar Athlete Award
2016

Salisbury University Environmental Studies Department Scholar Award
2016

Capital Athletic Conference Nominee for NCAA Women of the Year
2016

- 1 of 141 candidates chosen across Division I, II, and III from 517 school nominees
- Women of the Year award honors graduating female college athletes who have exhausted their eligibility and distinguished themselves throughout their collegiate career in academics, athletics, service, and leadership

Honda Inspiration Award Finalist
2016

- Award given to a deserving female student-athlete in Division I, II, or III who has experienced extraordinary physical and/or emotional adversity, injury and/or illness, or experienced extraordinary personal sacrifice during her college enrollment as a student-athlete and yet returns to athletic success

Capital Athletic Conference Medal of Inspiration
2016

- Award given to those from the CAC who have persevered through extraordinary circumstances and whose determination, devotion, and passion are exemplary, and revered among their peers

Elite 89 Recipient
Fall 2014

- The Elite 89 is presented to the student-athlete with the highest cumulative GPA participating at the finals site for each of the NCAA's 89 championships
- At present date, this award is titled Elite 90

RESEARCH EXPERIENCE

Hydrodynamic and Hydrologic Modeling Intern
Summer 2017
NOAA Facility- Mid-Atlantic River Forecasting Center, State College, PA

- Summer Intern for NOAA to evaluate the impacts of improved freshwater inflow modeling on the Chesapeake Bay Operational Forecast System (CBOFS) salinity simulations

Analyst of Chesapeake Bay Water Quality Trends
Summer 2015
EPA Facility- Chesapeake Bay Program, Annapolis, MD

- Summer Intern for the EPA evaluating long-term changes in water quality of upper tributaries of the Chesapeake Bay using statistical modeling tools

Student Researcher
Spring 2015
The Center of Applied Math and Sciences, Salisbury University

- Selected to practice mathematical science by aiding businesses and management organizations in the study of long-range problems
- Analyzing campus sustainability initiatives through MATH 495

ORAL CONFRENCE PRESENTATIONS

(Presenting author underlined)

- Sullivan BM, Fortier M-OP, Malmsheimer RW. February 16, 2018. "Geographically specific life cycle assessment of electricity from tidal turbines in the United States." *2018 Ocean Sciences Meeting*. Portland, OR.
- Seay J, Sullivan BM, Conrad M. January 2014. "SAM: Student Athlete Mentor," *Apple Conference*. Charlottesville, VA.

INVITED PRESENTATIONS

(Presenting author underlined)

- Sullivan BM, Fortier M-OP, Malmsheimer RW. April 2018. "Geographically specific life cycle assessment of electricity from tidal turbines in the United States." SUNY-ESF SRE 479/679- Life Cycle Assessment. Syracuse, NY.
- Sullivan BM, Fortier M-OP, Malmsheimer RW. April 2018. "Geographically specific life cycle assessment of electricity from tidal turbines in the United States." SUNY-ESF FOR 489/689- Natural Resources Law and Policy. Syracuse, NY.
- Sullivan BM. October 2015. "Chesapeake Bay Program: Summer Internship Research," *Salisbury University's Environmental Studies Colloquium Series*. Salisbury, MD.

PEER-REVIEWED PUBLICATIONS

- Fortier M-OP, Teron L, Reames TG, Munardy DT, Sullivan B. (under review at *Applied Energy*) "Social life cycle assessment metrics for energy justice."

POSTER PRESENTATIONS

(Presenting author underlined)

- Sullivan BM, Fortier M-OP, Malmsheimer RW, Brown TR. April 2018. “Geographically specific life cycle assessment of electricity from tidal turbines in the United States.” *SUNY-ESF Spotlight on Student Research*. Syracuse, NY.

TEACHING AND MENTORING

Graduate Assistant
Fall 2016 – Spring 2018
SUNY College of Environmental Science & Forestry

- Assisting professor with course work and offering office hours for over 180 students a semester for the following courses: Business Management Law, Natural Resource Law and Policy, Natural Resources Policy, Environmental Law and Policy

Residential Tutor Counselor
June – July 2014
Upward Bound Math and Science Program- Baltimore City Community College

- Tutor economically disadvantaged students in Algebra II/Trig, Calculus, Robotics, and other STEM courses
- Residential Supervisor in the Towson University dorms to lead students in cultural, recreational, and social activities
- Built interpersonal skills through communication with people of culture and social diversities
- Gained ability to function under limited supervision which strengthened skills to be a self- starter and exercise good judgment when making decisions

Supplemental Instructor for Calculus II
January – May 2014
Salisbury University- Salisbury, MD

- Selected by Math Department to work one on one with a professor and hold peer assisted study sessions to help students understand what-to-learn and how-to-learn
- Gained administrative skills by offering study strategies, time management, and organizational skills in the sessions

Tutor
June 2012 – Present
Self-Employed- Salisbury, MD

- Tutor Middle School and High School students in science and math

Student-Athlete Wellness Advisory Team
2013 – 2016
Salisbury University- Salisbury, MD

- One of six athletes nominated by Athletic Department to educate all 19 varsity sports about nutrition, stress, alcohol, tobacco, and other drug issues through the Student Athlete Mentoring Program

TECHNICAL SKILLS

- GIS
- WordPress
- Python
- SAS
- R

STUDENT ACTIVITIES

Salisbury University Varsity Field Hockey
August 2012 – November 2016

- A 5-time NCAA Division III National Champion Team
- 35 hours per week in season

Salisbury University Varsity Field Hockey Captain
2014 – 2015

NFHCA All-Region
2015

- 2nd Team for South Region

NFHCA National Academic Squad
Spring 2013 – 2016

- Selected by the SGI / NFHCA Collegiate National Academic Squad, the National Field Hockey Coaches Association
- To be eligible for the team, student-athletes must have recorded a cumulative grade-point average of 3.30 or higher through the fall semester

Gladiator Scholar of Distinction
Spring 2014 - 2016

- Selected by the SGI/NFHCA Division III Scholars of Distinction, the National Field Hockey Coaches Association
- To be eligible, a student-athlete must have a cumulative 3.90 GPA or higher through the fall semester

Academic All-District At-Large Team
2015

- To be eligible for the team, student-athlete must have at least a 3.30 GPA and be a starter or key reserve on their team
- One of 11 players of District 2 selected to the team out of the students nominated from field hockey, swimming, tennis, lacrosse, and golf

All-CAC Field Hockey Squad
Fall 2014 - 2015

- Capital Athletic Conference 1st Team

NCAA Field Hockey All-Tournament Team
Fall 2014

- One of 11 awarded for strong play in the NCAA 2014 Field Hockey Tournament

Eastern College Athletic Conference Mid- Atlantic Region 1st Team
Fall 2014

- 1 of 6 Defensive Field Hockey Players of the Mid-Atlantic Region chosen for All-Star team

Fellowship of Christian Athletes
2012 – 2016

- Gathering of coaches and athletes to study the Word of the Lord and empower people to make a difference for Christ on the field, in the classroom, and in the community

Relay For Life Captain for Salisbury University Field Hockey Team
2012 - 2016

- Fundraiser coordinator

Salisbury University's Scholar Day Panel Speaker
2015

- Top incoming scholars of Salisbury University are given the opportunity to ask past and present Salisbury University students on the panel about how SU will embrace and challenge their academic talents

MD Power Dialog
2016

- State-level dialog among students and state level regulators about the Clean Power Plan
- Provided a platform for the students to be involved in federal policy by communicating with state officials

REFRENCES

Marie-Odile Fortier, PhD, Assistant Professor in Energy Resources
Department of Forest and Natural Resources Management
SUNY College of Environmental Science and Forestry
(315) 470-4788
mfortier@esf.edu

Robert Malmsheimer, PhD, JD, Professor of Forest Policy and Law
Department of Forest and Natural Resources Management
SUNY College of Environmental Science and Forestry
(315) 470-6909
rwmalmsh@esf.edu

Tristan Brown, PhD, JD, Assistant Professor of Energy Law and Policy
Department of Forest and Natural Resources Management
SUNY College of Environmental Science and Forestry
(315) 565-3003
trbro100@esf.edu