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Renewable electricity generation for off grid remote communities; Life Cycle Assessment Study in Alaska, USA

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HIGHLIGHTS

- Life cycle assessment of river current device versus diesel electricity generation.
- Diesel for electrical generation for site produces 1345.46 gCO_2eq/kWh.
- RivGen© deployment at Igugig has a carbon intensity of 17.49–69.97 gCO_2eq/kWh.
- Training indigenous people to perform maintenance tasks has greatest LCA impact.

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ABSTRACT

Many remote communities are reliant on fossil fuels to produce electricity and/or heat. The environmental impact from these generation systems in remote regions have significant emissions from the transportation of fuel to the generation site and only exacerbate the effects of climate change on these communities. Power via sustainable methods is a priority to avoid further environmental damage and sustain local communities (aligns with UNSDG 7, 11 and 13).

A life cycle assessment for the deployment of a renewable electricity generation device (ORPC, Rivgen®) in Alaska, USA as a case study comparison against the existing diesel electricity generation method was analysed using ReCiPe methodology . The kg CO_2 eq/MWh is shown to decrease from 1345.45 kg CO_2 eq/MWh with diesel electricity generation to 17.49 kg CO_2 eq/MWh after a 20-year Rivgen® deployment. The impact of operations and maintenance is minimised if local operators service the device instead of OEMs, with an additional saving of between 0.03 and 25.50% across environmental impact categories. Although the marine hydrokinetic device is less environmentally harmful compared to diesel electricity generating sets, optimal deployment of the device is required to overcome some environmental burdens; agricultural land occupation, water depletion and metal depletion.

The results demonstrate that deployment of renewable electricity generation devices to off grid remote locations for electricity generation can have the same or less, environmental impact as urban grid systems.

1. Introduction

1.1. Remote community energy generation

Renewable electricity generation has increased by an average of 15% globally since 2000, 75% of which is via wind and solar energy generation [1]. This increase has primarily been focused on urban and grid connected communities; isolated communities are still supplied, predominately, through diesel electricity generation [2]. Pembina Institute reported that isolated communities in Canada alone used 665 million litres of diesel equivalent a year [3]. Emissions from fossil fuel are increasingly being monitored and regulated as atmospheric CO_2 has

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passed 400 ppm [4] as the global effort to limit warming to under 1.5 °C intensifies [5]. Isolated communities, particularly the Arctic regions, are still some of the most difficult areas to supply from a centralised grid with many remaining “off grid” on fossil fuel generated electricity. Mortensen, Hansen and Shestakov [6] reported the issues facing remote communities: erosion of fossil fuel subsidies, lack of infrastructure and energy efficiency over renewable implementation. Neves, Silva and Connors [7] reviewed the deployment of renewable energy to micro communities reporting that a backup is required to account for seasonal variations and over 50% renewable electricity penetration. Ensuring that these communities are sustainable and have clean, affordable energy helps combat climate change while meeting UN Sustainable Development Goals (UNSDGs) 7, 11 and 13.

In North America subsidies have maintained lower energy generation costs from diesel. Green, Mueller-Stoffels and Whitney reported Alaska fuel costs for diesel power generation of between 250 and 580 $/MWh. Cherniak, Dufresene, Keyte, Mallett and Schott [8] reported energy costs in the Canadian Arctic of between 280 and 500 $/MWh with subsidies included of between 2 and 50 $/MWh depending on jurisdiction for diesel energy. Robertson, Bekker and Buckham [9] reported a business as usual approach with diesel generation for remote communities could cost 760 $/MWh.

Outside of North America extreme energy cost from diesel of between 180 and 1099 US$/MWh have been reported [10–14]. Deutsche Energie-Agentur (DENA) published a report investigating renewable energy in Russia [10] with electricity reaching up to 925 EUR/MWh (1099 $/MWh) in some remote regions. Dejucos, Esparcia Jr. and Ocon [11] reported diesel electricity prices of between 235 and 310 $/MWh islands in the Philippines. Isolated communities need to secure a renewable electricity generation source, which is economically feasible and does not have the environmental or health implications associated with fossil fuel usage [14]. Malherio, Castro, Lima and Estanqueiro [12] reported diesel electricity costs of 558 EUR/MWh (675 $/MWh) via a hypothetical isolated communities model. A transition to a hybrid renewable model; Wind, PV, batteries and diesel could reduce the cost of energy to 223 EUR/MWh (270 $/kWh) while reduce diesel by 90%. Ogunjuyugbe, Ayodele and Akinola [13] reported a diesel energy generation system could cost between 180 and 210 $/MWh while a hybrid renewable system would lower the cost to 130 $/MWh with an 80% reduction in CO_2 emissions. Islam, Das, Das and Rahaman [15] reported the development of a hybrid renewable grid in Newfoundland Canada could save 910,459 kg CO_2 eq per annum with a reduction in energy cost from 355 $/MWh to 136 $/MWh.

1.2. Marine hydrokinetic (MHK) devices

According to the European Marine Energy Centre (EMEC) there were 97 MHK devices at various stages of development and deployment throughout the world [16]. The USA and UK are developing more tidal devices than other countries, 24 and 27 devices respectively. Nearly every country has at least one developer working on a horizontal axis turbine. However, the river based MHK device presented in this paper is a cross-flow turbine. The US Energy Information Administration (US IEA) reports that in the USA there are currently three MHK development projects, totalling 2 MW of installed capacity [17]. Ocean Energy Europe reported in 2019 that since 2010 there were 27.7 MW of tidal energy generation devices installed with 10.4 MW still in operation [18]. This has generated 15 GWh with a capacity factor between 6.18 and 16.46%. Energy generated from hydrokinetic and tidal systems has been reported and reviewed in life cycle analysis [19–23] showing hydrokinetic devices to have a carbon intensity of between 15 and 37 kg CO_2 eq/MWh. Douglas, Harrison and Chick [19] reported a carbon intensity of 15 gCO_2/kWh for Seagen located in Strangford Lough, Northern Ireland. Rule, Worth and Boyle [20] reported the proposed Crest Energy system has a potential carbon intensity of 1.8 gCO_2/kWh over a 100-year lifespan. Walker, Howell, Hodgson and Griffin [21] reported the life cycle analysis comparison and carbon intensities of 10 MW arrays of 4 devices; TGL DeepGen, OpenHydro, ScotRenewables SR2000 and Flumill demonstrating carbon intensities of between 18 and 35 g CO_2/kWh. Kaddoura, Tivander and Molander [22] reported the LCA of a proposed Deep Green 500 array in Anglesey with a carbon intensity of 26.3 g CO_2/kWhe. A detailed review of wave and tidal assessments was conducted by Zhang, Zhang, Yuan and Zhai [23].

1.3. Case Study: Igiugig, Alaska, USA

Alaska has over 365,000 miles of rivers and 33,000 miles of coastline making MHK energy conversion an optimal energy generation method. Igiugig is a small village located South West of Anchorage in Alaska, with access primarily by air due to limited infrastructure. Alaska is the 12th least carbon emitting state in the United States, producing 35 million metric tonnes of carbon dioxide each year. However, Alaskans produce 48 metric tonnes of carbon dioxide per capita each year (8.18% of which is from electricity generation) [24]. The Alaskan Centre for Energy and Power have reported case studies involving the deployment of diesel [2], wind [25], solar PV [26], biomass technologies [27] and storage [28] alongside the transmission and integration of these [29,30].

The deployment of an ORPC’s Rivgen® device, or other MHK device (s), in Kvichak River from a feasibility perspective has been reported numerous times, [31,32,33,34]. In 2011 Terrasound prepared a bathymetric and hydrokinetic assessment of the river during quarter 2 and 3 of 2011 [31]. The hydrokinetic study was developed further by Toniolo with a visualisation of the velocities and power density of the river alongside Igiugig [32]. Cavagnaro, Polagye, Thomson, Fabien, Forbush, Kilcher et al, conducted an analysis of grid integration with a Rivgen® turbine in the Kvichak river. [33]. This grid integration model was further developed by Erdogan, Murray, Giebhardt, Wecker and Donegan reporting exportable power from the generator to the grid [34]. The studies demonstrated the Rivgen® device to be feasible of producing energy from the area, with two micro scale devices providing adequate energy to power the adjacent village of Igiugig.

1.4. Life cycle analysis and renewable energy technologies

The turn of the century has seen increased use of Life Cycle Analysis (LCA) in the evaluation of Renewable Energy Systems (RES), in particular for the comparison between RES and non-renewable technologies for power generation [35]. The rapid expansion in its use for biofuels and bioenergy technologies presents challenges to the ongoing development of the methodology [36]. LCA was originally used as a tool primarily for the comparative evaluation of the environmental impacts of consumer products [37,38]. Renewable energy systems are frequently compared in terms of their environmental performance based on either carbon intensity of energy (mass of CO_2 or CO_2eq per unit of energy) or embodied energy (energy input to produce device per energy output of device). However, there are environmental impact categories beyond carbon intensity and embodied energy which need to be considered to fully understand and compare the merits of renewable energy technologies. Although a technology can report a low carbon intensity or embodied energy, it can have a substantial environmental impact or may never reach parity with the system it replaces within the deployment lifetimes. An example of this is land use change in first generation biofuels [39].

There are an increasing number of LCAs available for various RES systems, both on the overall RES and on the individual technology types [40,41].

1.5. Aims and objectives

The aim of this study was to carry out a comparative LCA of the deployment of a micro scale renewable electricity generation device (ORPC, Rivgen®) in a remote Arctic region (Igiugig, Alaska, USA) compared with the existing method using diesel for electricity generation. In addition, the evaluation includes two sensitivity analyses, namely:

- Variations in the Rivgen® maintenance cycle; and
- Variations in the Rivgen® site deployment and effect on power outputs.

The following objectives underpinned this aim:

- To quantify the full range of environmental benefits and costs from the deployment of a micro scale renewable electricity generation device;
- To develop the knowledge and evidence base for the deployment of micro scale renewable electricity generation device in remote rural communities; and
- To identify future research needs to further the use of Life Cycle Analysis for the development, deployment and operation of micro scale renewable electricity generation devices in remote rural communities.

We believe that the analysis combines several novel elements including:

- Life Cycle analysis and assessment based on an operational scale deployment using primary data for plant construction, operations and maintenance;
- Analysis focused on deployment of micro scale renewable electricity generation device in an off grid Arctic community; and
- Quantification of the environmental benefit of local operators performing O&M compared to OEMs

2. Methodology

2.1. LCA method

In this study, LCA has been used to evaluate environmental impacts of the operation of an ORPC Rivgen® device for micro scale renewable electricity generation within a remote region in Alaska, USA, substituting for the current electricity production using air lifted diesel supplied to generators. The study has been carried out following the ISO 14040/14044 standard (ISO, 2006).

2.2. Goal and scope

The goal of the study was to investigate the environmental impact of installing, operating and maintaining a micro scale renewable electricity generation device in Igiugig, Alaska, USA. The functional unit (FU) chosen for the analysis is 1 MWh of electricity. The rationale for this choice of FU was to enable direct comparison between two electricity generation systems, namely:

Baseline: electricity generation via air lifted diesel for generators; and
Renewable: electricity generation via ORPC Rivgen® MHK device for micro scale renewable electricity generation.

2.3. Life cycle impact assessment

The three scenarios for deployment of a micro scale renewable electricity generation device have been modelled using SimaPro LCA software, version 8.3. The impacts have been estimated using the ReCiPe method, Midpoint Hierarchical and Endpoint (PRé, 2019). The ReCiPe method, at the midpoint level, was followed to allow the estimation of 18 impact categories which are addressed as follows: climate change, ozone depletion, terrestrial acidification, fresh water eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion and fossil depletion. The ReCiPe midpoint method and impact areas were chosen to allow the analysis to spotlight single impact categories which might be of particular relevance to the system being analysed [42]. For example, the inclusion of metal depletion directly informs the impacts of the metals used in the manufacture of the renewable energy device.

Additionally, the impact results were also reported using Recipe Endpoint. Endpoint indicators show the environmental impact on three higher aggregation levels, converted from the Midpoint impact categories via damage pathways. Converting midpoints to endpoints can sometimes simplify interpretation of the results, however, the aggregation can also reduce transparency

2.4. Description of system and system boundaries

2.4.1. Baseline Scenario: Electricity generation via air lifted diesel for diesel generators

Within the study the baseline case involved the generation of electricity using a diesel generator with no energy storage facility. Igiugig is delivered 26,120 gallons of diesel annually, generating 336,651 kWh annually. This energy was generated via three 67 kW Magna Generators powered by John Deere 4045TMF75 75 kW diesel engines. Based on a higher heating value, HHV, for diesel of between 11.83 and 12.67 kWh/kg the system is operating at between 31.6 and 33.9% efficiency.

Based on the assumptions that the generators and storage facilities did not have to be constructed as the village already operated them, the embodied energy and CO_2 for this was outside of the boundaries of this study, and only additional wear was considered over the period of study. The diesel was taken from a refinery in Anchorage and transported when required to Igiugig by airplane, a distance of 384 km one way. It was assumed the plane was utilised on the return journey for other items and therefore only the outbound journey was included as part of the transportation. Thus, the tonne-kilometre to transport the fuel to the village was 32,256 tkm. The storage and utilisation of the fuel for the diesel generator was assumed to be at the airport and therefore no further transportation is required. A system boundary diagram is shown in Appendix, Figure B.

2.4.2. Renewable electricity generation: Micro scale river current device (Rivgen®)

The prime mover of a Rivgen® Power System is a cross-flow turbine with a maximum device rated output of 80 kW at 3.5 m/s [43]. The device was analysed using the power curve shown in Appendix, Figure A. A system boundary diagram is shown in Fig. 1. A full breakdown of components can be found in Appendix, Table B.

2.5. Assumptions

2.5.1. Power generation

The location of the Rivgen® device was assumed to be in the Kvichak River which flows alongside the village of Igiugig. In 2011 TerraSond Ltd. prepared a physical characterisation report for the state of Alaska [31]. This study utilised an Acoustic Doppler Current Profiler (ADCP) to monitor the speed of water along the river at three locations. This data was further developed by Toniolo [32] and demonstrated the viability of a deployment of the Rivgen® device. A power curve was assumed for the Rivgen® device with a cut-in speed of 1 m/s and cut-out speed of 3.5 m/s, as shown in Appendix A, Figure A. From this, the annual energy production in Igiugig presented in Table 1 was obtained.

Thus, it was estimated that the annual energy output (AEO) for the location, further known as Site A, is 349.32 MWh.

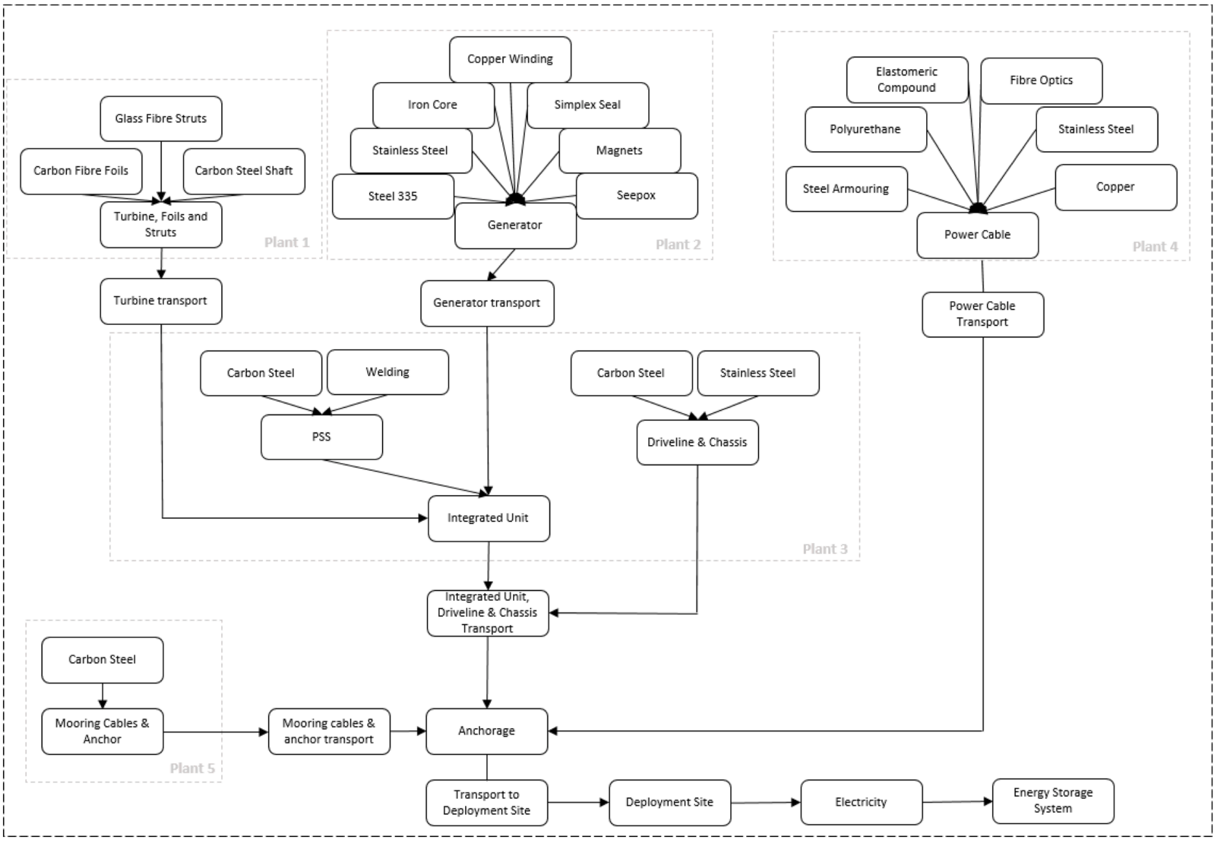

Fig. 1. System Boundary diagram depicting a scenario of electricity generation using a river hydrokinetic device for renewable electricity generation.

Table 1
Power Output of Rivgen® in Igiugig.

Month	Days	Hours	Power (kWh)
Jan	31	744	29,308.71
Feb	28	672	26,472.39
Mar	31	744	23,354.46
Apr	30	720	22,601.09
May	31	744	23,354.46
Jun	30	720	28,363.27
Jul	31	744	29,308.71
Aug	31	744	33,633.45
Sep	30	720	37,008.74
Oct	31	744	38,242.37
Nov	30	720	28,363.27
Dec	31	744	29,308.71
Total	365	8760	349,319.64

2.5.2. *Energy storage system*

A number of studies have reported the requirement for storage and backups with high renewable energy penetration, especially if the renewable energy is not dispatchable (on demand) [7,44]. A battery storage system capable of storing 1, 6, 12 and 24 h of average Igiugig village load (38.43, 230.58, 461.17 and 922.33 kWh respectively) was studied. Four commercially available battery systems were chosen for analysis: Lithium-ion (Li-ion), Nickel Metal Hydride (NiMH), Nickel-Managanese-Cobalt (NMC) and Sodium Salt (NaCl). The battery systems were analysed using the Ecoinvent database with the exception of NMC which utilises the LCA reported by Kallitsis [45]. The energy density of each storage system was as follows; Li-ion 2.1 kWh/kg, NiMH 0.08 kWh/kg, NaCl 0.116 kWh/kg and NCM 0.143 kWh/kg. The transportation of batteries to the site was not taken into consideration as part of the analysis.

2.5.3. *Maintenance cycle (O&M)*

Maintenance of renewable energy systems can have a significant impact both environmentally and economically. Douziech *et al.* reported Operations & Maintenance (O&M) accounts for between 0.1 and 81% of the midpoint environmental impact of a wave or tidal device [46]. International Renewable Energy Agency (IRENA) reported O&M can also account for up to 30% of levelised cost of energy (LCOE) of renewable energy devices [47].

According to ORPC, Rivgen® currently has a service cycle consisting of a minor service annually with a major service every five years [43]. Within this study the examination of three assumed repair actions are considered:

- Foil replacement,
- Generator seal replacement and;
- Transport of a service engineer.

Foil replacement was studied at intervals of triennially, quinquennially or decennially, which would require a new carbon fibre foil to be produced at Plant 1 and transported by air freight to site. As part of a generator seal replacement which typically occurs during a major service, it was assumed that the generator seal, brass and rubber were transported to Plant 3 by air freight from Igiugig to Anchorage and onwards to Portland, Maine with a new rubber component installed before returning to Igiugig. Triennial (once every three years), quinquennial (once every five years), and decennial (once every ten years) service intervals for generator seal replacements were investigated. Annual, biennial (once every two years) or triennial transport of a service engineer to Plant 3 in Portland, Maine was assumed for all services, requiring a total of 11,530 person km.

The seal replacement of the device has been extensively investigated by the Horizon 2020 TAOIDE project with multiyear savings being realised [48]. Seal replacements are required, in order to prevent water ingress to the bearing system and are a key preventive maintenance measure to ensure optimal operation of the device over the lifetime of the device. The transportation of a service engineer is investigated as the local community is isolated and therefore flying an engineer could be costly, both environmentally and economically. Therefore, limiting these visits would be beneficial and promote a more sustainable community.

The parts have been assumed to originate from the same plants used for construction of the total device as shown in 2.4.2.

3. Lifecycle assessment results

3.1. Midpoint analysis

Fig. 2 *shows* the midpoint analysis of Rivgen® device as constructed, transported and installed in Igiugig, Alaska. The categories which have the largest environmental impacts are climate change, human toxicity, metal depletion and fossil fuel depletion. These impacts are caused predominately by the construction of the materials, particularly the generator, PSS and driveline and chassis. The impact is due to the mass of material used in these sections of 4040 kg, 13,400 kg and 9400 kg respectively. The section containing foils, struts and shaft shows a disproportionate level of ionising radiation, in comparison to the weight of 1700 kg due to the epoxy and carbon fibre. The carbon fibre in this section 132 kg (7.70% of section) is responsible for 1027.19 kBq U_{235}eq (78.42% of section) ionising radiation. Every kg of carbon fibre is responsible for 7.78 kBq U_{235}eq compared to 0.09 kBq U_{235}eq for iron.

Table 2 summarises the environmental impacts for the annual electricity generation using the diesel generator system currently installed in Igiugig versus the electricity from a Rivgen® device deployed for 5, 10 or 20 years in the Kvichak River.

3.1.1. Climate change

Climate change is the environmental impact of greenhouses gases measured in equivalents of CO_2, kg CO_2 eq. Using diesel for the village's annual electricity generation of 336,651 kWh the carbon intensity is 1345.45 kg CO_2 eq/MWh. As Igiugig has a population of 69 people [49], this results in a per capita average energy demand of 4879 kWh per annum and carbon emissions of 6564.49 kg CO_2 eq/person. This is significantly above the carbon intensity reported by the United States Environmental Protection Agency (US EPA) for Alaska of 907.52 lbs CO_2/MWh (411.64 kg CO_2/MWh) [50]. On the other hand, transition to renewable power via Rivgen® presents a significant saving in kgCO_2 eq. Deployment of Rivgen® for 5 years has a carbon intensity of 69.97 kg CO_2 eq/MWh which equates to 5.20% of carbon emissions from electricity generated using diesel. This decreases further to carbon intensities of 34.99 and 17.49 kg CO_2 eq/MWh over 10 and 20 years respectively. In fact, a lifetime emission saving of between 2227–9277 tons CO_2 eq for the community can be achieved by deployment of the Rivgen® device which is a reduction of 94.80–98.70% when compared to electricity generation using diesel.

The carbon intensity of Rivgen® (69.97 kg CO_2 eq/MWh) is also favourable compared to other hydrokinetic energy devices. Douziech *et al.* [46] reported carbon intensities of 25.50 kg CO_2 eq/MWh for SeaGen, 37.00 kg CO_2 eq/MWh for HS1000 and 20.10 kg CO_2 eq/MWh for Hydra Tidal. Kaddoura *et al.* [22] reported a prospective LCA for Minesto Deep Green 500 of 26.30 kg CO_2 eq/MWh. However, these devices are larger hydrokinetic devices with plate capacities (maximum power output) of between 1 and 1.2 MW for deployments while Rivgen® has a plate capacity 0.08 MW.

3.1.2. Ozone depletion

Ozone depletion accounts for compounds emitted during the production or operation of the process leading to destruction of the ozone layer e.g., chloroflurocarbons (CFCs) measured in kg CFC-11 eq. The production of ozone depleting compounds from both electricity generation methods, per MWh is relatively low, 188 mg CFC-11 eq from diesel production. For a 5-year Rivgen® deployment is 6.71 mg CFC-11 eq, 10-year Rivgen® deployment is 3.36 mg CFC-11 eq and for a 20-year Rivgen® deployment 1.68 mg CFC-11 eq. By transitioning from diesel produced electricity to hydrokinetic produced electricity a lifetime emission saving of up between 316 and 1301 g CFC-11 eq. is achieved.

3.1.3. Terrestrial acidification

Terrestrial acidification is a measure of the amount of SO_2 eq released to the environment which can lead to acid rain and results in a more acidic environment. Diesel comes with an amount of sulfur per litre ranging from 10–1000 ppm (10–1000 mg/L). Due to the presence of

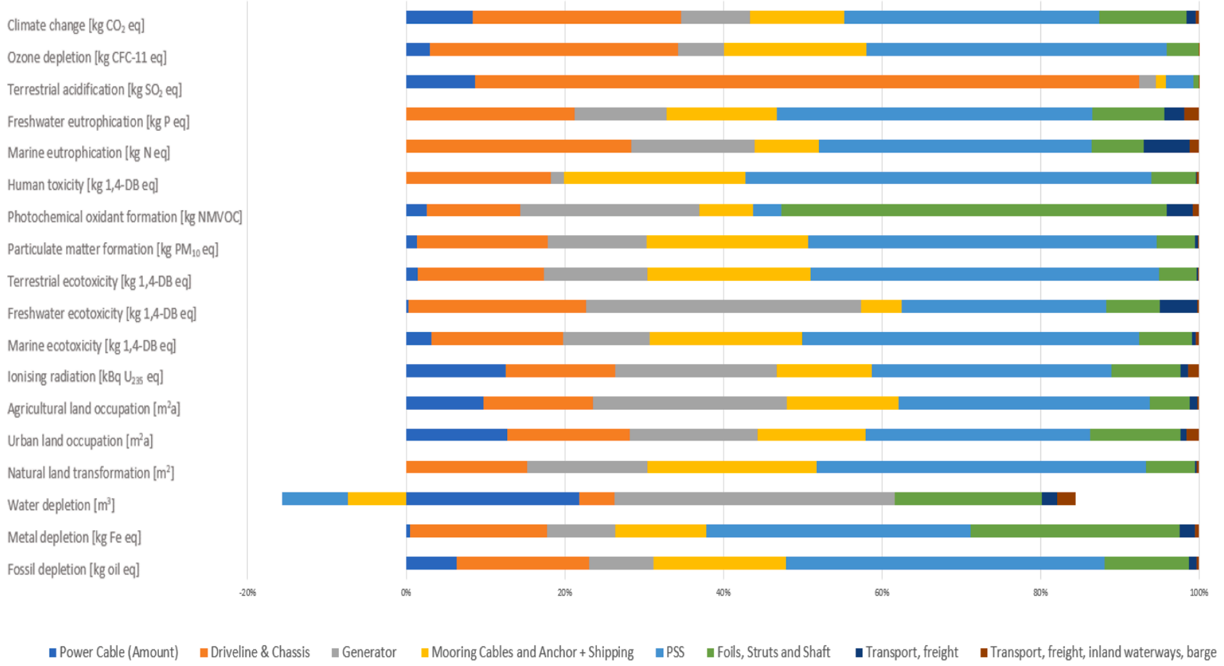

Fig. 2. Midpoint Analysis of Rivgen® Device deployment in Igiugig, Alaska.

Table 2

Midpoint environmental impacts of 1MWh diesel electricity (baseline) and 1 MWh of Rivgen® electricity production for Igiugig, Alaska.

Impact category	Unit	Baseline	Rivgen® Years of Deployment		
			5	10	20
Climate change	kg CO_2 eq	1345.46	69.97	34.99	17.49
Ozone depletion	kg CFC-11 eq	1.88E-04	6.71E-06	3.36E-06	1.68E-06
Terrestrial acidification	kg SO_2 eq	1.34E+01	7.08E-02	3.54E−02	1.77E−02
Freshwater eutrophication	kg P eq	9.96E−02	2.32E−02	1.16E−02	5.81E−03
Marine eutrophication	kg N eq	7.32E−01	8.36E−03	4.18E−03	2.09E−03
Human toxicity	kg 1,4-DB eq	720.05	27.44	13.72	6.86
Photochemical oxidant formation	kg NMVOC	2.05E+01	2.00E−01	9.99E−02	4.99E−02
Particulate matter formation	kg PM_{10} eq	6.80E+00	2.18E−01	1.09E−01	5.45E−02
Terrestrial ecotoxicity	kg 1,4-DB eq	3.42E−02	8.80E−03	4.40E−03	2.20E−03
Freshwater ecotoxicity	kg 1,4-DB eq	1.18E+01	1.28E+00	6.38E−01	3.19E−01
Marine ecotoxicity	kg 1,4-DB eq	1.13E+01	1.33E+00	6.65E−01	3.33E−01
Ionising radiation	kBq U_{235} eq	7.11E+01	1.68E+00	8.42E−01	4.21E−01
Agricultural land occupation	m^2a	6.11	9.01	4.51	2.25
Urban land occupation	m^2a	3.14E+00	1.13E+00	5.64E−01	2.82E−01
Natural land transformation	m^2	3.89E−01	1.08E−02	5.41E−03	2.70E−03
Water depletion	m^3	2.52E+00	8.52E+00	4.26E+00	2.13E+00
Metal depletion	kg Fe eq	38.16	99.01	49.51	24.75
Fossil depletion	kg oil eq	711.22	19.78	9.89	4.94

sulfur in the diesel fuel used in internal combustion engines, SO_x is produced as a by-product. The amount of SO_x produced from diesel production in Igiugig is calculated as 13.40 kg SO_2 eq/MWh. Using hydrokinetic electricity produced via Rivgen® will lower this output per MWh to 1.77×10^{-2}-7.08×10^{-2} kg SO_2 eq/MWh with an estimated lifetime saving of between 23.30 and 93.50 tons SO_2 eq.

3.1.4. Eutrophication potentials

Eutrophication occurs when excessive amounts of minerals such as phosphorus or nitrogen, enters the ecosystem resulting in excessive algae growths which in turn lowers the oxygen availability to other species and causes damage to ecosystems. Electricity production from Rivgen® compared to diesel for electricity generation in Igiugig results in a freshwater eutrophication decrease of between 133 and 655 kg P eq. While the decrease in marine eutrophication is a larger saving at between 1264 and 5009 kg N eq compared to generating energy from diesel.

3.1.5. Human and eco toxicities

There are four toxicities calculated as part of the analysis. Human toxicity examines the carcinogenic and non-carcinogenic effects of compounds. Terrestrial, freshwater and marine eco toxicities examine the damage potential to each respective ecosystem. All of these toxicities are measured equivalent to 1,4 dichlorobenzene i.e. kg 1,4-DB eq. There is a decrease in each toxicity reported when diesel generated electricity in Igiugig is replaced by MHK produced electricity. The largest effect is on human toxicity with 6.86–27.44 kg 1,4-DB eq/MWh for Rivgen® while diesel produces 720 kg 1,4 DB eq/MWh, equating to a 1.26–5.09 ton reduction in the emission of 1,4 DB eq over 5–20 years. Table 2 reports reductions for electricity generated using Rivgen® versus diesel of between 74.26–93.56 % for terrestrial ecotoxicity, 89.18–97.29% for freshwater ecotoxicity and 88.22–97.06% for marine ecotoxicity for a 5 to 20-year Rivgen® deployment versus diesel.

3.1.6. Photochemical oxidant formation

Photochemical oxidant formation occurs via the emission of nitrogen oxides (NO_x) into the atmosphere and is estimated by measuring the amount in kilograms of non-methane volatile organic compounds (NMVOC). The NMVOCs in turn produce ozone (O_3) in the atmosphere leading to damage of human and plant health. Generation of electricity via Rivgen® compared with diesel produces 99.03–99.76% less NMVOCs, resulting in a decrease of emissions of 35.50 tons of NMVOCs if deployed for 5 years or 142.90 tons of NMVOCs if deployed for 20 years for Igiugig.

3.1.7. Particulate matter (PM) formation

Particulate matter formation is the measure of small particles produced, typically, in the combustion of fuel. These are categorised as PM_{10}, matter under 10 μm, $PM_{2.5}$, matter under 2.5 μm, PM_1, particles under 1 μm and is measured as kg PM_{10} eq. Matter of $PM_{2.5}$ and smaller has recently been of increased focus due to the carcinogenic effects and respiratory consequences of inhalation, with combustion technology being cited as a major contributing factor to PM formation. Electricity generation from Rivgen® compared to diesel will decrease the emissions of PM_{10} by 96.80–99.20 % per MWh for Igiugig. For a deployment period of 5 years, a reduction of 11.50 tons of PM_{10} eq is achieved while increasing to 20-year deployment saves 47.10 tons of PM_{10} eq from being emitted.

3.1.8. Ionising radiation

Ionising radiation measures the emission to the atmosphere of radionuclides produced in kilobequerel Uranium 235 equivalent (kBq U_{235} eq). These radionuclides damage DNA leading to increased risk to human health through cancer and other illnesses. Electricity generation via Rivgen® emits 97.63 less kBq U_{235} eq if deployed for 5 years or 99.41% less kBq U_{235} eq if deployed for 20 years compared to electricity generated via diesel. These reductions would result in a lifetime emissions abatement of between 121.20 and 493.80 ton kBq U_{235} eq.

3.1.9. Land occupation

Land occupation is a measure of land used and is measured as m^2 per annum. The distinction is made between agricultural land and urban land and it considers the use of the original land along with what the land is being utilised for. Deployment of Rivgen® in Igiugig demonstrates a lower urban land occupation per MWh than diesel powered electricity generation, with 0.28–1.13 m^2/a (m^2/annum) compared to 3.14 m^2/a respectively. This results in 3513–19,965 m^2 less urban land occupied over a 5 to 20-year period. Rivgen® has however a larger impact on agricultural land occupation compared to diesel when deployed for shorter periods of time. If deployed for a 5-year period it is not beneficial for deployment compared to electricity generation using diesel, per MWh. The device is recommended for a minimal deployment period of 20 years. A 10-year deployment time results in 1.60 m^2 per annum/MWh less land being occupied by Rivgen® compared to diesel generators, with a 20-year deployment giving a reduction of 3.86 less m^2 per annum/MWh. A resulting total reduction of 5599–26,942 m^2/annum (1.38–6.66 acre/annum) over the project lifetime of between 10 and 20 years.

3.1.10. *Land transformation*

Land transformation is a measure of land which is altered, based on the land use classes set out in the Ecoinvent database, which are derived from Handbook on LCIA of Global Land Use within the framework of the UNEP/SETAC Life Cycle Initiative (for example, Forest, primary (non-use): Forests (tree cover > 15%), minimally disturbed by humans, where flora and fauna species abundance is near pristine) [51]. Electricity generation from Rivgen® has a substantially lower effect on land transformation compared to electricity generated from diesel, as shown by Table 2. Transition from diesel generated electricity will result in natural land transformation decreasing by 679.94 m^2 for a 5-year deployment, 1359.90 m^2 for a 10-year deployment and 2719.81 m^2 for a 20-year deployment.

3.1.11. *Water, metal and fossil depletion*

Water depletion is the amount of water used throughout the process and is measured in terms of m^3 of water. Metal depletion is a measure of the metal resources used throughout the process standardised against the equivalent amount of iron (kg Fe eq). Fossil fuel depletion is the amount of fossil energy used in the processing of the materials standardised against the higher heating value (HHV) of oil measured in kg oil eq. Rivgen® requires more water and metal, over 5- and 10-year deployment periods, compared to electricity generation from diesel. Increasing the deployment period to 20 years demonstrates that Rivgen® out performs diesel electricity generation with an abatement of 2724 m^3 of water and 93.60 tons of iron. Generating electricity from Rivgen® for Igiugig compared to generating electricity via diesel will result in 1207.60–4934.30 tons oil eq saving for a deployment of 10 or 20 years.

3.2. *Endpoint analysis*

Endpoint analysis was conducted on electricity generation from diesel versus electricity generation from Rivgen®, as shown in Table 3.

Transitioning from diesel electricity generation to electricity generated from the river current device produces a substantial decrease in disability adjusted life years (DALYs). Over a 5-, 10-, and 20-year period generating the same energy via Rivgen® a saving of 6.95, 14.22, and 28.74 DALY respectively is achieved. Transitioning away from diesel electricity generation over 5-, 10-, and 20-year deployments results in 93.87, 96.93, and 98.47% respectively fewer species per year lost due to less damage to ecosystems. There is also a significant resource saving, as analysed by copper, crude oil, hard coal and natural gas, producing energy from Rivgen® compared to diesel generation, as would be expected with renewable energy generation. The associated resource saving is US_{2013}\$ 192,059, US_{2013}\$ 402,254 and US_{2013}\$ 822,644 over a 5-, 10-, and 20-year deployment respectively.

3.3. *Return of equipment to manufacturers for recycling*

The end of life of equipment has become an important factor that is now considered during the design and manufacture of technology, especially when technology is created to produce renewable and sustainable energy to lower the environmental impact. Table 4 reports the percentage change in the relative impact categories (compared to values in Table 2) when return of components to relative manufacturers is incorporated as part of the environmental impact of Rivgen®.

When return of Rivgen® equipment to manufacturers for recycling is considered there is an increase of over 50% in four environmental impact categories: urban land occupation (81.34% increase), terrestrial acidification (76.33%), terrestrial ecotoxicity (63.49%) and ionising radiation (50.03%). This would also affect the carbon intensity of the energy produced by Rivgen®. Over a 5-year deployment, carbon intensity would increase from 69.97 to 83.25 kg CO_2 eq per MWh with 10- and 20-year deployments increasing from 34.99 to 41.63 and 17.49 to 20.81 kg CO_2 eq per MWh respectively. The impact of transport should decrease over time with the movement of global transportation towards carbon neutral and a hydrogen economy. This is therefore presented as a worst-case scenario of repatriation of materials.

Table 3
Endpoint Analysis of Baseline and Rivgen® deployment per MWh over a 5, 10 and 20 year deployment.

Impact category	Unit	Baseline	Years of Deployment 5	10	20
Human Health	DALY	4.16E−03	1.76E−04	8.81E−05	4.41E−05
Ecosystems	Species. yr	1.16E−05	7.10E−07	3.55E−07	1.78E−07
Resources	US_{2013}\$	120.35	10.38	5.19	2.6

3.4. *Energy storage system*

The mass of batteries required per energy storage option differs significantly. This is primarily due to higher energy density of Li-ion, 2.1 kWh/kg resulting in a mass difference of between 14.60 and 26.25 for other energy systems. A mass of 18–439 kg of Li-ion batteries is required to store the 1–24 h energy. Other storage solutions analysed: nickel metal hydride, sodium chloride and nickel cobalt manganese, require much larger masses of between 269–480 kg for 1 h storage to 6450–11,529 kg for 24 h of storage. A full environmental impact is shown in the Appendix.

Due to the mass being significantly larger for other energy battery storage systems, the Li-ion has the least environmental impact. The best performing battery storage technology is Li-ion across all categories due to the higher energy density.

4. Sensitivity analysis

Sensitivity analysis was performed to determine the contribution to the environmental impacts of variation in the maintenance cycle and power output from Rivgen®.

4.1. *Maintenance cycle*

For Rivgen® the following areas are examined to determine the environmental impact of assumed maintenance:

- Foil replacement,
- Generator seal replacement and;
- Transport of a service engineer.

4.1.1. *Foil replacement*

The percentage change per MWh of triennial (once every three years), quinquennial (once every five years) and decennial (once every ten years) replacement of a carbon fibre foil is shown in Appendix, Table J.

The three environmental impacts increased to the largest degree by the replacement of a carbon foil are terrestrial acidification, photochemical oxidant formation and fossil depletion. The transport of the foil to Igiugig generates over 90% of the environmental impact in most categories. The carbon intensity of the energy produced by Rivgen® would increase by between 0.17–0.28 % over a 5-year deployment, 0.17–0.55% over a 10-year deployment and 0.33–1.10% over a 20-year deployment.

4.1.2. *Generator seal replacement*

A seal is required to prevent water ingress into hydrokinetic device's generator bearing system. Over time this seal is worn down leading to a higher possibility of a need to replace. The percentage change per MWh

Table 4
Percentage increase of environmental impacts, per MWh, with inclusion of transport to relative manufactures for recycle/repurpose.

Impact category	Unit	Years of Deployment			% increase compared to Table 2
		5	10	20	
Climate change	kg CO_2 eq	83.25	41.63	20.81	18.97%
Ozone depletion	kg CFC-11 eq	8.61E−06	4.31E−06	2.15E−06	28.29%
Terrestrial acidification	kg SO_2 eq	1.25E−01	6.24E−02	3.12E−02	76.33%
Freshwater eutrophication	kg P eq	2.40E−02	1.20E−02	6.00E−03	3.41%
Marine eutrophication	kg N eq	1.05E−02	5.23E−03	2.61E−03	24.99%
Human toxicity	kg 1,4-DB eq	32.51	16.26	8.13	18.49%
Photochemical oxidant formation	kg NMVOC	2.62E−01	1.31E−01	6.54E−02	30.95%
Particulate matter formation	kg PM_{10} eq	2.44E−01	1.22E−01	6.10E−02	12.07%
Terrestrial ecotoxicity	kg 1,4-DB eq	1.44E−02	7.20E−03	3.60E−03	63.49%
Freshwater ecotoxicity	kg 1,4-DB eq	1.33E+00	6.64E−01	3.32E−01	4.01%
Marine ecotoxicity	kg 1,4-DB eq	1.42E+00	7.09E−01	3.54E−01	6.47%
Ionising radiation	kBq U_{235} eq	2.53E+00	1.26E+00	6.32E−01	50.03%
Agricultural land occupation	m^2a	9.16	4.58	2.29	1.62%
Urban land occupation	m^2a	2.05	1.02	0.51	81.34%
Natural land transformation	m^2	1.49E−02	7.45E−03	3.73E−03	37.84%
Water depletion	m^3	8.55E+00	4.28E+00	2.14E+00	0.38%
Metal depletion	kg Fe eq	99.30	49.65	24.82	0.29%
Fossil depletion	kg oil eq	24.70	12.35	6.17	24.86%

of triennial, quinquennial and decennial replacement of a carbon fibre foil is shown in Appendix, Table K.

The transportation of the seal to plant 3 (Fig. 1) for replacement accounts for over 95% of environmental impact in all but two categories; photochemical oxidant formation and terrestrial ecotoxicity. Reduction of a seal replacment from triennially to quinquennially or decennially will reduce the climate change effect by between 1.4 and 3.3 tonnes of CO_2 eq respectively.

4.1.3. Transport of service engineer

Inspections of renewable energy devices by service engineers from the original equipment manufacturer (OEM) are common to maintain optimal energy production. Although maintenance can be conducted by operators of more mature technologies where there are more systems in operation and more mature maintenance strategies, for example onshore wind, in a substantial amount of instances maintenance is still commonly conducted by the OEM. The percentage change per MWh of annual, biennial and triennial visits by an engineer is shown in Appendix, Table L.

The areas of significant change are those associated with air travel such as ionising radiation, natural land transformation and terrestrial acidification. Transporting an engineer increases the carbon intensity of a 5-year deployment by 6.11% for an annual service, 3.05% for a biennial service and 2.04% for a triennial service. An annual service on a 10-year deployment increases the carbon intensity by 12.21%, a biennial service by 6.11% and a triennial service by 4.07%. A service engineer visiting annually on a 20-year deployment increases carbon intensity by 24.43%, biennially by 12.21% and triennially by 8.14%. Over a 20-year deployment of Rivgen® a triennial engineer visit compared to an annual visit would create an additional saving of 19.90 tons of CO_2 eq.

In summary, due to the lower initial environmental impact associated with longer deployment times, transporting an engineer to Igiugig for service has a larger environmental impact on the 20-year than the 10-year deployment, and on the 10-year versus the 5-year deployment of Rivgen®.

4.2. Power output from Rivgen®

Depending on the siting of the device along the Kvichak River the velocity of the river can vary significantly, see Appendix, Table A. The resulting annual power outputs would be 150.28 or 222.59 MWh. The changes to environmental impacts are shown in Table 5 and Table 6.

Table 5
Midpoint environmental impacts of 1 MWh of Rivgen® electricity production for Igiugig, Alaska at Site B.

Impact category	Unit	Years of Deployment		
		5	10	20
Climate change	kg CO_2 eq	162.65	81.32	40.66
Ozone depletion	kg CFC-11 eq	1.56E−05	7.80E−06	3.90E−06
Terrestrial acidification	kg SO_2 eq	1.64E−01	8.22E−02	4.11E−02
Freshwater eutrophication	kg P eq	5.40E−02	2.70E−02	1.35E−02
Marine eutrophication	kg N eq	1.94E−02	9.72E−03	4.86E−03
Human toxicity	kg 1,4-DB eq	63.78	31.89	15.94
Photochemical oxidant formation	kg NMVOC	4.64E−01	2.32E−01	1.16E−01
Particulate matter formation	kg PM_{10} eq	5.06E−01	2.53E−01	1.27E−01
Terrestrial ecotoxicity	kg 1,4-DB eq	2.05E−02	1.02E−02	5.12E−03
Freshwater ecotoxicity	kg 1,4-DB eq	2.97E+00	1.48E+00	7.42E−01
Marine ecotoxicity	kg 1,4-DB eq	3.09E+00	1.55E+00	7.73E−01
Ionising radiation	kBq U_{235} eq	3.92E+00	1.96E+00	9.79E−01
Agricultural land occupation	m^2a	20.95	10.48	5.24
Urban land occupation	m^2a	2.62E+00	1.31E+00	6.56E−01
Natural land transformation	m^2	2.51E−02	1.26E−02	6.28E−03
Water depletion	m^3	1.98E+01	9.90E+00	4.95E+00
Metal depletion	kg Fe eq	230.15	115.07	57.54
Fossil depletion	kg oil eq	45.98	22.99	11.49

5. Discussion

Isolated remote communities currently have to rely on fossil fuel resources which are transported large distances to provide electricity. The associated effects of this electricity production method can be a burden, both environmentally and economically. The current carbon intensity of Igiugig electricity generation is 1345 kg CO_2 eq/MWh, and along with several other environmental impacts there is an annual emission from energy alone of 451 tons of CO_2 eq. In order to summarise the main results, Fig. 3 shows a comparison of environmental impacts of

Table 6
Midpoint environmental impacts of 1 MWh of Rivgen® electricity production for Igiugig, Alaska at Site C.

Impact category	Unit	Years of Deployment 5	10	20
Climate change	kg CO_2 eq	109.81	54.91	27.45
Ozone depletion	kg CFC-11 eq	1.05E−05	5.27E−06	2.63E−06
Terrestrial acidification	kg SO_2 eq	1.11E−01	5.55E−02	2.78E−02
Freshwater eutrophication	kg P eq	3.65E−02	1.82E−02	9.11E−03
Marine eutrophication	kg N eq	1.31E−02	6.56E−03	3.28E−03
Human toxicity	kg 1,4-DB eq	43.06	21.53	10.77
Photochemical oxidant formation	kg NMVOC	3.13E−01	1.57E−01	7.84E−02
Particulate matter formation	kg PM_{10} eq	3.42E−01	1.71E−01	8.55E−02
Terrestrial ecotoxicity	kg 1,4-DB eq	1.38E−02	6.91E−03	3.45E−03
Freshwater ecotoxicity	kg 1,4-DB eq	2.00E+00	1.00E+00	5.01E−01
Marine ecotoxicity	kg 1,4-DB eq	2.09E+00	1.04E+00	5.22E−01
Ionising radiation	kBq U_{235} eq	2.64E+00	1.32E+00	6.61E−01
Agricultural land occupation	m^2a	14.15	7.07	3.54
Urban land occupation	m^2a	1.77E+00	8.86E−01	4.43E−01
Natural land transformation	m^2	1.70E−02	8.48E−03	4.24E−03
Water depletion	m^3	1.34E+01	6.69E+00	3.34E+00
Metal depletion	kg Fe eq	155.39	77.69	38.85
Fossil depletion	kg oil eq	31.04	15.52	7.76

the following scenarios; unfavourable, median, favourable and best. A definition of the scenarios encompassing years of deployment, site, service engineer visits, foil replacement, and seal replacement shown in Appendix A, Table M. Table 7 shows the environmental saving compared to the same energy generation from the baseline, diesel electricity generation.

Across the scenarios climate change effects were produced of 175.56 kg CO_2eq/MWh, 59.40 kg CO_2 eq/MWh, 19.28 kg CO_2 eq/MWh and 17.60 kg CO_2 eq/MWh for the unfavourable, median, favourable and best cases respectively. However, even the unfavourable electricity generation scenario using the river current device will outperform electricity generation using diesel where 879 tonnes of CO_2 eq would be produced. A best-case scenario will create a saving of 9277 tonnes of CO_2 eq over the period of deployment, 20 years, versus diesel electricity production. As would be expected, a significant saving in fossil depletion is also produced. In an unfavourable scenario a reduction of 496 tonnes oil eq is achieved while in a best case 4934 tonnes of oil eq is achieved.

While a number of environmental savings can be achieved there are some environmental burdens if the device is deployed unfavourably. Agricultural land occupation, water depletion and metal depletion will not produce an environmental saving in both unfavourable and median scenarios. It is therefore suggested that at least a 10 to 20-year deployment is used to reduce these impact categories, which are all linked to the mass of metal contained within the Rivgen® device. These devices should have a deployment of at least 20 years, as is ORPC's design life which is also in line with other hydrokinetic devices. Improvement of maintenance practices for devices will be key to reducing environmental impact and sustainability. It is the key to improvement of longevity, decreasing of the cost of deployment and ultimately the cost of energy production. Adoption of the renewable energy technology in a single site can have a substantial environmental saving versus electricity generation from diesel. A point of note is that Sood and Singal [52] reviewed MHK devices, reporting limited environmental impact as long as excessive energy extraction does not occur e.g. does not affect environmental equilibrium of the system. Recent developments in the use of LCA to evaluate the merits of RES have applied multi-criteria decision-making analysis to further assess the environmental impacts of the technologies and better inform decision making processes in the construction of RES [53]. Therefore, it is recommended that a detailed environmental analysis is conducted upon installation of a device to test and monitor any environmental changes.

Comparing RivGen® with other MHK and tidal devices shows, even in this remote region, a comparable figure for climate change and other environment burdens is possible. Compared against the 800 kW Oyster 800 device [46], the Rivgen® device out performs Oyster in terms of

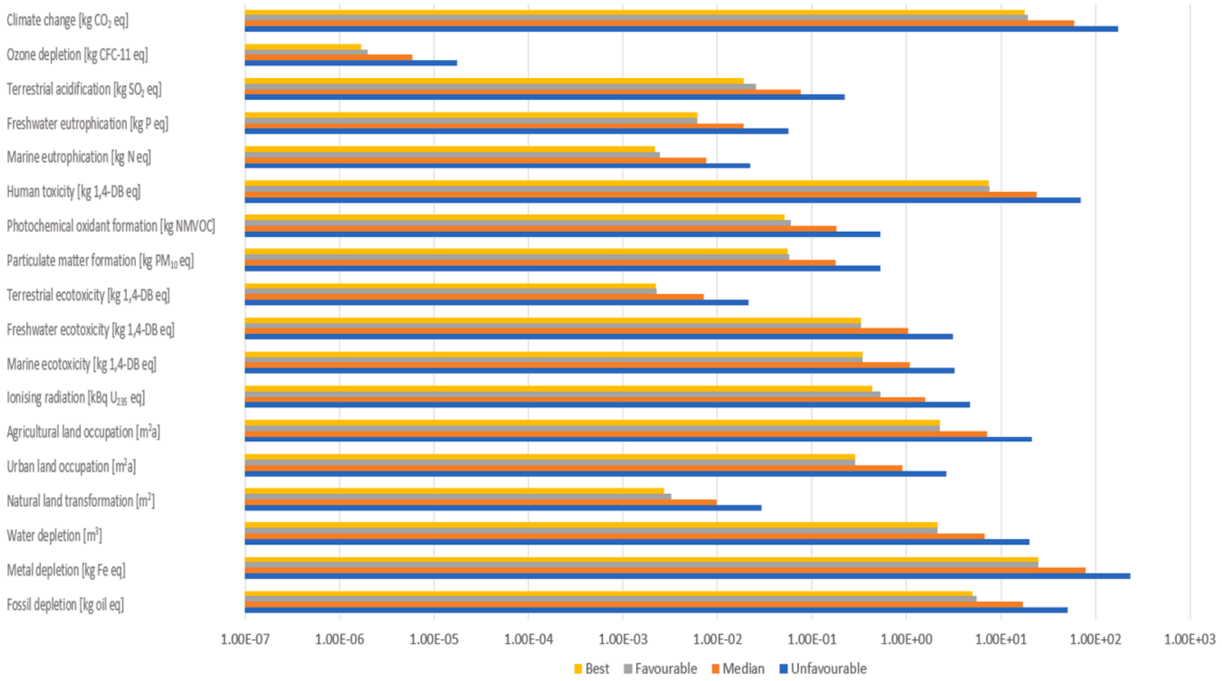

Fig. 3. Midpoint Analysis of Rivgen® deployment under best, favourable, median and unfavourable deployment scenarios.

Table 7
Summary of environmental savings compared to baseline electricity generation.

Impact category	Unit	Unfavourable	Median	Favourable	Best
Climate change	kg CO_2 eq	879,063	2,862,636	9,265,196	9,276,966
Ozone depletion	kg CFC-11 eq	1.28E-01	4.05E−01	1.30E+00	1.30E+00
Terrestrial acidification	kg SO_2 eq	9928	29,736	93,681	93,726
Freshwater eutrophication	kg P eq	32.23	179.05	653.03	653.30
Marine eutrophication	kg N eq	533.33	1612.78	5097.61	5099.78
Human toxicity	kg 1,4-DB eq	488,446	1,549,988	4,977,685	4,979,046
Photochemical oxidant formation	kg NMVOC	14,995	45,204	142,731	142,792
Particulate matter formation	kg PM_{10} eq	4714	14,741	47,113	47,129
Terrestrial ecotoxicity	kg 1,4-DB eq	9.80	60.25	223.06	223.37
Freshwater ecotoxicity	kg 1,4-DB eq	6587	24,058	80,464	80,483
Marine ecotoxicity	kg 1,4-DB eq	6045	22,635	76,202	76,221
Ionising radiation	kBq U_{235} eq	49,870	154,684	492,917	493,604
Agricultural land occupation	m^2a	−11,236	−2232	26,830	26,864
Urban land occupation	m^2a	350	4976	19,904	19,929
Natural land transformation	m^2	270.65	844.67	2697	2701
Water depletion	m^3	−13,014	−9305	2667	2684
Metal depletion	kg Fe eq	−145,850	−89,583	92,069	92,116
Fossil depletion	kg oil eq	496,569	1,545,160	4,930,063	4,934,106

carbon intensity 65.5 kg CO_2eq/MWh compared to 59.40 kg CO_2 eq/MWh in a median scenario even though it produces only 10% of the power. The Rivgen® device has a larger carbon intensity (kg CO_2/MWh) compared to larger devices, such as SeaGen, 15 kg CO_2 eq/MWh and river barrage devices [21]. Although the overall climate change figure for construction of SeaGen (1418 tCO_2eq) is significantly higher than that Rivgen® (122 tCO_2eq). In comparison to other renewable energy technologies, Rivgen® also compares favourably. A study by Javed, Ma, Jurasz and Mikulik [54] reported a renewable energy system for Jiuduansha, China, using solar PV and pumped hydro, had emissions of between 72 and 148 kg CO_2 eq/MWh. A photovoltaic power system, including batteries, as reported by Akinyele and Rayudu [55] had emissions of 50 kg CO_2/MWh.

Beyond the environmental benefits, the application of a micro scale renewable electricity generation device harnessing hydrokinetic river energy has potential for other remote and/or island communities. The lack of civil works required for the installation of the RivGen® device compared to the other renewable energy technologies in remote regions are of particular interest. A RivGen® device is deployed in under a week with the majority of work being performed to connect to the microgrid. An interesting area of deployment is in remote regions with shallow water depths, for example Malaysia [56], as the Rivgen® device is not bottom mounted, and can therefore be floated down a river compared to fixed bottom tidal devices. By communities also being able to perform maintenance the improved environmental benefit is matched with a decreased dependency on OEMs. The community can become renewable and sustainable while reducing the energy cost by a potential 30% [47].

6. Conclusions

The overall aim of this study was to evaluate the life cycle environmental impacts of a river current device, ORPC's Rivgen®, being substituted for diesel electricity generation in Igiugig, Alaska as a case study for remote community electricity generation. The river current device is situated in an area, which has taken cognisance of economic, environmental and socio-cultural factors.

The evaluation of the environmental impacts via ReCiPe midpoint and endpoint suggests that the transition from diesel electricity generation will be environmentally beneficial. At a minimum the carbon intensity of energy generation will be reduced by at least 1169.90 kg CO_2 eq/MWh from 1345.46 to 175.56 kg CO_2 eq/MWh in the most unfavourable scenario. This lowers the carbon intensity of the electricity from 6564.49 kg CO_2 eq/person to 85.33 kg CO_2eq/person. While O&M in other renewable energy devices contributes to the environmental impact of the device, the main issue with O&M in this study is the transportation of materials and resources to the area. The device can become more environmentally benign by training local operators to service the device and produce components locally, if needed. The demonstration of community lead O&M reducing the environmental impact of electricity production by between 0.03 to 25.50 %, depending on environmental impact category presents a significant environmental benefit of alongside a potential socioeconomic benefit.

This will not only make the device environmentally perform better but also help develop a more sustainable community, as set out under UN SDG 11. The production of renewable electricity and reduction of environmental impact will also contribute to UN SDG 7 and 13.

7. Disclaimer

The views and opinions expressed in this paper do not necessarily reflect those of the European Commission or the Special EU Programmes Body (SEUPB).

CRediT authorship contribution statement

Christopher S. McCallum: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **Narendran Kumar:** Data curation, Writing - review & editing. **Robin Curry:** Resources, Formal analysis, Writing - review & editing. **Katherine McBride:** Writing - review & editing. **John Doran:** Conceptualization, Resources, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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