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A benchmark for life cycle air emissions and life cycle impact assessment of hydrokinetic energy extraction using life cycle assessment

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A B S T R A C T

As the demand for renewable energy increases, it becomes important to critically examine the environmental impacts of renewable energy production. Often, the approach has been trial and error in renewable energy with respect to its impact on the environment. Hydrokinetic Energy Extraction (HEE) has been seen as a potentially “benign” form of renewable hydropower. This paper provides a benchmark for initial measurement of HEE environmental impacts, since negative outcomes have been present with previously assumed “benign” renewable hydropower. A Gorlov system was used to represent a HEE system. Life Cycle Assessment (LCA) was utilized to compare the environmental impacts of HEE with small hydropower, coal, natural gas and nuclear power. Environmental Protection Agency (EPA) criteria air emissions were quantified and compared over the life cycle of the systems. Life cycle air emissions were used in combination with TRACI to compare the systems. The Gorlov system was found to have the lowest life cycle impact with a system lifetime comparison, and did compare closely with small hydropower.

1. Introduction

Increasing energy needs and strained energy supply are the forces behind advocacy for more renewable energy. However, renewable energy implementations in the past have not always been entirely environmentally beneficial. The case has been made in previous publications for environmentally-conscious efforts in approaching and determining the value of such technologies [1–4]. Here, the focus is on hydrokinetics for energy extraction in rivers, also termed river current energy. Hydrokinetic energy extraction (HEE) may also be applied in other cases, such as tidal or wave, and involves the extraction of kinetic energy, rather than potential, which is the energy mode present in traditional hydropower dams.

The various hydrokinetic energy technologies have some overlap, but can be generally categorized as: axial and cross flow turbines (shown in Fig. 1), vortex shedding, and dynamic augmentation for localized increased extraction [5–10]. To date, cross flow turbines have shown the greatest potential in river HEE [11,12]. Of these types, Savonius (Fig. 1a) and squirrel cage (Fig. 1b) and Gorlov (helical) Darrieus (similar to Fig. 1b, but with twisted blades) turbines have been tested. A more detailed summary of these turbines is given in Miller and Schaefer [13]. Squirrel cage and Gorlov (helical) Darrieus turbines were found to have higher energy extraction levels due to the lift extraction mechanism. Basic principles were applied to calculate this energy extraction, but detailed computational fluid dynamics (CFD) and life cycle assessment (LCA) models have not been developed and analyzed.

In addition to illuminating turbine performance details, such as shape and orientation for power optimization, CFD can be used to provide details of the flow regime. Fish impingement and sediment movement are just two of the environmental impacts for concern in implementing HEE systems [2]. Fish swimming studies have shown preference for lower turbulent regions within the flow field. With flow field CFD, low turbulent regions can be determined and, therefore, fish passage can be estimated. Representative CFD models are presented in [13,14]. In this same manner, LCA principles give insight into specific environmental impacts related to emissions and life cycle energy consumption associated with HEE. Environmental impact assessment methods, in general, have not been developed to quantitatively measure environmental impact for HEE systems. With these data types, it can be made clear which type of energy generation has fewer emissions and is therefore better for the environment.

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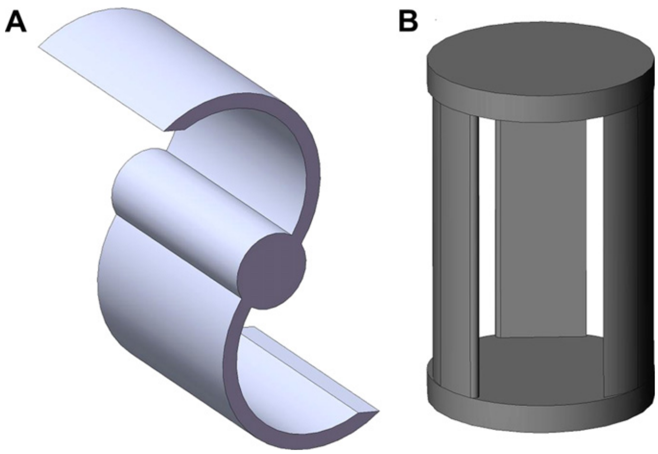

Fig. 1. Cross flow hydrokinetic energy extraction turbines.

Traditional hydropower has been reviewed within LCA to give insight toward emissions expelled during construction, operation, and decommissioning. A variety of outcomes were found. In a comparison of a large dam and small dam, the larger dam was found to be favorable based on Green House Gas (GHG) emissions and payback ratios [15]. However, unlike the small dam case, HEE is not expected to have high emissions per material levels, as its inherent design gives a more reasonable material/infrastructure need per power output. For a general energy assessment, hydropower and run-of-river hydropower (which is the type of small hydropower that HEE is compared within this analysis) were found to have excellent performance with respect to the emissions given off for each system [16]. This study also pointed to some issues with applying LCA to hydropower; namely, that it does not include the benefits of having a reservoir, and its marked improvement of electricity reliability over other renewable technologies. Furthermore, not all LCAs account for other negative impacts associated with large scale hydropower, such as land use, industry disruption, and aesthetics. This study compares hydrokinetics with small hydropower, as these devices can be placed in similar locations.

2. Life cycle assessment of hydrokinetic energy extraction

To complete an emissions measurement for hydrokinetic energy extraction, Life Cycle Assessment (LCA) is used. Often when a process or product is examined or optimized, only the direct materials, labor, and operations cost are considered and not, for example, emissions and land use. LCA allows the practitioner to evaluate the environmental impacts caused throughout the entire life of the HEE system, from raw materials extraction and construction of the system to its use and maintenance for energy production, and ultimately, decommissioning. The associated guidelines are derived from the American National Standards Institute (ANSI) and the International Organization of Standardization (ISO) 14040 series [17,18]. Within LCA, four stages exist: the goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and interpretation and improvements. There are two types of LCI (process and input/output [19]), but for this case, process LCI will be used. Process LCI involves performing a material balance at each step in the product or process system where the boundaries have been defined by the analyst; the LCI databases are further described in Table 1. In comparing different types of energy extraction, it is beneficial to use process LCI because it allows for system breakdown, analysis, and improvement, which is not achievable in input/output LCI.

Table 1
Gorlov HEE system inputs.

Material	Amount	Description	Database
X12CrNi17 7 (301)I	64.2 kg	steel shafts	IDE MAT 2001 (24)
X12CrNi17 7 (301)I	30.84 kg	supports to mooring	IDE MAT 2001 (24)
ABS 30% Glass Fibre	103.98 kg	fiberglass turbine blades	IDE MAT 2001 (24)
Petrol unleaded stock CH S	2 kg	maintenance	ETH-ESU 96 (24)
X12CrNi17 7 (301)I	44.26 kg	generator, steel portion	IDE MAT 2001 (24)
Cu-E I	23.83 kg	generator, copper portion	IDE MAT 2001 (24)
Electricity UCPTE	7 kWh	construction and transport	ETH-ESU 96 (24)

The third stage of LCA, LCIA, then quantifies the impacts of each LCI. The LCIA is evaluated in this study using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) [20]. There are a wide range of impact assessment methods, including Eco-indicator 99, CML, TRACI, and others [20–22]. Eco-indicator 99 and TRACI are more common impact assessment methods to use based on their categorization of impact types (i.e., aquatic toxicity, ecotoxicity, and human health) and weighting methods. TRACI was chosen as the LCIA method because the impact categories are appropriate for the systems in this analysis, and they are defined for North America, giving a general impact assessment.

2.1. Goals, objectives, and scope

The general goal for HEE research is to improve its viability and advance the field through improved energy extraction, while also considering its potential environmental footprint. Specifically, in this study, the goal is to provide a benchmark life cycle air emissions and LCIA for HEE. The objectives to accomplish this are:

- Use LCI to provide an emissions framework associated with HEE. A functional unit of 100 years system lifetime in MJ will be used to compare HEE with small hydropower, and coal, gas, and nuclear plants.
- Use TRACI to conduct an LCIA for HEE, small hydropower, and coal, gas, and nuclear plants for comparison.

The choice of MJ as a system lifetime functional unit is based on the type of energy analysis conducted and the corresponding sizes of the systems. The use of kW − h, or kW on an hourly basis, is more appropriate for energy consumption analyses.

This study highlights air emissions through comparison of HEE use with small hydropower or run-of-river power, and coal, gas, and nuclear plants. Air emissions that are of particular interest with energy systems are CO_2, CO, CH_4, NO_x, and SO_x. These are specifically identified by the Environmental Protection Agency (EPA) as key pollutants given off by the system types reviewed in this analysis. Furthermore, these are pollutants chosen when comparing energy systems in other analyses [23]. The system boundary for HEE is described in Section 2.2. System boundaries for small hydropower, and coal, natural gas, and nuclear power are set in SimaPro 7.1, the software used to compile the LCI. They include production and preparation, processing, storage, and transportation. Further details for the comparison systems in this analysis are given in the following section.

2.2. System boundaries

Fig. 2 describes the HEE system boundaries. The diagram shows "upstream" materials, which is a general term describing the raw materials needed to make the primary 'materials' or components of each system. The "upstream" designation also includes the energy