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

Veronica B. Miller, Amy E. Landis, Laura A. Schaefer

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.

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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.
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.

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 of HEE systems are CO₂, CH₄, NOₓ, and SO₂. 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

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
<th>Description</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>X12CrNi17 7 (301)</td>
<td>64.2 kg</td>
<td>steel shafts</td>
<td>IDE MAT 2001 (24)</td>
</tr>
<tr>
<td>X12CrNi17 7 (301)</td>
<td>30.84 kg</td>
<td>supports to mooring</td>
<td>IDE MAT 2001 (24)</td>
</tr>
<tr>
<td>ABS 30% Glass Fibre</td>
<td>103.98 kg</td>
<td>fiberglass turbine blades</td>
<td>IDE MAT 2001 (24)</td>
</tr>
<tr>
<td>Petrol unleaded</td>
<td>2 kg</td>
<td>maintenance</td>
<td>ETH-ESU 96 (24)</td>
</tr>
<tr>
<td>stock CH S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X12CrNi17 7 (301)</td>
<td>44.26 kg</td>
<td>generator, steel portion</td>
<td>IDE MAT 2001 (24)</td>
</tr>
<tr>
<td>Cu-E 1</td>
<td>23.83 kg</td>
<td>generator, copper portion</td>
<td>IDE MAT 2001 (24)</td>
</tr>
<tr>
<td>Electricity UCPE</td>
<td>7 kWh</td>
<td>construction and transport</td>
<td>ETH-ESU 96 (24)</td>
</tr>
</tbody>
</table>
and emissions associated with each raw material. The processes for
the comparative energy systems are similar to those of the HEE
system, except that transportation, construction and/or assembly,
operation, and decommissioning may vary. In the case of construction
of a small hydropower plant versus assembly and set-up of the
hydrokinetic system, there will likely be more emissions involved
with the former since it has a more intricate infrastructure for the
development and extraction of energy. The same is true for trans-
portation and decommissioning.

Fig. 3 is analogous to Fig. 2 and represents the LCA-designated
materials and energy requirements of a HEE system. Table 1 provides
more detail for the inputs of Fig. 3 with the respective datasources
and construction and transportation detail specific to the HEE
process and used in the inventory analysis. The use of ‘generator’ in
Table 1 is a general term that includes power connections, lines, and
controls in addition to the system generator.

The LCIs for the comparison systems are available within
SimaPro 7.1 (an LCI software package based on process LCI) and are
based on energy extraction for Switzerland or Western Europe,
from the ETH-ESU 96 library [24]. One of the comparison systems is
a flow-through hydro system, also referred to as run-of-river set-
up, or small hydro. It is a system that uses potential energy from
rivers through extracting a small portion and developing head over
changes in elevation across land. Little or no storage is needed and
electricity is produced continually [24]. The inventory includes the
dam structure, tunnel, turbine, generator, plant operation, and
dismantling. More traditional generation systems are also used for
comparison to a HEE system. The coal energy plant definition
includes production of coal products (coke, briquettes, steam coal,
liignite) and electricity and thermal energy (industrial and
domestic) from coal combustion [24]. The inventory consists of coal
production and preparation, coal processing, storage and trans-
portation. Similarly, the gas electric plant includes production and
delivery of natural gas for industrial and domestic applications. The
inventory consists of gas field exploration, natural gas production,
gas purification, long distance transportation, and regional distri-
bution. Finally, the nuclear power plant includes uranium extrac-
tion and preparation, uranium conversion and enrichment, fuel
fabrication, electricity production with boiling water reactor (BWR)
and pressurized water reactor (PWR), reprocessing and interim and
final storage for low intermediate and high level waste.

2.3. Life cycle inventory

The LCI provides a complete list of materials and energy going
into and coming out of the entire process of each system. Informa-
tion for the system products come from databases within
SimaPro, as noted in Table 1. All available databases in this version
were used, including the Franklin database (a database containing
complete materials, transport, and energy for North America), but
IDE MAT 2001 and ETH-ESU 96 are the primary databases in use for
this study. Assumptions made in the analysis are the following:

- Since HEE does not currently exist within SimaPro, it was
defined as an energy process in SimaPro under the hydro
category. It was defined based on estimates of material,
transportation, and electricity use in constructing and oper-
ating the system. The basis for the inputs into this system
derives from available HEE literature [25].

- The functional system lifetime unit was calculated for each of
the systems and was recorded in MJ, since that represents
energy extracted from each system over the respective lifetimes (100 years).

Inventory for the HEE system was primarily based on an extensive report for a Gorlov turbine system [25]. HEE was entered into SimaPro as an energy category, meaning that SimaPro recognizes it as an energy producing system, taking into account available energy from nature (230 GJ in this case). Inputs are illustrated in Fig. 3 and given in Table 1. The input tree (Fig. 3) shows the main material/process categories that are used to produce a Gorlov turbine. They are X12CrNi17 7 (301), ABS 30% glass fibre, petrol unloaded stock CH T, Cu-E I, and electricity UCPE, all of which are defined in SimaPro. Transportation was accounted for using the petrol unloaded stock CH T, and the total amount is based on using semi-local materials, as was defined in a previous wind turbine project [26]. The X12CrNi17 7 (301) is a material type in SimaPro describing stainless steel, and in the tree it is only one block that contains three separate uses: steel shafts for the turbine, a mooring structure for the turbine, and a portion of the generator (as indicated in the table). ABS 30% fiberglass is the material indicated for the turbine blades according to the report used for this LCA. Since fiberglass is a highly valuable material for turbine blades in the Gorlov system, other material replacements were not investigated further. However, it should be noted that although this does effect the LCA results, since this is a base line analysis, pointing to various points of improvement, the overall effect is relatively insignificant. Furthermore, SimaPro 7.1 does not contain extensive information on fiberglass types. In addition to these material/process categories, electricity hydropower in CH S is included to account for auxiliary energy use in the overall Gorlov system. The amounts given in Table 1 were estimated based on information in the report about a single device weight and detail for implementation [25]. This was scaled to twelve units for a realistic power extraction scheme. The choice of twelve units is somewhat arbitrary and dependant upon system utilization, meaning an implementation site may not allow for this system size or may allow for a larger system size. However, the size was chosen to give a realistic comparison to actual system implementation, since it may not be cost effective to use a smaller system, and also to compare it with the other similar systems, such as small hydropower. One Gorlov turbine is rated to give 500 W, so twelve units give 6 kW of energy, which converts to 189 GJ annually. Information for the generator portion was estimated based on an LCI for wind turbines [26].

### 2.4. Results

In this comparison of power systems, it was important to analyze them over their total lifetimes, as different plants will have different emissions ratings for the corresponding lifetimes. Coal, gas, and nuclear were assumed to have 100 years of operation, a reasonable lifetime [15]. A more conservative estimate is 50 years for small hydropower and the Gorlov system; however, for comparison, two of each system were used [23], meaning two 50 year systems equaling 100 years of small hydropower and Gorlov system operation. CO₂, CH₄, NOx, and NOx air emissions were highlighted within this study because they are often associated with energy systems. NO₂ could also be included in this list; however these emissions are generally negligible. Table 2 contains life cycle air emissions of interest for each energy system. In Table 2, Small Hydro is an abbreviation for small hydropower. The Gorlov HEE has a lifetime NO₂ emission of 17 kg, which substantiates the assertion that this contribution can be treated as negligible.

As expected, Table 2 shows large life cycle air emissions for a coal and gas power plants. Each system emits large amounts of CO₂: 82,808 kg from small hydropower, 24,428,587 kg from coal power, 16,339,490 kg from gas power, and 380,836 kg from nuclear power. The Gorlov HEE system emits less of each compound compared with the small hydropower system.

TRACI was applied to each entire energy system LCI developed within SimaPro, which includes approximately 1500 inventory compounds in addition to the air emissions highlighted in Table 2. The results were normalized by setting the largest system impact equal to one and calculating the percentage impact in comparison for the rest of the systems shown in Fig. 4. In Fig. 4, Sm Hydro is the abbreviation for small hydropower. The TRACI results show similar trends to the emissions data, in that the coal and gas power plants were found have significant environmental impacts related to global warming, acidification, eutrophication, ecotoxicity, and smog formation. Nuclear was found to contribute the highest level ozone depletion among these systems. In fact, Fig. 4 shows the Gorlov and small hydropower systems to have virtually no global warming or ozone depletion impact in comparison to the traditional systems. This is a key point since a considerable reason for their implementation is to reduce emissions in these specific areas. For further comparison, Fig. 5 shows normalized TRACI results for small hydropower and the Gorlov HEE system. Small hydropower has higher impacts in each category with the exception of acidification and respiratory effects.

To investigate this further, a component impact analysis was performed. Fig. 6 shows the contribution of major inventory emissions to the LCIA for acidification impacts. This is a complete list of compounds emitted for these systems where all compounds were emitted to air; water and soil emissions were insignificant. The largest contributor in the Gorlov system is sulfur dioxide, equaling 22,269 hydrogen moles per 100 years (a unit used to characterize acidification within TRACI). The largest contributors for the small hydropower system were nitrogen oxides at 6519 hydrogen moles per 100 years and sulfur oxides at 5404 hydrogen moles per 100 years. The respiratory effects component breakdown is shown in Fig. 7, and is a complete list of emitted compounds. Again, the major inventory compounds are air emissions, and the

<table>
<thead>
<tr>
<th>Power type</th>
<th>CO₂ (kg)</th>
<th>CO (kg)</th>
<th>CH₄ (kg)</th>
<th>NOx (kg)</th>
<th>SO₂ (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gorlov HEE</td>
<td>24848</td>
<td>178</td>
<td>26</td>
<td>102</td>
<td>55</td>
</tr>
<tr>
<td>Small hydro</td>
<td>82808</td>
<td>534</td>
<td>206</td>
<td>326</td>
<td>213</td>
</tr>
<tr>
<td>Coal plant</td>
<td>24428587</td>
<td>6090</td>
<td>97989</td>
<td>25020</td>
<td>26217</td>
</tr>
<tr>
<td>Gas plant</td>
<td>16339490</td>
<td>10923</td>
<td>96814</td>
<td>30647</td>
<td>12404</td>
</tr>
<tr>
<td>Nuclear plant</td>
<td>3808316</td>
<td>582</td>
<td>1296</td>
<td>1052</td>
<td>2506</td>
</tr>
</tbody>
</table>

*Fig. 4. Normalized impact assessment using TRACI.*
largest contributor in the Gorlov system is sulfur dioxide at 106 kg PM2.5 equivalent per 100 years. Fig. 8 shows the percentage impact in each category from the Gorlov system materials and processes. It should be noted that in both the acidification and respiratory effects categories the main contributor is copper from the generator within the system. Copper contributes 85 and 93% to the respective categories. This is from the production of copper; however, new paths for SO2-free copper production are under investigation [27].

Some of the categories where the small hydropower system was dominate were also partitioned further. These categories are ecotoxicity, shown in Fig. 9, and non-carcinogens, shown in Fig. 10. The contributors to ecotoxicity are more complex than the two previously mentioned categories. Table 3 is provided to show the breakdown of each component by water, air, and soil, and also by ion versus non ion component, where Fig. 9 sums each of these. These results show 95% of compounds emitted. Other compound emission contributors were less than 5%, and therefore negligible. The original aluminum ion contribution to water by both systems were reported as significantly high, 36,230 and 327 kg 2,4-D equivalent for the small hydropower and Gorlov systems respectively. Aluminum water contribution was approximately 85% for small hydropower and approximately 53% for the Gorlov system. This high contribution is not supported by literature and was therefore removed and the impact was recalculated, as reflected in Table 3 and Fig. 9. This error in the impact assessment component breakdown is thought to be an error within the SimaPro database, which cannot be determined within this analysis. After the impact recalculation, the dominant inventory emissions for the small hydropower system are aluminum in air and soil contribution equaling 1581 2,4-D equivalent; copper, ions in water and copper in air equaling 1888 2,4-D equivalent; zinc in water, air, and soil equaling 1934 2,4-D equivalent; and nickel, ions in water and nickel in air equaling 842 2,4-D equivalent. For the non-carcinogens breakdown (Fig. 10), the components are separate and shown in kg toluene equivalent. Emission contributors of less than 5% were neglected. Lead emissions to both water and air are the largest contributors for small hydropower within non-carcinogens, 2,798,220 and 123,685 kg toluene equivalent, respectively. The largest contributor for the Gorlov system in this category is dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin, equaling 86,133 kg toluene equivalent.

2.5. Discussion

The comparative LCA models a Gorlov system’s life cycle impacts and compares them with the emissions from other energy systems: small hydropower, and coal, gas, and nuclear power. LCA models of
any type have currently not been applied to hydrokinetic energy, and this model therefore provides a base upon which future work can build. From this analysis, it can be seen that Gorlov hydrokinetic energy extraction is favorable when compared with small hydropower. Furthermore, it is noteworthy to point out the similarities of the squirrel cage Darrieus turbine (shown in Fig. 1b) to the Gorlov system, indicating the possible use of the Gorlov LCI for the squirrel cage Darrieus system. This is possible because turbine construction is similar and the support system (mooring structure and generator) would be the same. Much of this study is based on estimates derived from HEE literature, and specifically the Gorlov system. The analysis could be improved with more detailed system construction and installation information and would be most appropriately performed as a case study or in combination with a specific HEE project for data collection.

Further environmental investigations could also indicate the Gorlov system superiority over small hydropower because of their infrastructure differences. This is based on the negative environmental effects experienced by small hydropower use, such as changes to the overall flow regime (decreased flow and temperature differences) from stream diversion [1,4,28,29]. In addition to the work that is already being conducted on fish passage estimation based on swimming preference data and CFD, a new impact metric should be developed to effectively account for system degradation to the local river ecosystem due to energy production.

In the hydrokinetic energy field, LCA has not been previously applied. Often, hydrokinetic energy is viewed as an environmentally benign form of energy, since it is a form of renewable energy and has been designed with the environment in mind. Given today’s energy needs and increasing GHG emissions, it may not be entirely appropriate to assign much weight to small amounts of GHG emissions or other slightly harmful effects a potential system may have. However, it is important to have this information, which is proven by the way dams have been approached. Dams were put forth as a means to extract cheap, environmentally benign energy. However, data show this last point to not be true. In addition to flooded lands and decreased downstream flow, these outcomes caused vegetation changes, impacts on fish and bird populations, and destruction of wetlands and local flora and fauna [3,30–36].

### 3. Conclusions

GHG emissions have not previously been quantified for any HEE system. This paper presents GHG emissions for a Gorlov HEE system. The results are compared with that of small hydropower, and coal, gas, and nuclear plants. Small hydropower is a comparable system to a Gorlov HEE system, while the other types are viewed as a mix of energy types. Details are presented to provide a benchmark in HEE inventory analysis, which can be used in future LCA studies of comparative power generation types. Gorlov HEE was found to have similar life cycle impacts to that of small hydropower. The results of the study show that additional environmental metrics are needed. Similar to large scale hydropower, the issues of fish and local river ecology health still exist for hydrokinetic energy, and so a new LCA impact category is needed. Using estimated fish passage from HEE CFD and fish swimming data, a statistical metric can be constructed to give value for an impact category associated with aquatic technologies. Furthermore, the choice of fiberglass for turbine blades warrants more research. Fiberglass materials have been found to be rather toxic, thus highlighting the need for a suitable replacement.

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### References
