Life Cycle Assessment of Micro-hydropower Projects: Assessing Environmental Impacts and Identifying Carbon and Resource Efficiency Opportunities in Current Design

Takashi Ueda
taka4065@gmail.com

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract This research was conducted using a process-based life cycle assessment (LCA) to evaluate the environmental impacts associated with eleven micro-hydropower (MHP) installations in Wales. The primary data for the life cycle inventory (LCI) were collected and environmental burden data were accessed through some LCA databases in combination with a LCA software. Contribution and sensitivity analyses were conducted to identify the contribution of raw materials and activities to each major environmental impact category within MHP installations and examine the robustness of the results. The impact categories chosen to evaluate in this study are global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP), abiotic resource depletion (ARDP), and fossil resource depletion potential (FRDP). The means and standard deviation for these selected impact categories associated with the MHP schemes investigated (over an operational lifetime of 50 years) were as follows: 7.15 ± 3.10 gCO_2 eq./kWh GWP; 0.031± 0.011 g SO_2 eq./kWh AP; 13.19 ± 8.73 1,4-DCB eq./kWh HTP; 6.89E-05 ± 3.36 g Sb eq./kWh ARDP; 0.14 ± 0.049 MJ/kWh FRDP. Overall, the results of environmental impact categories investigated in this study were generally low compared with previous run-of-river HP LCA studies.

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1. Introduction

The introduction the Renewable Obligation led to significant growth in small-scale renewable energy systems in the UK, including micro-hydropower (MHP) plants. To date, only a few studies have investigated the environmental impacts associated with these MHP installations, with recent studies suggesting that carbon and resource savings can be attained through a life cycle design approach [1].

The aim of this study quantifies the environmental impacts of fourteen run-of-river MHP projects using life cycle assessment (LCA), and identify opportunities for carbon and resources savings. Four specific objectives have been identified to achieve this aim:

1. Carry out an Environmental Impact Assessment (EIA) to determine the environmental impacts for each MHP installation;
2. Investigate how flow rate and head characteristics affects environmental burden categories for each site;
3. Identify opportunities for mitigating the environmental impacts through a comparison of installation designs;
4. Explore eco-design opportunities in the construction of future run-of-river MHP schemes.

2. Methods

2.1. Hydropower case study

The location of the MHP plants investigated are predominantly within Snowdonia National Park (see Figure 1) in North Wales. High rainfall and steep mountainous terrain offer medium to high head hydropower sites, and the area has suitable water courses for developing run-of-river schemes. This makes North Wales a suitable region for the assessment of run-of-river MHP installation.

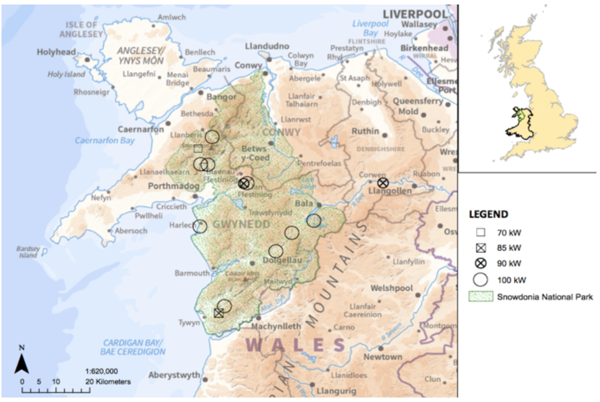

Figure 1. Locations of MHP schemes across North Wales.

The selected MHP schemes were constructed in North Wales in the UK between 2014-2015, and have a design capacity ranging from 70 to 100 kW. All projects are run-of-river schemes and share the same components: weir and intake, penstock, powerhouse including turbine and generator, and tailrace. A summary of the characteristics for each hydropower plant is listed in Table 1.

Table 1. Design characteristics of MHP schemes.

Site	Head [m]	Flow [l/s]	Design Capacity [kW]	Annual Energy Output [MWh]	Turbine Type
1	24	580	90	189	Crossflow
2	29	401	100	306	Crossflow
3	41	340	100	481	Crossflow
4	44	336	100	285	Crossflow
5	60	207	85	226	Turgo
6	82	190	100	372	Turgo
7	105	145	100	386	Turgo
8	128	100	100	390	Turgo
9	130	115	90	220	Turgo
10	133	70	70	212	Turgo
11	135	108	100	471	Turgo
12	144	101	100	499	Turgo
13	171	85	100	553	Turgo
14	215	44	70	237	Turgo

2.2. LCA of MHP plants

In order to assess the environmental impacts of the MHP schemes investigated, a process-based LCA method was adopted and carried out following ISO 14040 guidelines [2]. To undertake the LCA, a 'cradle-to-gate' system boundary was selected and hence the operation stage and the end of life stages were omitted from this investigation (Figure 2). The functional unit selected for this study was 1 kWh of electricity generated. The primary data for the life cycle inventory (LCI) were collected and environmental burden data were provided by the *Ecoinvent database v2.2* [3]. LCA software, Open LCA version 1.6.1 [4], was used for all calculations, in combination with the CML baseline method [5].

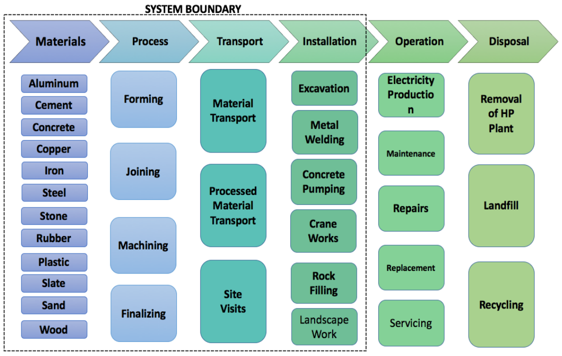

Figure 2. Process map and LCA system boundary for a MHP scheme.

2.3. Inventory for LCA case studies

Primary data related to the MHP installations were collected from the following sources, as outlined by Table 2, which shows the availability of the following data availability for each site:

- Approved drawings
  General manufacturing system layout drawings, including electricity generation plan;
- Detailed drawings
  Including further details of intake, penstock and power house structures;
- Bills of Materials and Actual data
  A detailed list that contains all the materials used in the design process. Manufacturing processes, transportation and logistics for components were also provided by contractors, suppliers and project manager.

As presented in Table 2, the data obtained for sites No.4, No.11, and No.14 were only approved drawings, and the material quantities and manufacturing processes calculated at these sites were mostly based on assumptions. Since their data quality is questionable and limits the accuracy, the LCA results calculated for these sites were omitted, leaving eleven run-of-river MHP projects for analysis

Table 2. Data availability for each MHP scheme.

Site No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Approved drawings	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Detailed drawings	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓	
Material bills & actual data	✓	✓	✓		✓	✓	✓		✓	✓		✓	✓	

3. Results & discussion

This chapter presents the results and discussion of the LCA associated with the eleven MHP projects. For the sake of simplicity, the following five relevant impact categories from the CML-IA baseline method [5] were chosen to present: global warming potential (GWP); acidification potential (AP); human toxicity potential (HTP); abiotic resource depletion (ARDP); fossil resource depletion potential (FRDP). Each of these impact categories directly signify three major impact areas – ecosystem, human health and resources. In addition, the number of previous LCA studies reviewed [1,8,9, 10,11] have included to analyze four or more of these impact categories. Accordingly, the selection of impact categories to be presented in this results section is based on valid criteria.

3.1. Contribution analysis

To determine the contribution of each material to different impact categories per kWh of electricity generated for each MHP scheme, a contribution analysis was conducted. Figure 3, provides a material breakdown of five selected environmental burdens for each HP project.

As can be seen in Figure 3, plastics are the main contributor to GWP (accounts for 27 - 50% of the total GWP) and FRDP (accounts for 57 – 77% of the total FRDP) for the MHP case studies in terms of material categories. This was mainly due to a large amount of high-density polyethylene (HDPE) plastics contained within the penstock, causing high GWP and FRDP impacts within this section. Metals are predominantly responsible for several impact categories, especially AP, HTP and ARDP. This was caused by the need for a long sensing cable connection at each site, which is assumed to be installed 5-core copper steel wired armored cable. The installation of site No. 6 is significant compared to the rest of MHP installations. This was mainly due to an upgrade of nearly 3 km of single1-phase HV cable to three-phase HV cable, which is assumed to a bare copper cable. Since copper is one of the main contributors to the environmental impact associated with HTP and ARDP, this scheme made a significant impact on these two impact categories.

3.2. Normalized results of MHP case studies

To observe the overall environmental performance of the MHP case studies, each impact category has been normalized with respect to European reference values obtained from CML characterization database [5]. The normalized results are presented based on two characteristics: installed capacity and types of turbines. While Figure 4a demonstrates the results between the average of the four representative MHP schemes with respect to the installed capacities, Figure 4b represents the normalized results based on the average values of each impact category for the crossflow and Turgo schemes.

In relation to installed capacity, the investigated MHP installations fall into four different categories (70 kW, 85 kW, 90 kW and 100 KW), and hence, the mean of the normalized results for the four representative MHP schemes are presented in Figure 4.11. Since the installed capacity of the majority of MHP schemes are 100 kW (sites 2,3,6,7,8,12 and 13), the mean normalized results for the rest of three categories of kW size are based on one or two schemes. As such, whilst the mean of seven 100 kW and two 90 kW (sites 1 and 9) installation have a range of values, the mean of 70 kW (site 10) and 85 kW (site 5) installations are based on one single scheme with no range value, which limit the confidence in the results.

As presented in Figure 4a, the 90 kW MHP schemes have the highest contribution to the majority of impact categories, whereas the installations of 100 kW MHP show the least overall environmental impact. This is mainly caused by the lowest head installation of site No.1 that has the highest impact on GWP and FRDP burdens (see Figure 4.12).

In addition, it can be seen that the contributions to study impact categories are similar between each MHP installation with different installed capacities, except for the impacts on GWP and FRDP. As seen in the previous results, the penstock comprised of HDPE plastics accounts for the vast majority of the environmental impact categories investigated, especially on GWP and FRDP in the MHP case studies. This reflects the results of high impact on these two categories. Overall, as the narrow range of installed capacity of MHP plants was investigated, the trend observed in previous studies – the smaller the installed capacity, the higher the environmental impacts tended to be – was not witnessed in this research.

Figure 4b indicates that crossflow turbine MHP installations have higher GWP, AP and FRDP impact contributions than the MHP sites installed with Turgo turbine. This is mainly due to the difference in size of each component. Since each crossflow MHP schemes required larger intake structure and larger turbines, the construction of these components contribute more overall environmental impact compared with the Turgo MHP sites investigated. Furthermore, as the Turgo MHP sites with higher head can offer more nature-oriented intake systems, this assist to reduce intake construction materials and works, which involves the use of concrete and excavation work.

Although the Turgo MHP sites investigated, have higher impact on HTP and ARDP, their contributions to these impact categories are only slightly higher than the crossflow schemes. Thus, it is prominent to state that the crossflow MHP case studies have the worst environmental performance. On the other hand, the Turgo MHP schemes considered in this study show less overall environmental impacts on the five relevant impact categories and hence are the better project from an environmental performance perspective.

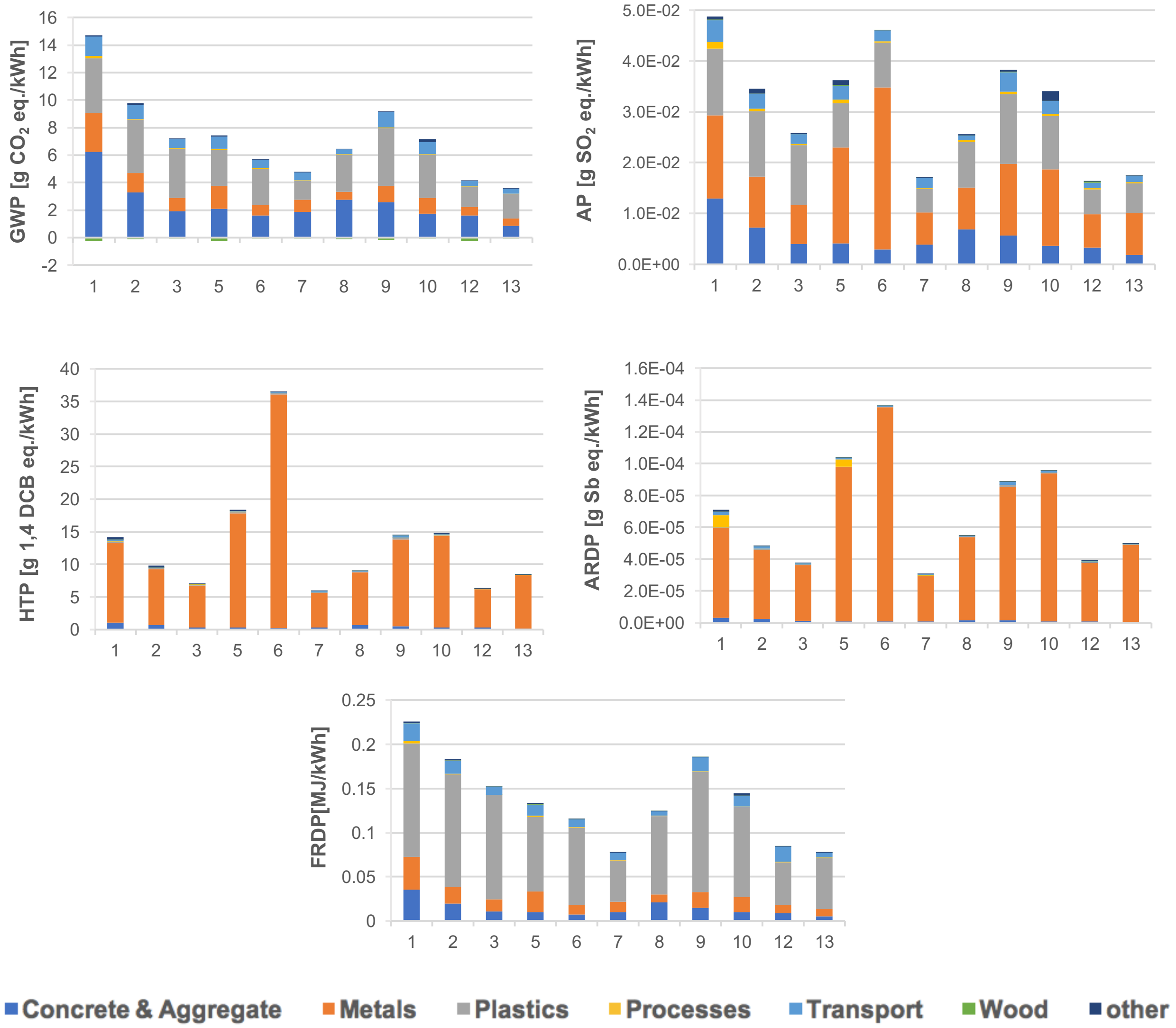

Figure 3. Material breakdown of environmental impacts of MHP schemes (expressed per kWh generated over project 50-year lifespan).

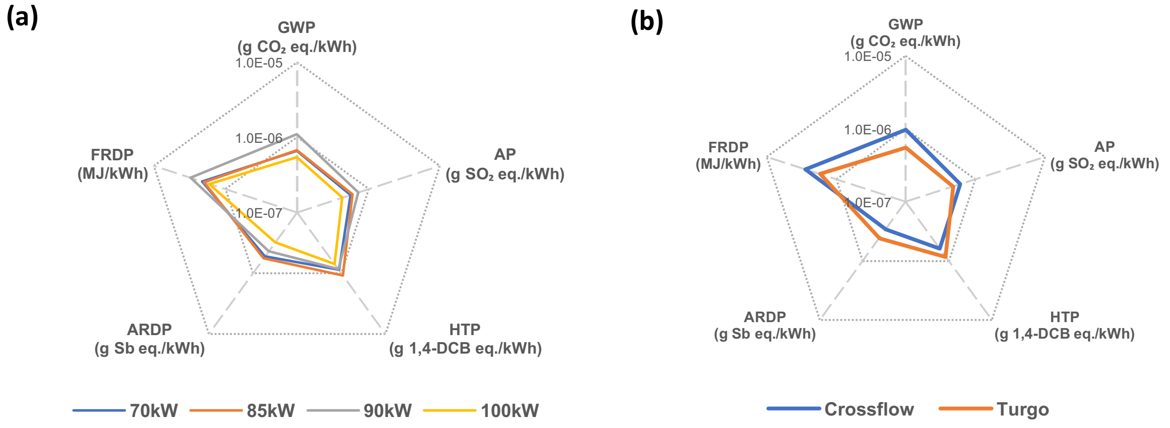

Figure 4. Normalized impact category results of MHP case studies (a) with respect to installed capacity (b) with respect to installed turbine type

3.3. Comparison of LCA results with previous research findings

In order to compare the results of this study with previous run-of-river LCA [1,6,7,8,9,10,11,12], Figure 5 illustrates the comparison between the LCA results of this study and previous studies. Even though the range of operational lifetime citied in the previous literature extends from 20 to 100 years, an operational lifetime of 50 years was assumed for this comparison. As such, the uncertainty associated with the lifespan of HP projects were omitted.

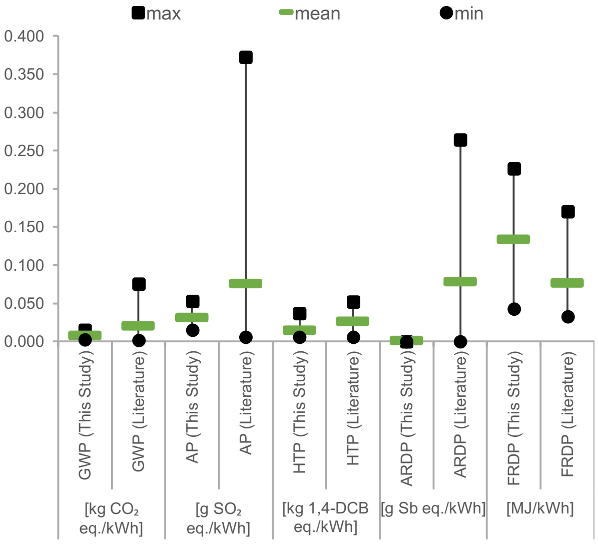

Figure 5. Comparison of results with other run-of-river HP LCA studies(expressed per kWh generated).

In comparison to other run-of-river schemes, the results of five selected environmental impact categories investigated in this study were generally low. Although a significant impact on HTP and ARDP associated with one of eleven MHP case studies was observed in this study, the impact category contributions to these two impact categories are nearly negligible compared to the results from previous studies. The large difference between the maximum and minimum values of AP and ARDP found in the previous literature were most likely due to the long-distance connection requirements to the electricity grid at some case studies [6,7,8]. As some HP installations are located in developing countries [10,11,12] with inadequate financial resource and improper construction, significantly higher environmental impact contributions were observed compare to the MHP schemes investigated in this study.

FRDP associated with the MHP case studies, however, showed higher contributions than the values presented in the previous studies. The possible factors cause these results are due to difference in materials used for penstock pipe. While HDPE penstock pipes are installed in the MHP case studies, some schemes investigated in the previous research [11] used steel penstock pipes that causes less impact on FRDP or GWP but higher impact on AP or ARDP compared to HDPE pipes. Hence, the trend shown in the figure was observed.

3.4. Environmental impacts vs. head & flow variations

Figure 6 represents the trends for the two selected environmental impacts, GWP and FRDP, with respect to hydraulic head and flow. The two impact categories were selected as the results clearly showed a correlation between these impact categories and the two parameters.

As can be seen in the figures, the contributions by each selected impact category appear to decrease with increase in head and vice versa. The possible factors responsible for this trend include different construction environments and component requirements. As discussed previously, since the river bed become more rock-strewn as reaching the top of rivers, high head sites can offer more natural types of intake systems and reduce intake construction materials and works.

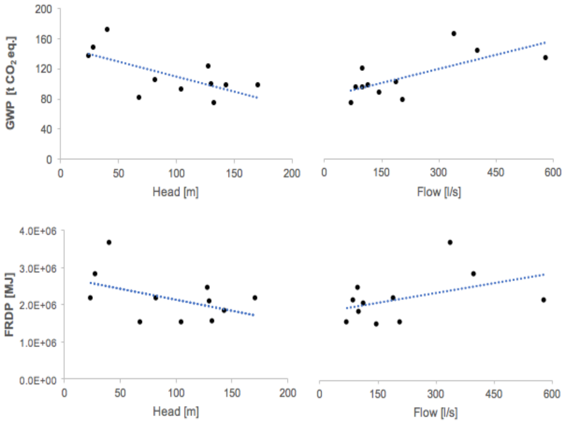

Figure 6. Selected environmental impacts vs. head and flow of MHP installation.

Contrary to the trend observed in the figures with respect to head, the impacts of the selected impact categories increases with increases in the rate of flow. One possible explanation for this trend is due to the implementation of different turbines based on the flow rate and head. Since high flow sites use a crossflow turbine, which is generally larger in size than the Turgo turbine of similar capacity, the sites involve a higher quantity of material and more manufacturing processes. In addition, as stated earlier, storing acrossflow turbine will require a larger space, and hence, more infrastructure work and materials will be needed to build a powerhouse furnishing with the crossflow turbine. Consequently, these factors cause the low head and high flow schemes considered in this study to have a higher impact on GWP and FRDP.

3.5. Environmental impacts vs. power cables for grid connection

As the LCIA results of MHP case studies showed, several meters of cables in each MHP installation made a significant impact on the environmental impact categories presented, especially on HTP and ARDP. To observe more prominent patterns between these two impact categories and the cumulative length of cablings (summation of the lengths of HV/LV cables and sensing cables) involved in each MHP site, Figure 7 was plotted. Since the cablings used for site No.6 is extensively long, the results of this scheme show a large deviation from the rest of investigated MHP schemes, hence considered the scheme as an outlier. In order to detect a more consistent pattern, two best-fit lines, both including and excluding the outlier, are plotted in Figure 7.

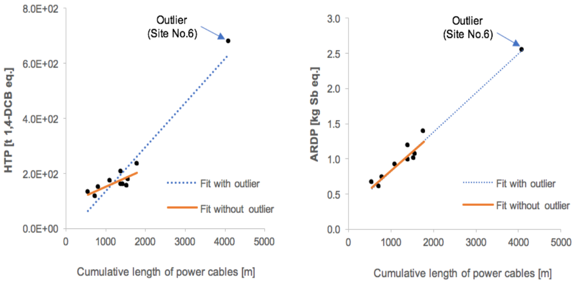

Figure 7. Selected environmental impacts vs. cumulative length of power cables at each MHP site with best-fit lines including and excluding outlier (site No.6 scheme).

As the lines of best-fit illustrate, all two impact categories show an increasing pattern as the length of cabling involved at the MHP sites is raised, even excluding the outlier. The positive linear relationships between these two impact categories and the length of cables were observed mainly due to the vast majority of impact on HTP and ARDP caused by the power cables installed at each site. This suggested that to minimize the impact caused by copper - intensive wires and cable, the length of the electrical cables should be shortened at each site. This is possible by constructing MHP scheme relatively close to a suitable grid connection distance. However, this solution can be challenging to apply for some MHP schemes, especially in remote locations with an inadequate grid access.

3.6. Potential reductions in the environmental impact of MHP schemes

From the results of contribution analysis, HDPE plastics, mainly contained within the penstock pipes, contribute the highest impact on GWP and FRDP, whilst power cables (HV/LV cables and sensing cables) for grid connection cause a major impact on HTP and ARDP.

HDPE vs. Mild Steel In order to reduce the GWP and FRDP burdens caused by penstock, one possible solution is to construct a penstock with alternative materials, such as mild steel. As steel-related materials have potentially less impact on these two impact categories compared with plastic-related materials, installing mild steel pipes instead of HDPE pipes can minimize the impact on GWP and FRDP. This was one main factor that results in higher FRDP associated with this MHP case studies in comparison to the values presented in previous research.

However, according to the buyer's guide of micro-hydropower systems published by CANMET Energy Technology Centre [13], HDPE offers superb penstock performance characteristics including low friction losses and corrosion resistance. In addition, since HDPE is much lighter product than steel, the use of HDPE pipes is also advantageous for reducing environmental impact associated with transporting and shipping finished products. Thus, although using mild steel as an alternative material to HDPE plastics in the manufacture of a penstock can potentially offset a large amount of GWP and FRDP burdens, its overall performance after installation can be questionable.

Underground vs. above-ground penstock installation Reducing the trench excavation for the penstock can also potentially minimize the environmental burden of MHP case studies. While there are several benefits to burying the penstock pipe, such as preventing frost damage and protecting from mechanical damage [13], above-ground installation of the penstock pipe can minimize adverse environmental effects associate with the excavations and trenching. Though when a penstock pipe is installed above ground, it is important to take into consideration of the effects of UV degradation due to the exposure to sunlight. According to the HDPE handbook published by the Plastics Pipe Institute [14] the UV exposure of HDPE pipes can cause a degradation process of the polymers that results in damaging the pipes that are installed in an exposed environment.

One possible solution to the problem of UV degradation of HDPE penstock is the use of UV stabilizer such as carbon black. American Water Works Association [15] states that carbon black is the most effective UV stabilizer which can absorb UV radiation and slow down the UV degradation of HDPE. Based on studies undertook by Bell Laboratories, the application of carbon black as an additive can prevent the UV degradation and preserve the physical properties of the HDPE pipes under the long-term sunlight exposure – over 30 years [16]. In addition, to reduce the visual impact of the above-ground penstock installation, the reforestation of excavated areas can be an effective solution that allows the penstock to match with the natural environment [17].

Grid connection As power cables for grid connection account for the major impact on HTP and ARDP with the MHP case studies, to reduce the length of the electrical cables can be a possible solution. This can be achieved, for instance, by constructing MHP scheme relatively close to a suitable grid connection distance that can mitigate the environmental impact caused by copper-intensive wires and cable. This solution, however, is rather location dependent, and it can be challenging to apply for the MHP schemes in remote locations with limited grid access.

3.7. Sensitivity analysis

Taking into consideration the LCA results obtained, the sensitivity analysis with the margin of error approach were conducted under the scenarios listed in Table 3 to evaluate the effect of the environmental impacts of three representative MHP installations, sites No.1 (low head, head < 30m), No.3 (medium head, 30m < Head < 60m), and No. 13 (high head, head > 60m).

Table 3. Sensitivity analysis scenarios.

Scenario	Margin of error considered	Reason to be considered as scenarios
1. Increasing material quantities	10% increase of material quantities	It is possible that some slight material quantity variances involved for the MHP constructed.
2. Increasing the impact of rock excavation work	100% increase of rock excavation work	The amount of work involved with rock excavation can be increased depending on river bed characteristics
3. Increasing transport distance to suppliers	50% increase of transportation distance	Transport of raw materials and MHP components to suppliers possibly involved a longer distance
4. Above-ground penstock installations	No excavation work for penstock installations	Less excavation work will potentially reduce the impact associated with the excavation procedure for the penstock installation
5. Alternative materials for powerhouse construction	Replacing blockwork used for walls with hardwood timber cladding (hardwood)	Since the use of blockwork for powerhouse construction shows one of the highest impact, increasing the timber portion of the powerhouse can minimize the environmental impact

Table 4. Results of impact categories for MHP projects based on sensitivity analysis scenarios

Scenario	Impact categories	% Change in impact categories		
		Site 1 (Low Head)	Site 3 (Med Head)	Site 13 (High Head)
Scenario 1	GWP	4.0%	8.1%	7.7%
	AP	6.6%	7.2%	5.8%
	HTP	8.5%	4.8%	3.7%
	ARDP	7.8%	2.6%	1.9%
	FRDP	7.4%	8.4%	8.1%
Scenario 2	GWP	0.5%	1.3%	3.0%
	AP	1.2%	2.7%	4.4%
	HTP	0.1%	0.2%	0.2%
	ARDP	0.0%	0.1%	0.1%
	FRDP	0.5%	0.9%	1.9%
Scenario 3	GWP	0.4%	0.4%	0.8%
	AP	0.4%	0.4%	0.4%
	HTP	0.0%	0.0%	0.0%
	ARDP	0.0%	0.0%	0.0%
	FRDP	0.4%	0.4%	0.5%
Scenario 4	GWP	-1.1%	-1.3%	-1.5%
	AP	-1.2%	-1.4%	-1.6%
	HTP	-0.1%	-0.1%	-0.1%
	ARDP	-0.3%	-0.3%	-0.3%
	FRDP	-0.7%	-0.8%	-0.9%
Scenario 5	GWP	-9.5%	-4.1%	-8.4%
	AP	0.6%	0.2%	0.4%
	HTP	0.1%	0.0%	0.0%
	ARDP	0.1%	0.0%	0.0%
	FRDP	0.3%	0.0%	0.2%

The main purpose of the sensitivity analysis is to examine the robustness of the LCA results, and a suitable margin of error was used that would lead to the reduction of environmental impacts for each scenario. The first three scenarios are based on the possible underestimation of the data obtained, while the last two scenarios that can potentially minimize the impact associated with the MHP case studies.

Table 4 represents the results of the sensitivity analysis, and as shown in the table, scenario 1 (10% increase of the measured material quantities) indicates the most influence on the results of selected environmental impact categories for each MHP installation. Scenario 2 shows that the results of high head MHP installation were the most sensitive to increasing the amount of rock excavation works. This is rather intuitive, as the river bed at higher head sites have more rock-strewn environment with high slopes, the sites require more excavation works compared with the environment offer at lower head sites. The sensitivity results with scenario 3 that is to increase the transportation distance from the default results shows a similar impact to scenario 2 - the higher the head of MHP plant, the higher the environmental impact due to the requirement of longer distance transportation. Overall, the high and low head MHP scheme show the most and least sensitive to changes in values of input data, respectively.

As for the scenarios intended to reduce the default environmental impact results, scenario 4 (above-ground penstock installations) has a subtle reduction for all impact category, whilst scenario 5 (partly using an alternative material for powerhouse construction) indicates a reduction in GWP alone.

As wood-related products are considered as carbon sequestration, a significant reduction in GWP can be achieved by replacing blockwork based walls with hardwood timber cladding. Due to difference in the design of each powerhouse, the trend observed is different from the sensitivity results with other scenario; while a large portion of the powerhouse of site No.3 is consisted with natural stone rather than blockwork, the powerhouses of other two sites are mainly built with blockwork.

Table 4 shows that the percentage variation in the environmental impact categories turns out to be relatively small with a maximum of 8.5% increase from the original results. Therefore, the LCA results of this study are quite robust as the original results were insensitive to variations in the major uncertain input data.

5. Conclusions

5.1 Research conclusions

This study uses a life cycle assessment method to evaluate the environmental impacts associated with eleven MHP installations in Wales. To assess the environmental impacts, a process-based LCA method was adopted following the guidelines ISO 14040 guidelines [2]. Taking into consideration of data availability to support each life cycle stage, including processing, transportation and raw materials information, a cradle-to-gate system boundary was chosen to undertake the LCA. Although the maintenance, decommission, and demolish phases of MHP plants were not considered in the analysis, the environmental impact associated with these stages are significantly low as found in the literature. Thus, the results would not vary substantially from the ones with the end-of-life cycle stages.

From the results of contribution analysis, the contribution of raw materials and activities to each major environmental impact category within MHP installations were identified. Whereas HDPE plastics, mainly used to manufacture the penstock pipes, contribute the highest impact on global warming potential (GWP) and fossil resource depletion potential (FRDP), power cables (HV/LV cables and sensing cables) for grid connection cause a major impact on acidification potential (AP), human toxicity potential (HTP) and abiotic resource depletion potential (ARDP).

To minimize the GWP and FRDP burdens caused by penstock, installing mild steel pipes instead of HDPE pipes can be an effective solution. However, as HDPE offers superb penstock performance characteristics including low friction losses, corrosion resistance and light-weight, the use of HDPE pipes is favorable despite the potential offset of GWP and FRDP burdens offered by mild steel pipes. In addition, to mitigate the environmental impact caused by copper-intensive wires and cables, constructing MHP plant with a short grid-connection is recommended.

The normalized environmental impacts of MHP case studies show that, on average, the crossflow MHP installations investigated in this study contribute higher impact to environmental impact categories than the Turgo MHP case studies examined. The possible factors responsible for this trend is due to the difference in intake structure and turbine size – as higher head sites can offer more nature-oriented intake systems, this helps to reduce intake construction materials and works, which involves the use of concrete and excavation work.

The sensitivity analysis observed the effect on the environmental impacts of the MHP schemes investigated and to evaluate the robustness of the LCA results. Overall, the result of high head MHP scheme was highly sensitive to changes in input data value, while the result of low head MHP scheme was least sensitive to the effects of uncertainties. This is mainly because high head sites include rock-strewn river bed and steep slopes, and hence involve more construction labor and materials such as excavation and transportation. Of the sensitivity analysis scenarios applied, increases to the amount of material quantities had the highest effect on the default results with a maximum of 8.5% increase. This suggest that the LCA results of the research are robust enough to offer valuable information that can be beneficial when considering and planning for the micro-scale hydropower plant.

5.2 Further research

- As this research with LCA approach was conducted based on values obtained mainly from facility plan drawings and bills of materials due to lack of real data, the quality of some results obtained under this condition remains questionable and uncertain. In order to reduce the uncertainty and errors, a further collection of actual data is advised so that the outcomes become more accurate and valid.

- Even though the possible alternative materials and potential improvements for MHP installations were explored, findings from the sensitivity analysis did not show a significant reduction in environmental impact associated with the MHP case studies. However, it is recommended that the use of eco-design products, such as ready-made building materials and environmentally sound items, can lead to further reduction of the negative environmental impact of MHP installations.
- Further research should be conducted to quantify the recyclability of materials, such as steel and plastic. This also provides good insights when comparing HDPE plastic penstock to traditional mild steel pipe.
- Investigating pressure drop variations in pipes in response to changes in the diameter and length is another crucial physical characteristic to be considered in further research.
- Since the MHP case studies have been built quite recently, only a few years history of the operation data available. It is, however, worthwhile to evaluate the total emissions and environmental burdens can be avoided compared with grid electricity generation.

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