Life Cycle Assessment of Micro-hydropower Projects:

Assessing Environmental Impacts and Identifying Carbon and Resource Efficiency Opportunities in Current Design

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Abstract

The introduction of Renewables Obligation has led to 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.

This research was conducted using a process-based life cycle assessment (LCA) to evaluate the environmental impacts associated with eleven 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.

Keywords: Micro-hydropower, run-of-river hydropower, life cycle assessment, environmental impacts, renewable energy.

Resumo

A introdução da obrigação de energia renovável no Reino Unido, conduziu ao crescimento de sistemas de energia renovável em pequena escala, incluindo as micro-hídricas (MHP). Ainda são poucas as análises que investigam os impactes ambientais associados a essas instalações MHP, com estudos recentes sugerindo que a economia do carbono e dos recursos pode ser alcançada através de uma abordagem do projeto do ciclo de vida.

Esta investigação foi realizada utilizando uma avaliação do ciclo de vida (ACV) baseada em processos para analisar os impactes ambientais associados a onze instalações de MHP, no País de Gales. Foram recolhidos os dados principais para o inventário do ciclo de vida (ICV) e os dos efeitos ambientais foram obtidos através de bases de dados ACV, em combinação com um modelo de ACV.

As categorias de impacto escolhidas neste estudo são o potencial de aquecimento global (GWP), o potencial de acidificação (AP), o potencial de toxicidade humana (HTP), a depleção de recursos abióticos (ARDP) e o potencial de depleção de recursos fósseis (FRDP). As médias e o desvio padrão para essas categorias de impacte selecionadas, associadas aos sistemas MHP investigados foram os seguintes: 7,15 ± 3,10 gCO2 eq./kWh GWP; 0,031 ± 0,011 g SO2 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. Em geral, os resultados dessas categorias de impacte ambiental investigadas neste estudo foram considerados baixos, em comparação com os estudos prévios de ACV de pequenos aproveitamentos hidroelétricos a fio de água.

Palavras-chave: Micro-hídricas, pequenos aproveitamentos a fio de água, avalisção do ciclo de vida, impactes ambientais, energia renovável.

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List of Abbreviations

Nomenclature

AP	Acidification Potential
ARDP	Abiotic Resource Depletion Potential
BHA	British Hydropower Association
CF	Characterization Factor
CML	Chain Management by Life Cycle Assessment
DCB	Dichlorobenzene
DECC	Department of Energy and Climate Change
DTI	Department of Trade and Industry
EIO	Economic Input Output
EP	Eutrophication Potential
FIT	Feed-In Tariff
FAETP	Freshwater Aquatic Ecotoxicity Potential
FRDP	Fossil Resource Depletion Potential
GHG	Greenhouse Gas
GRP	Glass Reinforced Plastics
GWP	Global Warming Potential
HDPE	High Density Polyethylene
HTP	Human Toxicity Potential
HGV	Heavy Goods Vehicle
HV	High Voltage
IEA	International Energy Agency
IHA	International Hydropower Association
IPCC	Intergovernmental Panel on Climate Change
IR	Indicator result
IRENA	International Renewable Energy Agency
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LV	Low Voltage
MAETP	Marine Aquatic Ecotoxicity Potential
M&E	Mechanical and Electrical
MHP	Micro-hydropower
Ofgem	Office of Gas and Electricity Markets
POCP	Photochemical oxidants creation potential
SWA	Steel Wired Armoured
TETP	Terrestrial Ecotoxicity Potential
WEC	World Energy Council

Units

1,4-DCB eq.	1,4-Dichlorobenzene equivalent
CFC-11 eq.	Trichlorofluoromethane equivalent
C_2H_4 eq.	Ethylene equivalent
CO_2 eq.	Carbon dioxide equivalent
PO_4 eq.	Phosphate equivalent
Sb eq.	Antimony equivalent
SO_2 eq.	Sulfur dioxide equivalent

Chapter 1 Introduction

1.1 Background of the project

Since the introduction of the Renewables Obligation (DTI, 2001) in 2002, the share of electricity generation from renewable sources in the UK has continued to increase. According to the office of gas and electricity markets (Ofgem), the current share of renewable energy in the UK's energy mix is 23.4%, which is more than 20% increase in renewable energy share since 2003 (Ofgem, 2017). Although environmental impacts are inherent characteristics of all electricity generating systems, unlike fossil-fuel based electricity generation, the environmental impacts caused by electricity generated from renewable resources is significantly reduced. As Ofgem's report states, a reduction of 33.7 million tonnes of CO_2 equivalents, that is a reduction rate increase by 14.4% in comparison with the previous year, were accomplished during 2015-16 in the UK alone (Ofgem, 2017).

In addition, the Feed-in Tariff (FIT) system introduced in 2010 assists to expand the installation of renewable energy systems in the UK, including the hydropower sector. Figure 1.1 (Ofgem, 2016a) represents the total eligible installed capacity for hydropower installations per quarter under the FIT scheme in the UK, and the figure indicates that the hydropower installations in the UK has relatively continued to expand since the FIT scheme has been launched in 2010.

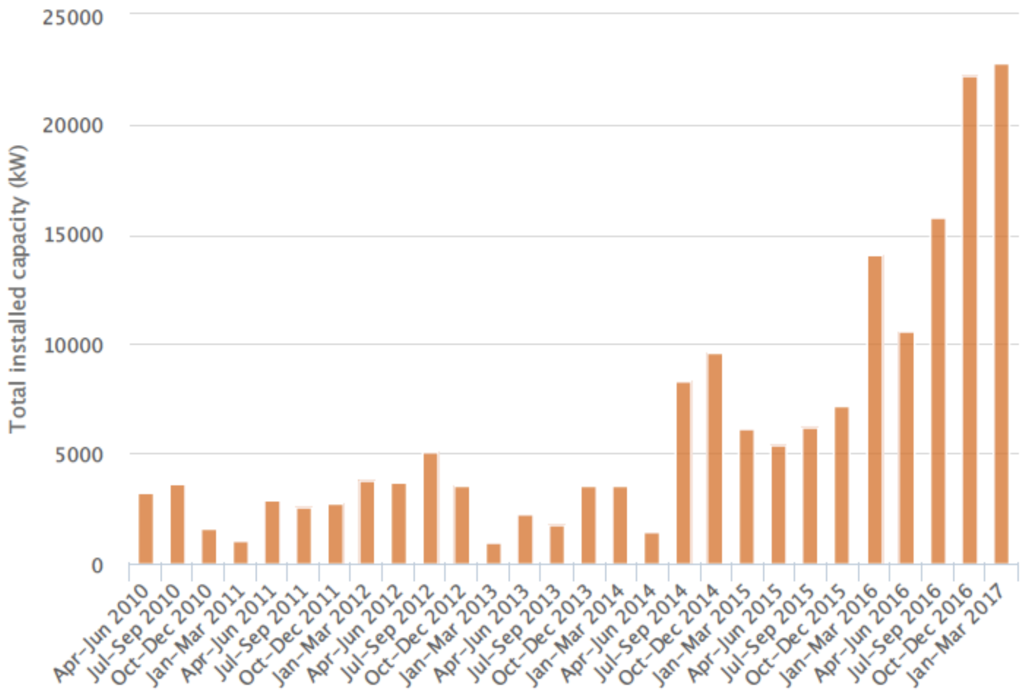

Figure 1.1. Total Installed capacity of hydropower eligible for FIT scheme in the UK (Ofgem, 2016a).

Figure 1.2 (DECC, 2015) examines in more details the number of hydropower installations under the FIT scheme by capacity. As the lower FIT rates are applied for large-scale renewable energy technologies, a prominent growth in the installation of micro-hydropower plants (MHP) (5-100kW) with a capacity from 5 kW to 100 kW has been seen in the UK. As the number of MHP installations increases sharply, especially the schemes with less than or equal to 15 kW installed capacity, the number of hydropower installations with a capacity from 100 kW to 2 MW has been increased slightly since the FIT scheme was launched in the UK. Thus, the majority number of hydropower installations under the FIT scheme are currently MHP projects in the UK.

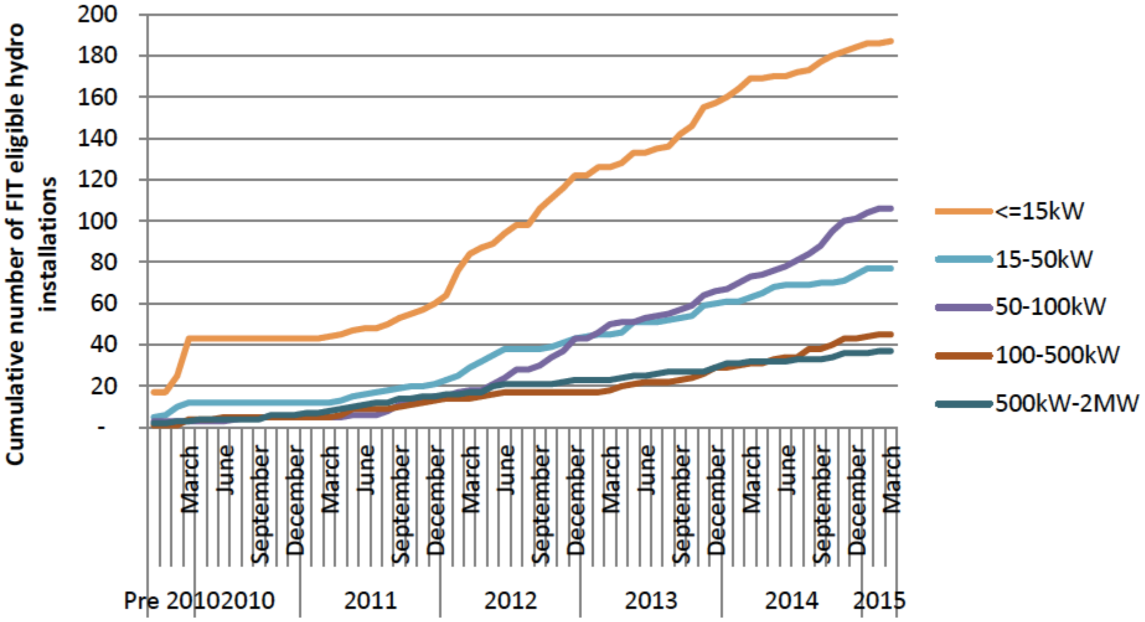

Figure 1.2. Cumulative number of hydropower installations under the FIT scheme (DECC, 2015).

One of the major advantage of construing MHP plant is due to their less complicated technology compared with large-scale hydropower systems. Since MHP installations, which generally are run-of-river scheme, can provide electricity to small communities with a river or a stream, the UK, especially Wales, where high rainfall and steep mountainous terrain are available, offers appropriate regions for developing MHP plants. While the environmental impact associated with MHP installations is less significant compared with large-scale hydropower, the installations of MHP scheme can still causes negative environmental impact, and there are still opportunities for further improvements. As yet, only a few studies have investigated the possible environmental impacts associated with MHP in the UK. To develop more environmentally sound MHP systems, the assessment of environmental impacts takes a crucial role which further contributes to evaluate the potential improvements to the future hydropower development.

1.2 Project aim and objectives

To obtain a better understanding of the environmental impact associated with MHP schemes, the aim of this study quantifies the environmental impacts generated by the construction of several MHP projects in Wales using the life cycle assessment (LCA) and identifies opportunities for carbon and resources savings.

The selected MHP schemes were constructed in North Wales between 2014-2015, and have a design capacity ranging from 70 to 100 kW. To achieve this overall aim of the project, four specific objectives have been identified:

i. Carry out an Life Cycle Assessment (LCA) to determine the environmental impacts for each MHP installation;
ii. Investigate how flow rate and head characteristics affects environmental burden categories for each site;
iii. Identify opportunities for mitigating the environmental impacts through a comparison of installation designs;
iv. Explore eco-design opportunities in the construction of future run-of-river MHP schemes.

By accomplishing these objectives, the crucial factors to be assessed, such as the environmental impact of raw materials and manufacturing processes, are obtained, and hence achieving the overall aim of this dissertation

Chapter 2 Literature review

2.1 Water-energy nexus

Water and energy security takes an important role in order to achieve sustainable economic growth. According to the International Energy Agency's (IEA) *World Energy Outlook 2016* (IEA, 2016), as countries experience rapid economic growth, their energy demand also increases due to the improvement in the living standards. On the other side, increasing economic growth promotes unsustainable consumption and production patterns. Such an unsustainable growth pattern may accelerate climate change and environmental degradation and cause the depletion of natural resources, including energy and water. In response to human-driven environmental changes and scarcities of natural resources, renewable energy technologies, such as hydro, wind and solar power have gained attention around the world. An increased dependence on renewable energy sources assists to promote sustainable development, and water is a crucial factor in the renewable energy sector. For instance, the use of water for hydropower generation is inevitable hydropower, or solar power generation systems, especially concentrated solar power systems require water for cooling process (Rodriguez *et al*., 2015). To optimize this water-use and energy production relationship called the water-energy nexus in the renewable energy sector, hydropower which is highly dependent on water for energy generation, plays an important role.

2.1.1 Role of hydropower in water-energy nexus

Meng *et al.* (2014) examine sustainable hydropower from the water-energy nexus perspective and underlines the vital role of hydropower development in terms of addressing climate change adaptation. The report states that hydropower remains an important element to accomplish the Sustainable Energy for All (SE4ALL)'s goal of doubling the share of renewable energy in the global energy mix by 2030 (IEA and World Bank, 2015). According to International Hydropower Association's (IHA) *2017 Key Trends in Hydropower* (2017), hydropower development continued to grow at a steady rate around the world in 2016. It is estimated that 31.5 GW of newly installed hydropower capacity were added worldwide during 2016, and out of those newly installed hydropower capacity, pumped storage made nearly double the amount installed in 2015 (see Figure 2.1). This delivers total of 4,102 TWh global hydropower generation in 2016, and it is the highest ever output from one single renewable energy source (IHA, 2017). This implies that hydropower has a crucial role in supporting the SE4ALL's objective of doubling the world's the share of renewable energy by 2030. In addition, there are still many potential sites of hydropower development exist at a global scale, and the World Energy Council (WEC) estimates approximately 10,000 TWh/year of unutilized hydropower potential sites around the world (WEC, 2016).

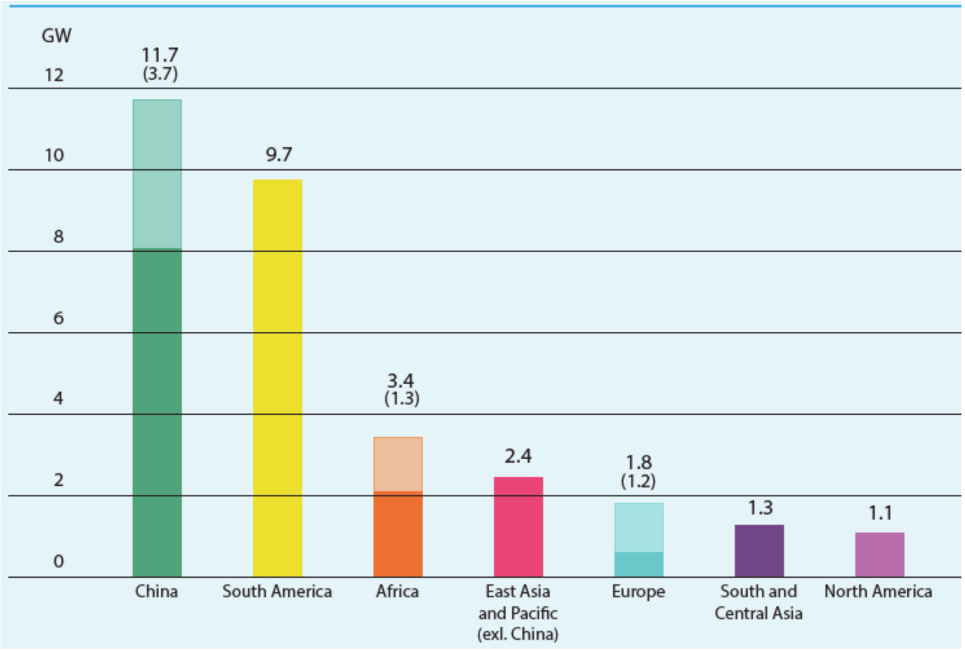

Figure 2.1. Regional distribution of estimate newly hydropower capacity installed (Pumped storage shown in parenthesis) (IHA, 2017).

2.2 Hydropower technologies and applications

Hydropower basically generates electricity from flowing water by using turbines and generators that convert kinetic energy into mechanical energy to produce electricity. The amount of power output of a hydro scheme is proportional to the head – the height difference between upstream and downstream water levels – and the water flow rate (Kumar *et al*., 2012). Each hydropower plant has different characteristics such as installed capacity sizes, head and flow conditions, and turbine selections.

2.2.1 Types of hydropower schemes

Hydropower plants can be classified based on the facility configuration and design, and there are mainly three types of hydropower schemes: reservoir, pumped storage, and run-of-river.

2.2.1.1 Reservoir schemes

Reservoir hydropower schemes use a dam to store water in a reservoir. Electricity is generated by releasing this stored water from the reservoir to flow through a turbine, which makes generator operate. By storing water in a reservoir, reservoir hydropower schemes offer the flexibility to generate electricity according to the demand requirements and can respond to the sudden load variations; hence they are capable for meeting both base-load and peak-load demand. Since the significant amount of water can be stored in the reservoir, they can also operate regardless of the inflow conditions and can be functioned for multiple purposes, such as flood control, irrigation, or water supply, or drainage (IEA, 2012; WEC, 2016) The structure and size of reservoir are highly dependent on geological and topographic conditions, and constructing reservoir hydropower plants also require high up-front investment costs. However, the recent development of construction techniques offers more opportunities to build the reservoir hydropower schemes under more different geological conditions with further low costs (IRENA, 2012).

2.2.1.2 Pumped storage schemes

Pumped storage hydropower schemes generate electricity by charging or discharging the water between two reservoirs, upper and lower ones. When electricity demand is high, the water stored in an upper reservoir is released and flows through turbines to generate electricity. During low demand periods, water is pumped back from the lower reservoir to the upper reservoir. This allows the pumped storage hydropower facility to be functioned as a form of renewable energy storage, and it can be operated along with other renewable energy technologies such as solar and wind power as a renewable energy hybrid system (WEC, 2016). While the pumped storage plants can offer significant benefit to the electricity grid, due to the requirement of two reservoirs, the construction site is very limited. Though compared with other form of energy storage system such as flywheels, or lithium- ion and lead-acid batteries, pumped storage remains as a less expensive option in term of the lifecycle cost of electricity storage systems (IRENA, 2012).

2.2.1.3 Run-of-river schemes

In a run-of-river hydropower scheme, electricity is produced primarily using the downward flow of rivers. These hydropower plants generally consist of a weir which assists to divert upstream water from the river flowing water into the intake. The water is then carried through a pressure pipe called a penstock and is further conveys to the turbine, which is connected to the generator to produce electricity (BHA, 2012). Although these hydropower schemes can possibly possess a small amount of storage called “pondage”, they normally operate without employing any form of a water storage; thereby, they mainly run as a base load power station (IEA, 2012). The main advantages of installing this hydropower scheme is that it is a more economically feasible option than a reservoir hydropower system due to the lower construction costs and potentially causes less environmental impact than other hydropower schemes (IRENA, 2012).

2.2.2 Classification of hydropower by capacity size and hydraulic head

Hydropower plants can be classified based on various aspects, but the most common approaches to classify hydropower plants are according to installed capacity size and hydraulic head. In terms of capacity, although there is no international agreement on the classification of the size hydropower of system, hydropower plants generally fall into the six categories as shown in Table 2.1.

While large- and medium-hydropower plants are capable of feeding power into a large-scale electricity grid, small- and mini- hydro schemes often operate under isolated grid conditions. Micro- and pico-hydro projects normally operate to provide power to a small, remote community away from the electricity grid. In general, large-scale hydropower plants tend to be reservoir schemes, whereas small-scale hydropower plants fit into run-of-river schemes (IRENA, 2012).

Table 2.1. Hydropower classification by installed capacity (IRENA, 2012).

Type of Hydropower	Capacity range
Large-Hydro	> 100 MW
Medium-hydro	20MW – 100 MW
Small-hydro	1MW – 20MW
Mini-hydro	100kW – 1 MW
Micro-hydro	5kW – 100kW
Pico-hydro	< 5kW

With respect to hydraulic head, hydropower plants are classified based on the difference in water levels upstream and downstream. While a hydropower plant operating under head exceeding 300 meters refers to a "high head" system, a "medium head" hydropower system typically has a head of between 30 and 300 meters. Lastly, a hydropower system operating under heads below 30 meters is generally classified as a "low head" hydropower plant. Hydraulic head together with flow rate are essential parameters to select the appropriate turbine type. Pelton turbines are commonly used on high-head and low-flow rate hydropower stations, while Francis turbines are suitable for the medium-head hydropower with high flow rate conditions. Lastly, for low-head hydropower plants with large flow rates, Kaplan turbines are widely implemented (IEA, 2012).

2.3 Social and environmental impacts of hydropower projects

Although hydropower can contribute a number of advantages beyond energy production, it can lead to negative consequences caused by inadequately designed and implemented systems. Despite all the benefits of hydropower, the development of hydropower projects must take into account of potential negative impacts on both social and environmental aspects.

2.3.1 Social impacts

Since most hydropower installations, especially large-scale ones are expected to have a dramatic change in natural environment, they can potentially affect natural habitats and local human environments. In the case of reservoir-based hydropower, the population nearby the reservoir are possibly displaced to unfamiliar areas, and the communities downstream may suffer from health issues (IPCC, 2011). Furthermore, Ramos (2009) states that the construction of a small-scale hydropower can be challenging due to potential adverse effects on lands that are part of ecological and agricultural protected areas (Ramos, 2009). Such adverse effects can potentially bring about strong social opposition to hydropower projects. Although the current hydropower projects generally adopt careful and detailed studies to reduce or to prevent these negative impacts, to obtain public acceptance of hydropower development still remains challenging. One of the most crucial aspects to increase public acceptance is to engage in more transparent communication approach with stakeholders, including all the affected citizens. This should be conducted by explicitly specifying the potential impacts on local communities and raising the public awareness of the importance of the hydropower sector within the water-energy nexus for sustainable development (IEA, 2012).

2.3.2 Environmental impacts

Environmental impacts associated with the hydropower development include: land uses; water quality impacts; greenhouse gas emissions (GHGs) throughout its lifecycle; intensive resource use (IEA, 2012; IEA, 2000).

The construction of dams and reservoirs often requires the flooding of land; this can possibly damage the natural environment and can also lead to the relocation of communities. Moreover, creating the reservoir can adversely alter existing land uses upstream and downstream of the hydropower projects. Due to the modification of upstream river flow patterns, fish migrations may be obstructed, thus leading to a decline in fish population and causing a major impact on fisheries. In order to prevent these potential environmental risks, it is crucial to impose land use regulations that will result in environmental protection and ensure the preservation of biodiversity (IEA, 2000).

Since hydropower relies on water as its primary energy source, it is unavoidable to take into consideration the water quality impacts that may arise during the hydropower operation phase. However, the water quality impacts of hydropower projects vary according to the hydropower schemes. For instance, run-of-river hydropower schemes often increase dissolved oxygen levels through water aeration and hence improves the water quality. On the other hand, water quality impacts associated with reservoirs can be difficult to solve. Unlike run-of-river plants, water in the reservoir retained for a longer period, which leads to poor water aeration condition and reduces dissolved oxygen levels (IEA, 2012; Kumar et al., 2011).

While hydropower generation does not directly emit GHGs or other air pollutants, it still generates GHG emissions on a lifecycle basis. The lifecycle stages of hydropower plants are mainly divided into construction, operation, and dismantling phases, and each phase is responsible for GHG emissions. For example, GHGs are emitted from the manufacturing and transportation process of materials in the construction phase. GHGs can also be induced by transportation required to conduct maintenance activities during the operation phase. Decommissioning of hydropower plants generates GHG emissions, yet emissions within this phase are normally excluded because the plants usually remain at site (Kumar et al., 2011). Figure 2.2 (IPCC, 2011) presents the results of lifecycle GHG emissions from hydropower technologies collected from different studies. As represented by outliers, GHG emissions generated by reservoir hydropower plant can potentially be nearly ten times higher than run-of-river or pumped storage system. This result is intuitive due to the fact that the reservoir hydropower plants are often involved in large-scale concrete production for constructing dams, which is one of the major contributors to the GHG emissions throughout the life cycle of hydropower plants. Despite the possibility of inducing high GHG emissions, as it is shown in Figure 2.3 (IPCC, 2011), hydropower has one of the lowest lifecycle GHG emissions among the renewable energy technologies.

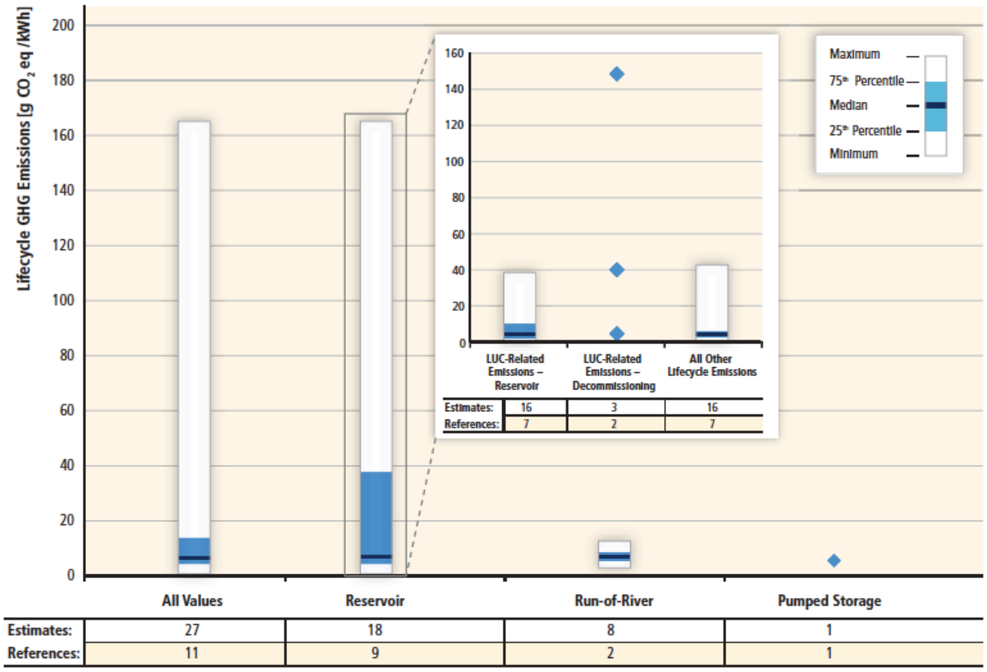

Figure 2.2. Lifecycle GHG emissions of hydropower technologies (IPCC, 2011).

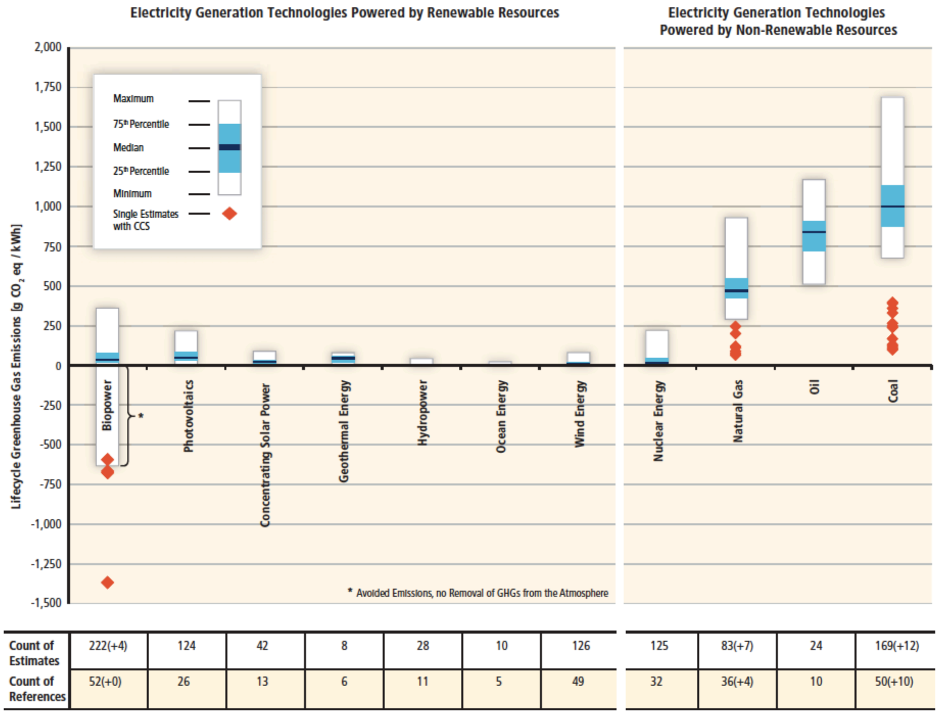

Figure 2.3. Lifecycle GHG emissions of different electricity generation technologies (IPCC, 2011).

Natural resource depletion which includes depletion of minerals, metals, and fossil fuels is another environmental issue related to hydropower development. The construction of hydropower plants, especially for the reservoir scheme with a large dam, can be resulted in intensive resource use. For instance, the vast amount of cement is necessary to build a concrete dam, and cement production is often an energy generating more GHG emissions. Intensive use of metals for the development of hydropower technologies can potentially lead to the potential environmental impacts such as water contamination risks and further GHG emissions associated with metal production (IEA, 2000).

To address the potential negative issues associated with hydropower projects, as presented in Figure 2.4, Meng *et al.* emphasized the importance of understanding and managing the links between "energy production, water security, environmental flows and healthy ecosystem integrity" (Meng *et al.*, 2014, p.30).

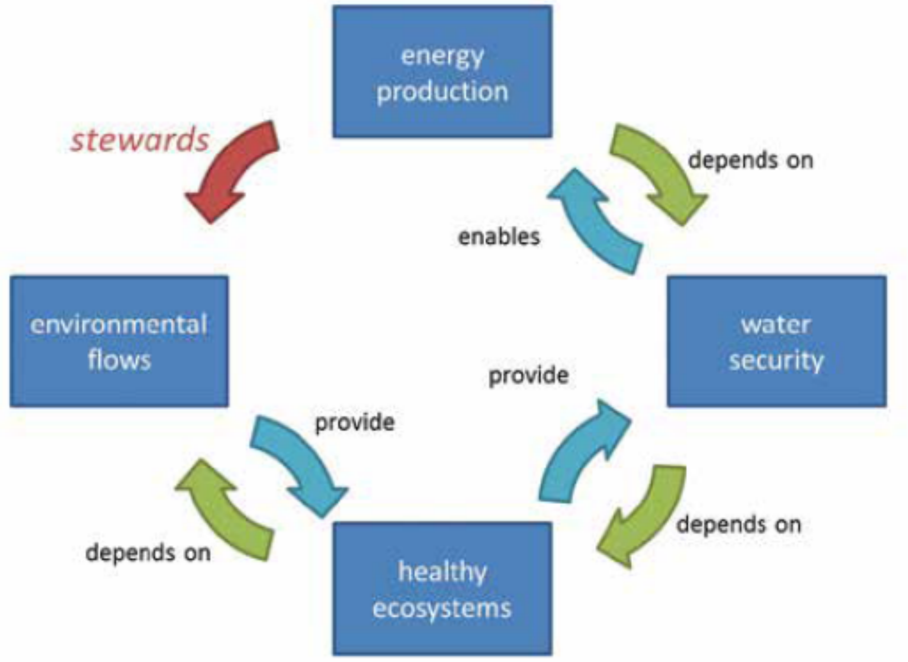

Figure 2.4. The Reciprocal relationship of energy production, water security, environmental flows and healthy ecosystem integrity (Meng *et al.*, 2014).

As such, in order to develop sustainable hydropower plants, one key role is to quantify and analyze the environmental flows throughout the life cycle of hydropower projects (e.g. GHG emissions, pollution and natural resource depletion from the construction of hydropower facilities). This life cycle assessment (LCA) can assist to design more environmentally conscious hydropower facility by tackling the negative impacts accordingly.

2.4 Life cycle assessment

In recent years, the environmental issues due to intensive human activities become more prominent, and the need for environmental protection and conservation increases around the world. As an approach to avoid the risk of further environmental degradation, identifying and evaluating the potential environmental impacts associated with a product or service system throughout its entire life cycle is widely performed; this systematic evaluation approach is called Life Cycle Assessment (LCA) (ISO, 2006a). According to the principles and framework of the LCA proposed by the international Organization for Standardization (ISO) 14040 (ISO, 2006a), LCA consists of the following four phases:

1. Goal and scope definition
2. Life cycle inventory (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation

2.4.1 Phase 1: goal and scope definition

The initial phase of an LCA is to define the goal and scope of the study. Within the goal component, the study objective and reasons behind performing the study need to clearly be stated. The aim of scope part is mainly to establish and specify the *functional unit* and *system boundaries* of the studied system. The functional unit represents a “quantified performance of a product system for use as a reference unit” (ISO, 2006a), and it is a key parameter that enables a comparison of the environmental performance of alternative systems. For instance, the functional unit for electricity generation is normally defined as 1 kWh of electricity produced. By having the same functional unit, a comparison of the environmental impacts of different electricity generation technologies becomes possible. The system boundaries define which elements or processes to be included (e.g. raw material inputs and outputs) in an LCA analysis. Decisions on inclusion of processes in the system boundaries, the so-called ‘cut-off criteria’, should be clearly stated and consistent with the goal and scope of the LCA (ISO, 2006b). As such, it is important that this cut-off criteria should be drawn within the range of data sources available and at a point where an input or output contributes an insignificant portion of the overall LCA.

In addition to identifying a threshold of data elements for each process, the spatial and temporal boundaries of LCA analysis should also be established. Inclusion of spatial boundaries is crucial not only because of different technological system and infrastructures in each location, but also because of different environmental legislation and regulations in each country or region. In most case, LCAs include with an excessive amount of data, and the LCA practitioner likely becomes overwhelmed with irreverent information. By setting temporal boundaries (e.g. the expected lifetime of a power plant), however, the LCA practitioner can perform the analysis with relevant information. Moreover, LCAs are often conducted using a combination of primary and secondary data, and it is possible that all data, especially secondary data, are not based on the relevant time range. Hence it is crucial for the LCA practitioner to evaluate if the data is updated or outdated and if the data can be accepted as reliable (Curran, 2017).

2.4.2 Phase 2: life cycle inventory (LCI)

Life cycle inventory (LCI) is the second phase of the LCA that involves the data collection within the system being studied. In order to carry out LCI, there are two major approaches available: a process-based approach and an Economic Input-Output (EIO)-LCA approach. The process-based method is a ‘bottom-up’ approach, mainly following the ISO 14040 guidelines, and this method accounts for all the environmental burdens of each input and output throughout the life cycle of the material or product. The EIO-LCA method is a ‘top-down’ approach, which relies on economic quantities to identify environmental impacts. Thus, the EIO-LCA method primarily focuses on money flows, instead of material and energy flows (Clark, 2012; Powell *et al*. 2016).

Although processed-based approach allows the LCA practitioner to evaluate environmental impacts in detail, selecting the system boundary can be subjective or uncertain, especially when dealing with the complex input and output environmental flows of a product system. EIO-LCA method, on the other hand, avoids the issues of system boundary selection by treating the entire economy as the system boundary, but the level of detail is limited compared with the processed-based LCA method (Bilec *et al.* 2006). Hence, the LCA practitioner needs to be aware of the trade-off associated with those approaches when selecting the LCA methodology to follow.

2.4.3 Phase 3: life cycle impact assessment (LCIA)

2.4.3.1 General framework of life cycle impact assessment

The purpose of Life Cycle Impact Assessment (LCIA) phase is to quantify the potential environmental impacts of individual inventory parameters (e.g. energy use, industrial processes, emissions, waste), which is accomplished by converting LCI results into the so-called category indicator results. Figure 2.5 (ISO, 2006a) shows the general structure of LCIA, and the LCIA phase is composed of the mandatory and optional elements. The mandatory elements, which must be comprised in LCA studies, consist of three steps: impact categories selection, classification and characterization. The optional elements, which are not necessary to be included in LCA studies include: normalization, grouping and weighting.

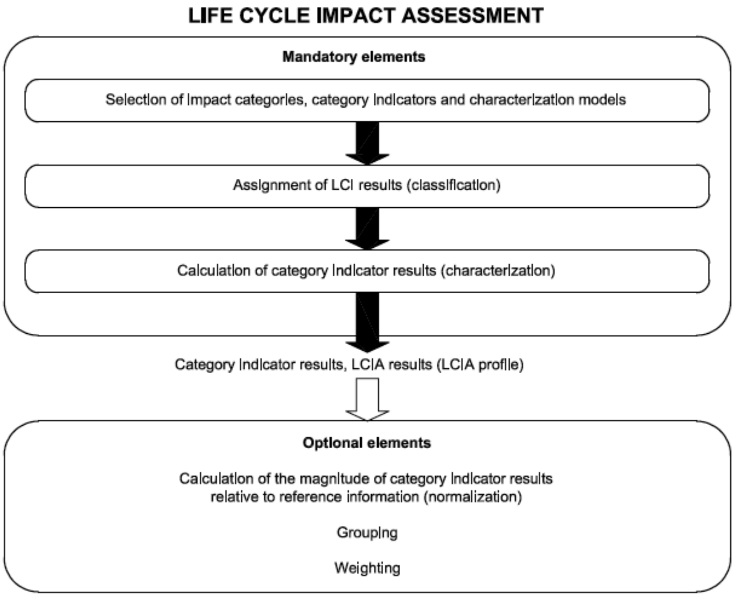

Figure 2.5. Elements of LCIA phase according to ISO 14040 (ISO, 2006a).

2.4.3.2 Selection of impact categories

The first stage of LCIA involves with the selection of impact categories, which will be evaluated on the basis of the whole LCA. According to ISO 14042, *Life Cycle Impact Assessment* (ISO, 2000a), there is no compulsory on which impact categories need to be presented in LCA. Although the choice of impact categories depends on the practitioner’s preference, the selection of impact categories need to be a reflection of the goal and scope of the LCA. The following list the so-called baseline impact categories recommended in the CML Handbook (Guinée et al., 2002) are commonly used in the LCA studies:

- Abiotic resource depletion (ARDP);
- Global warming potential (GWP);
- Ozone depletion potential (ODP);
- Human toxicity potential (HTP);
- Fossil resource depletion potential (FRDP);
- Acidification potential (AP);
- Freshwater aquatic ecotoxicity potential (FAETP);
- Marine aquatic ecotoxicity potential (MAETP);
- Photochemical oxidants creation potential (POCP);
- Eutrophication potential (EP);
- Terrestrial ecotoxicity potential (TETP).

2.4.3.3 Classification

The purpose of the classification phase is to assign the results of the LCI inventory to impact categories. While some inventory results contribute to a single impact category (*e.g.* linking methane emissions with global warming potential), others can be allocated to multiple impact categories; for example, sodium oxide related emissions are normally assigned to both acidification and human health impact categories (Curran, 2006; ISO 2006b).

2.4.3.4 Characterization

In the characterization step, the impact categories are quantified by converting LCI results to potential environmental impacts based on so-called characterization factors. Through the characterization process, each inventory data is translated into the value represented as the category indicator result (Curran, 2006). In general, the following equation is used to convert the inventory data into indicator result (Heijungs *et al.* 2004):

$$IR_k = \sum_k CF_k \times e_k \tag{2.1}$$

where IR_k stands for the indicator result for impact category k, CF_k is the characterization factor, and e_k is the inventory data for an item (e.g. the mass of chemical k consumed in process). Therefore, the practitioner can calculate, for instance, the indicator results for the climate change, or global warming potential (expressed as CO_2 equivalents) if the CO2 emission inventories and a relevant characterization factor are known (Heijungs *et al.* 2004).

Furthermore, the characterization stage includes classifying the category indicator results based on different stages along the ‘environmental mechanism’; ISO 14044 defines the term environmental mechanism as “a system of physical, chemical and biological processes for a given impact category, linking the LCI results to category indicators and to category endpoints” (ISO, 2006b).

There are mainly two different approaches to sort environmental impacts: the midpoint and endpoint methods. As shown in Figure 2.6 (ISO, 2006b), the midpoint approach focuses on the impacts in the mid-stage of the environmental mechanism, generally related to environmental issues, such as global warming potentials, ozone depletion potential. On the other hand, the endpoint approach focuses on the impacts at the end of the environmental mechanism, including loss of species, damage to human health (ISO, 2006b; Guinée, 2002).

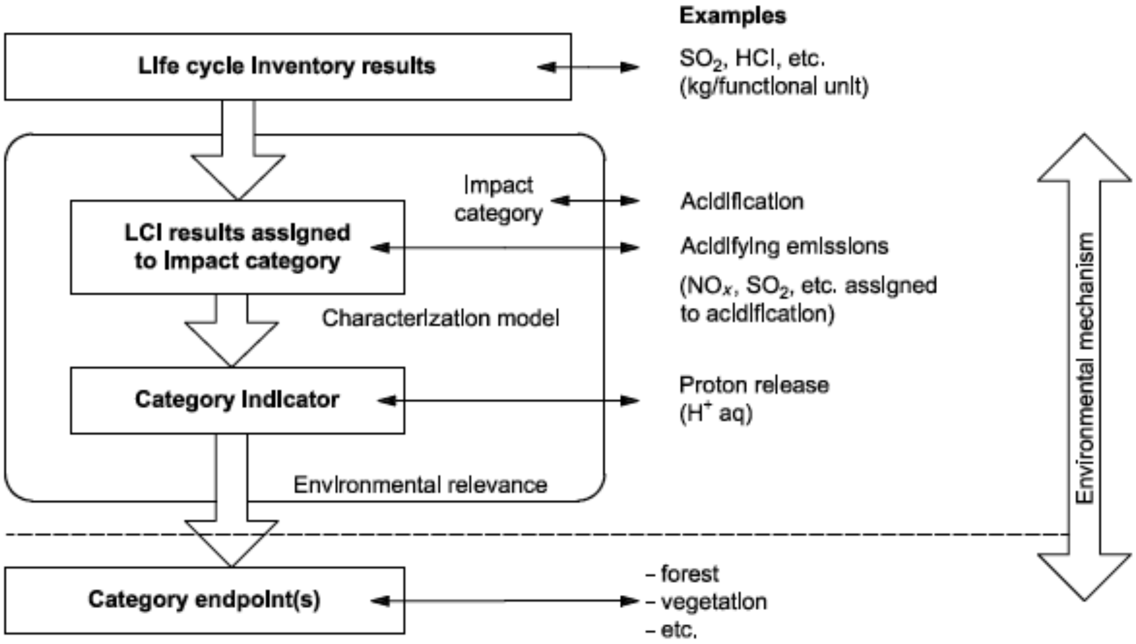

Figure 2.6. Concept of LCA impact category indicator (ISO, 2006b).

2.4.3.5 Optional LCIA elements

Depending on the goal and scope of the LCA study, the following optional elements can be applied (ISO, 2006b):

- *Normalization* refers to compute the magnitude of category indicator results relative to reference information;
- *Grouping* involves sorting impact categories on a nominal basis (e.g. global, regional, local scales) and/or ranking the impact categories in a hierarchical order (e.g. high, medium, and low priority);
- *Weighting* procedure converts the indicator results across impact categories based on selected indicators.

The inclusion of optional elements into LCIA can possibly be beneficial, particularly when reviewing inconsistencies and exchanging information on the relative importance of the indicator results. However, the normalized and weighted outcomes are subjective due to the fact that the conversion of indicator results takes place based on 'value-choices' (ISO, 2006b). In addition, there are always certain limitations associated with LCIA as ISO 14040 states:

> "The *LCIA addresses only the environment issues that are specified in the goal and scope definition, LCIA is not a complete assessment of all environmental issues of the product system under study. LCIA cannot always demonstrate significant differences between impact categories and the related indicator results of alternative product system."* (ISO, 2006a, 15)

Since the LCIA can hardly take into account of assessing all the inputs, outputs and processes due to the limitations in the LCI data, the LCA practitioner ought to state key assumptions and limitations faced in the report. Clearly resenting these key factors, in turn, makes the report more transparent and consistent

2.4.4. Phase 4: interpretation

The final phase of LCA is the life cycle interpretation, which consists of identifying the major issues in both LCI and LCIA phases and evaluating consistency and sensitivity of the final LCA results. To assist identifying the most significant environmental impacts throughout the whole life cycle, ISO 14044 (ISO, 2006b) recommended the following methods:

- *Contribution analysis* determines which environmental impacts (energy, emissions, waste, and material input) contrite most to the overall LCA results
- *Dominance analysis* involves examining which statistical methods are appropriate to identify significant contributions
- *Anomaly assessment* explores unexpected or abnormal results, such as significantly high or low environmental impacts based on previous outcomes

The interpretation phase also comprises further additional tasks, including drawing conclusions, explaining limitations, analyzing the uncertainties, and proposing recommendations based on the findings from LCA studies. The ultimate goal of this phase is to search for opportunities to reduce the environmental impacts of the system investigated (Curran, 2006; ISO 2006b).

2.5 Review of LCA studies on run-of-river hydropower schemes

In order to proceed the appropriate process of LCA, this section provides an overview of previous LCA studies conducted specifically on run-of-river hydropower scheme (Arnøy and Modahl, 2013a,b; Axpo, 2012; Gallagher *et al.* 2015; Hanafi and Riman, 2015; Pascale *et al*. 2011; Suwanit and Gheewala, 2011, Varun *et al*. 2008).

2.5.1 Review of goal & scope phase

While the majority of previous LCA studies on run-of-river hydropower scheme (Arnøy and Modahl, 2013a,b; Axpo, 2012; Gallagher *et al.* 2015; Hanafi and Riman, 2015; Pascale *et al*. 2011; Varun *et al*. 2008) used a functional unit of 1 kWh electricity generated, two different approaches were mainly applied in terms of system boundaries. Since the environmental impacts during the O&M and demolishing phases of hydropower plants are significantly low, Gallagher *et al*. (2015), and Suwanit and Gheewala (2011) set a cradle-to-gate system boundary for their LCA's and excluded the usage and end-of-life process. On the other hand, Varun *et al*. (2008), Arnøy and Modahl (2013a, b), and Pascale *et al*. (2011), applied cradle-to-grave system boundary and included the O&M and demolishing stages of hydropower plants in their LCA's. However, although Varun *et al*. (2008) stated that a cradle-to grave system boundary was applied for their study, the decommissioning stage of HP plants were excluded from the results and they concluded that demolishing the existing HP plants are unnecessary. This contradicts the definition of a cradle-to-grave approach and hence Varun *et al*. (2008) did not set an appropriate system boundary in their LCA studies. Although a cradle-to-grave approach can yield the environmental impacts of a process over the whole life cycle, it can lead to uncertainty and inconsistency due to its complexity in the end-of-life process (i.e. infinite ways to reuse materials). Thus, the LCA practitioner should carefully select the system boundary depending on the availability of data to support each life cycle stage.

2.5.2 Review of LCI Phase

Among the reviewed papers, most LCA studies on run-of-river HP scheme applied the process-based method following the LCA principles described by ISO 14040 (ISO, 2006a) as opposed to the EIO-LCA method. While Arnøy and Modahl (2013a,b), Gallagher *et al*. (2015), Pascale *et al*. (2011), Hanafi and Riman (2015), and Suwanit and Gheewala (2011) used the process-based approach, Varun *et al*. (2008) is the only LCA studies reviewed that applied an EIO-LCA method. In most cases, LCI is categorized as primary and secondary data. Primary data refers to the data obtained from direct measurement or through interviews and questionnaires. By contrast, secondary data is associated with sources such as literature or database (Weidema et al. 2003). The life cycle of a run-of-river HP installation involves with the complex supply chain across production, processing and manufacturing, and it is possible to have inadequate primary data available to complete LCI. Using databases as secondary sources can assist to fill such gaps in the primary data and is also beneficial when dealing with LCIs consist of large amounts of diverse data. However, assessing inventory data based on the secondary data is likely to cause more uncertainty rather than based on primary due to insufficient data quality caused by “uncertainties or difference in allocation and aggregation procedures” (ISO, 2006a). Accordingly, inclusion of uncertainty analysis is an important element, which in turn increases the transparency on the limitations of the whole LCA studies.

2.5.3 Review of LCIA interpretation phase

One of the earliest LCA studies on run-of-river HP scheme is carried out by Varun *et al*. (2008), and they assessed the life cycle GHG emissions of three run-of-river hydropower schemes in India ranges from 50 kW to 3,000 kW. The outcomes are distributed into different life cycle stages, namely civil works, electro-mechanical (E&M) equipment, and operation and maintenance (O&M). This breakdown of life cycle stages allows the reader to grasp the contribution of GHG emissions from a specific stage for the evaluated HP plants, and the study reported the GHG emissions ranging from 35 to 75 g CO_2 eq./kWh over an expected lifetime of 30 years on the investigated HP plants. Moreover, the results from Varun *et al*.’s (2008) study show the trend that the higher the installed HP capacity, the lower the GHG emissions. In contrary to other reviewed literature (Hanafi and Riman, 2015; Pascale *et al*. 2011; Suwanit and Gheewala, 2011), according to Varun *et al*. (2008), O&M phase contributes the highest GHG emissions in each investigated HP schemes. This may be because their applied method, Economic Input-Output (EIO) method, directly converts the cost of each project into GHG emissions including O&M costs, which were most likely overestimated. The sum of 3% of the total civil works plus 3 % of total E&M equipment were applied to compute the O&M cost, but

any reference for using this portion is not provided. This could misrepresent the total life-cycle O&M cost and hence the real GHG emissions
associated with this stage.

Of the processed-based LCAs reviewed, the run-of-river scheme investigated by Pascale *et al*. (2011) has the highest life cycle GHG emissions at 52.7 gCO_2eq/kWh over a 20-year lifetime. Since the hydropower scheme examined in this study has a significantly low installed capacity with only 3 kW, this may potentially be causing such high life cycle GHG emissions compared with other LCAs reviewed. In contrast, Hanafi and Riman (2015) reported the lowest life cycle GHG emissions at 1.2 g CO_2 eq./kWh with the capacity of 9MW. However, their LCA studies did not take into account of the emissions caused by transportation of material and equipment to and from site, which is found to be one of the major GHG contributors in other reviewed reports (Atilgan and Azapagic, 2016; Axpo, 2012; Suwanit, 2011). As such, if transportation impacts are included within their system boundaries, the amount of GHG emissions Hanafi and Riman (2015) presented can possibly be increased.

Whereas Varun *et al*. (2008) evaluated only the GHG emission impacts from run-of-river HP plants in their LCA studies, the majority of previous LCA studies reviewed (Gallagher *et al*., 2015; Hanafi and Riman, 2015; Pascale *et al*., 2011; Suwanit and Gheewala, 2011) identified various environmental impact categories in their LCA's, following CML-IA baseline methods. Although the number of impact categories presented are different among these literature, all of them included GWP, AP, ARDP, and HTP in addition to one or two more impact categories in LCIA. For instance, Pascale *et al*. (2011) conducted LCA study on a run-of-river HP scheme in Thailand and assessed additional environmental impact categories ODP, EP, POCP, while Gallagher *et al*. (2015) Hanafi and Riman (2015), and Suwanit and Gheewala (2011) also assessed FRDP.

Although GHG emissions represented as GWP tend to pay more attention than other environmental impact categories, computing other impacts offers further perspectives on the potential effect of run-of-river hydropower. Hanafi and Riman (2015) found that marine aquatic ecotoxicity, which represents pollutants toxic to aquatic ecosystem, contributes the major impact due to the use of steel pipe for the penstock as opposed other environmental impact categories. Suwanit and Gheewala (2011) performed contribution analysis to have a better perspective on the environmental impact of each lifecycle stage of multiple run-of-river hydropower schemes. Their LCIA results demonstrated that HTP associated with the schemes investigated had the highest mean value of 35.3 kg 1,4-DCB eq./MWh among the reviewed literature due to the installation of steel penstocks. Thus, an inclusion of more environmental impact categories gives various perspectives on the environmental impact associated with run-of-river hydropower project.

In order to measure the influence of the results based on possible uncertainties involved, Gallagher *et al*. (2015) and Pascale *et al*. (2011) performed a sensitivity analysis. Gallagher *et al*. (2015) conducted a sensitivity analysis based on the scenarios that can affect the LCIA results for manufacturing components processes and transportation of materials and indicated that variations in the manufacturing for the turbine or generated had the most significant impact on the results. Pascale *et al.* (2011) performed sensitivity analyses based on the best and worst scenarios applied on the hydropower scheme considered by varying the raw material consumption, specifically cement. The result shows even the hydropower scheme with the worst scenario conditioned considered can contribute less impact on some impact categories than grid connections systems. Therefore, undertaking sensitivity analyses is important to identify potential improvements to be applied during the entire lifecycle of run-of-river hydropower plant.

2.6 Summary of key findings

- The future role of hydropower in the water-energy nexus is crucial to accomplish the SE4ALL's goal.
- Although hydropower development can contribute a number of benefits beyond energy production, it can lead to adverse impacts caused by inadequately designed and implemented systems.
- Despite the possibility of inducing high GHG emissions in construction, hydropower has one of the lowest lifecycle GHG emissions among the renewable energy technologies.
- In order to develop sustainable hydropower plants, the life cycle impact assessment (LCA) can assist to design more environmentally conscious hydropower facility by tackling the negative impacts accordingly.
- While the majority of previous LCA studies on run-of-river schemes have been small- to medium-scale installations (1 MW – 100 MW), a few studies undertook a LCA for mini or micro HP range (5kW – 1MW) projects.
- In terms of setting system boundaries, the LCA practitioners should carefully select the cut-off criteria depending on the availability of data to support each life cycle stage.
- A processed based LCA approach offers a greater level of detail compared with an EIO-based LCA method.
- Using databases as secondary sources is helpful to fill data gaps in the primary data and is also beneficial when dealing with diverse LCI datasets.
- Conducting sensitivity analyses for taking into account of uncertainties involved in the LCA analysis is a crucial element to increases the transparency on the limitations of the whole LCA studies.

Chapter 3 Methodology

3.1 Selection of hydropower case study

The location of the MHP plants investigated are predominantly within Snowdonia National Park in North Wales (see Figure 3.1). 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.

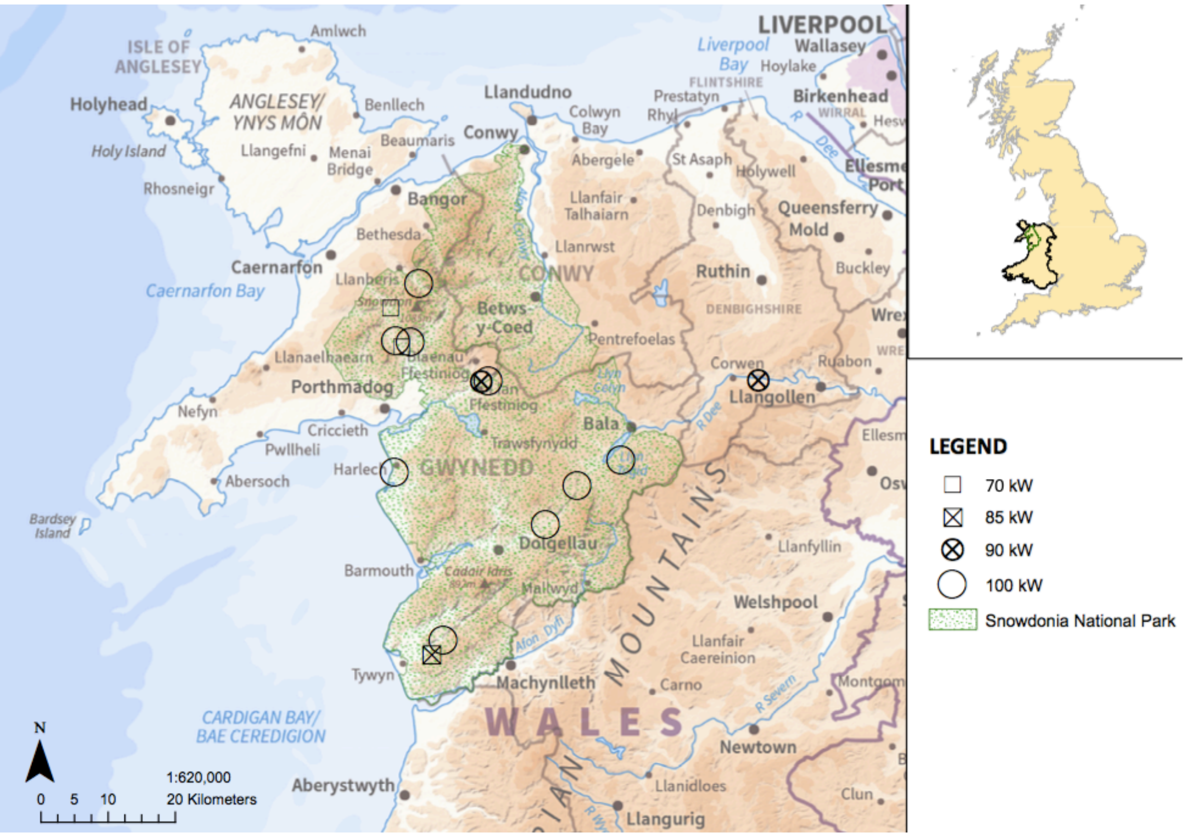

Figure 3.1. Location of hydropower schemes investigated.

The selected hydropower plants were constructed in North Wales between 2014-2015 and all have a design capacity ranging from 70 to 100 kW. All fourteen plants are run-of-river hydropower schemes and share the same components: weir and intake, penstock, powerhouse including turbine and generator, and tailrace. The details of each hydropower plant are listed in Table 3.1.

The capacity factor for each MHP plant is calculated as follows:

$$Capacity\ Factor = \frac{Annual\ Energy\ Output\ [kWh]}{Design\ Capacity\ [kW] \times 8760[hour/year]} \tag{3.1}$$

Table 3.1. Design characteristics of MHP schemes.

Site No.	Name	Head [m]	Flow [l/s]	Design Capacity [kW]	Capacity Factor	Annual Energy Output [MWh]	Turbine Type
1	Teliau Bach	24	580	90	0.24	189	Crossflow
2	Llangower	29	401	100	0.35	306	Crossflow
3	Nant Colwyn	41	340	100	0.55	481	Crossflow
4	Afon Dyfrdwy	44	336	100	0.33	285	Crossflow
5	Pandy	60	207	85	0.30	226	Turgo
6	Rhyd Wen	82	190	100	0.43	372	Turgo
7	Hafod Yspytty	105	145	100	0.44	386	Turgo
8	Hafod y Porth	128	100	100	0.45	390	Turgo
9	Nant Ffriddisel	130	115	90	0.28	220	Turgo
10	Clogwyn y Gwin	133	70	70	0.35	212	Turgo
11	Afon Las	135	108	100	0.54	471	Turgo
12	Wern Gawr	144	101	100	0.57	499	Turgo
13	Dolgoch	171	85	100	0.63	553	Turgo
14	Cwn Cloch	215	44	70	0.39	237	Turgo

Each hydropower plant consists of weir, intake, penstock, powerhouse and head race. The weir, serves to divert upstream water to the intake and has been designed as a concrete structure. Coanda screens, which assists to exclude fish and debris from the diverted water (Strong and Ott, 1988), are mounted with intake. The diverted water is then carried through the penstock and is further conveys to the turbine, which is connected to the generator to produce electricity. All MHP schemes investigated consist of high-density polyethylene (HDPE)-based penstock. As shown in Table 3.1, Turgo turbines are used on the high head MPH sites, whereas crossflow turbines are operated at the low and medium head MHP sites.

3.2 LCA of MHP plants

The LCA of run-of-river MHP plants was conducted in accordance with ISO 14040 and 14044 guidelines. Therefore, this study involves four following LCA phases (ISO, 2006a):

1. Goal and Scope Definition – includes establishing the functional unit and system boundary;
2. Life Cycle Inventory – compiling an inventory of relevant inputs and outputs for each activity and material;
3. Life Cycle Impact Assessment – assessing the potential environmental impacts associated with the inventory results;
4. Interpretation – interpreting the inventory results and impact categories in relation to the objectives.

Each phase of the LCA process performed is described more detail in the following sections.

3.2.1 Goal and scope definition

The goal of this study was to quantify the environmental impacts of several run-of-river MHP projects in Wales using LCA technique and to identify opportunities for carbon and resources savings.

3.2.1.1 Functional unit

As presented in the literature review, the majority of LCA analyses for run-of-river HP scheme defined the functional unit as 1 kWh electricity generated; accordingly, the functional unit selected for this study was 1 kWh electricity generated during the reference year 2015. The same functional unit as the majority of pre-existing LCA studies was chosen to easily perform a comparison of the environmental impacts with other run-of-river schemes.

3.2.1.2 System boundary for LCA process

Findings from the literature review demonstrated that a “cradle-to-grave” approach leads to uncertainty due to its complexity in the end-of-life process. Moreover, as considered in the reviewed literature, the hydropower plants often remain at sites, and thus the demolishing or end-of-life stage from this study was neglected. The availability of data to support each life cycle stage is a crucial factor to define system boundary. Due to a lack of data availability, the operation stage was also not considered in this study. Taking into consideration of all these factors together with the data availability for construction phases, including transportation, processing and raw materials information, a “cradle-to-gate” system boundary was selected. As such, the analysis includes pre-construction and construction stages of the schemes investigated. The details of key processes considered are represented in Figure 3.2. In terms of operational lifetime, the reviewed literature presents various number of years ranging from 20 to 100 years (Arnøy, 2013a,b; Axpo, 2012; Gallagher, 2015; Hanfai, 2015; Pascale, 2011; Suwanit, 2011; Varun, 2008). For this study, an expected lifetime of 50 years was considered based on the average lifetime of run-of-river HP schemes assumed in the reviewed literature.

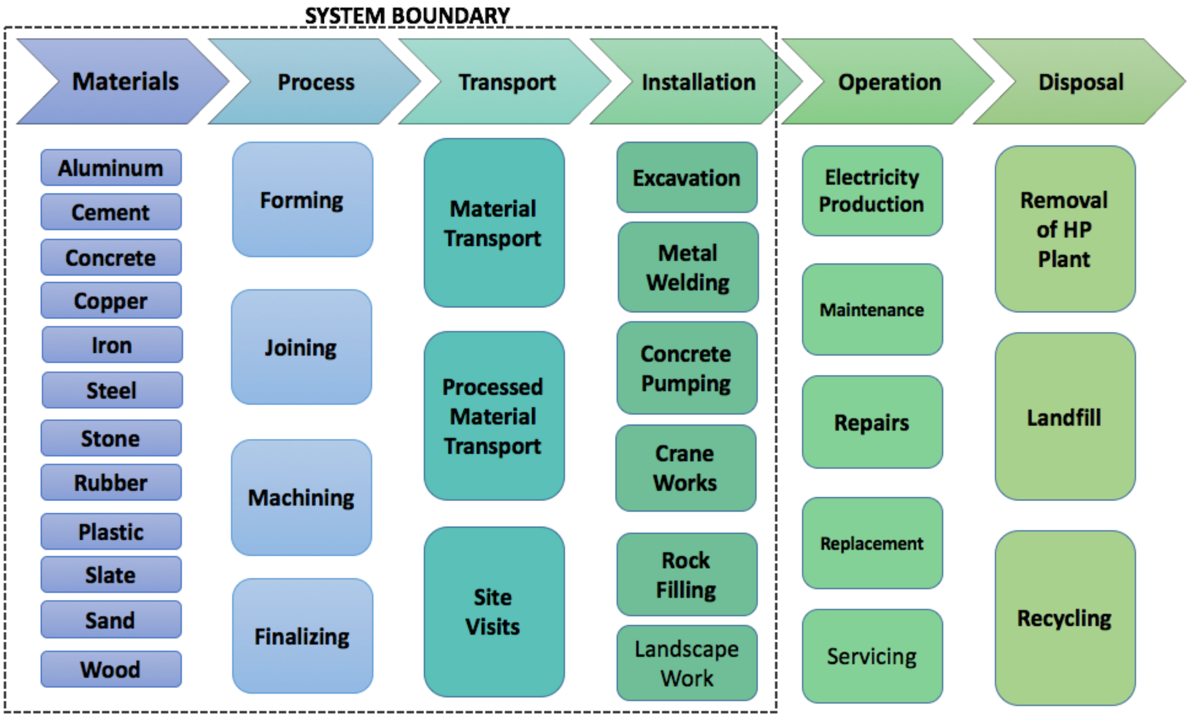

Figure 3.2. Process map and LCA system boundary for MHP scheme.

3.2.2 Life cycle inventory

In order to assess the environmental impacts, a process-based LCA method was adopted and carried out following the guidelines ISO 14040 (ISO, 2006a). Due to a lack of economic data, the EIO-LCA method was not considered as an option in this study.

3.2.2.1 Primary data

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 – include 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 3.2. Primary 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	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓	
Bill of Materials & Actual Data	✓	✓	✓		✓	✓	✓		✓	✓		✓	✓	

The approved drawings show a description of the overall project layout, whereas the detailed drawings illustrate more precise layout of the structures of each section of the scheme. These two layout drawings allow to calculate the quantity of inputs, including raw materials, manufacturing processes, energy consumption, and transportation. The bill of materials and actual data, which are obtained from the contractors and suppliers, consists of a detailed list of materials and components with quantities. In general, the life cycle inventories for raw materials used are expressed in kg or m^3, while electricity and fuel consumptions are represented as kWh and MJ, respectively. If necessary, density values are used to convert the functional unit of primary data to the other for the sake of convenience in the characterization process. Table 3.3 provide the list of major items and processes considered for each HP scheme during LCA procedure.

Table 3.3. Key Items and processes considered during LCA.

Intake Weir	**Penstock**	**Powerhouse**	**M & E**	**Site Visits**
Anchor rods	Concrete	Concrete block	Control panel	Construction visits
Concrete	Excavation	Drainage pipes	Draught tube	Excavator
Eel & Elver tiles	Formwork	Excavation	Excavation	Delivery &
Excavation	Pipes	Formwork	Generator	Collection
Facing stone	Pipe welding	General stone	HV cable	Machinery
Formwork	Thrust blocks	Gutter pipes	I-beam steel	Delivery &
Intake screen	Transport	Mortar	LV cable	Collection
Manhole cover		RC steel	Power cable	
Mortar		Pipe welding	Sensing cable	
Penstock gate		Slate tiles	Thrust blocks	
Pipes		Screws	Transport	
RC steel		Timber	Turbine casing	
Transport		Thrust blocks	Turbine runner	
Weir Gate		Transport	Valves	

Since the actual data of items listed in the table above were not available at some sites, the data was replicated to match the scheme with actual data available. For instance, the actual data obtained for a Turgo turbine was replicated for those schemes consists of Turgo turbine. The other data, such as excavation works, sensing cable, screws, were replicated in a similar manner for the sites with missing actual data.

3.2.2.2 Secondary data

In the case when there are limitations in collecting or accessing primary data due to data collection constraints, the LCI was compiled using a combination of secondary data, Ecoinvent v.3.2 database, invented by Swiss Centre for Life Cycle Inventories. Ecoinvent database is a comprehensive database that provides LCI datasets for raw materials, processes, activities, and transports throughout all the life cycle stages. The datasets are based on an average data for a nationwide scale rather than a regional or local scale (Ecoinvent, 2015). As it is an internationally recognized and is considered as the most consistent datasets available in the respective fields, the Ecoinvent database is an appropriate alternative option for dealing with missing primary data.

For the inventory items that are not available in the Ecoinvent database, the raw material proportion by weight of these items were estimated, and the original inventories were created with a combination of the data available in Ecoinvent v.3.2 (see Table 3.4).

Table 3.4. Original inventory dataset for certain Items.

Item	Construction materials	Proportion (%)
Wall mounted gate	Stainless steel (frame)	50
	HMPE (slide gate)	30
	HDPE (backing plate)	20
	EPDM (sealing)	10
Control panel	Sheet steel cabinet	95
	LCD screen	5
Generator (Alsema, 2000)	Cast steel	30
	Steel	30
	Aluminium	35
	Plastic	3
	Copper	2

In addition, since the UK electricity production mix data provided by Ecoinvent is outdated, a modified dataset was modelled using the UK's electricity generation mix during 2015, as shown in Table 3.5 (DECC, 2016).

Table 3.5. UK electricity generation mix in 2015 (TWh) (DECC, 2016).

Imports	Wind, Wave & Solar	Hydro	Nuclear	Petroleum	Thermal Renewables	Other thermal renewables	Natural gas	Coal
22.7	47.9	9.0	180.0	7.2	86.8	23.1	213.0	212.3

3.2.3 Selection of LCA software

Today, the use of LCA software is a common technique of performing LCA among practitioner, and the establishment of LCA software tools offers more efficient and effective LCA procedures. There a number of different LCA software packages available in the market. Table 3.6 (Lehtinen, 2011) contains a list of some software packages available for LCA analysis.

In general, each LCA software package includes different LCI databases together with several LCIA methods. Since various LCIA methods can be easily applied through using LCA software, the practitioner can obtain different representations of category indicator results and select the most appropriate ones, which are consistent with the goal and scope of the study.

In this study, OpenLCA v.1.6 (GreenDelta, 2017) as a software tool with a combination of Ecoinvent v.3.2. databases were selected, as these sources available to the author. OpenLCA is an open-source software developed by GreenDelta for LCA analysis. With its fully transparent feature, it offers more freedom to software users and can be modified according to their needs. It also allows users to conduct LCIA with a variety of impact assessment methodologies (Ciroth *et al,* 2008). Although SimaPro is widely used by LCA practitioners, according to the study made a comparison of OpenLCA and SimpaPro, only slight differences were found in terms of LCIA results, and the majority of results turned out to be the same between the two LCA software (Rodríguez and Ciroth, 2014).

Table 3.6. List of selected LCA software packages.

Software name	Supplier	License cost	Reference
CCaLC	The University of Manchester	NO	www.ccalc.org.uk
GaBi 4	PE International GmbH University of Stuttgart, LBP-GaBi	YES	www.gabi-software.com
OpenLCA	GreenDeltaTC GmbH	NO	www.openlca.org
Quantis suite 2.0	Quantis	YES	www.quantis-intl.com
SimaPro 7	PRé Consultants B.V.	YES	www.pre-sustainability.com
Umberto 5.5	ifu Hamburg GmbH	YES	www.ifu.com

3.2.4 Life cycle impact assessment

LCIA was carried out to determine the environmental impacts associated with the investigated MHP installations, and the conversion of LCI results into the category indicators were accomplished in this LCA phase. In this study, the mandatory elements of the LCIA phase – impact categories selection, classification and characterization – were performed, but the optional elements were not included.

3.2.4.1 Selection of impact categories

Prior to quantifying the potential environmental impacts of the MHP schemes, the selection of LCIA impact categories, which is to decide an LCIA method to be conducted, was achieved. Even though there are a number of different LCIA methods available, the reviewed LCA studies (Suwanit, 2011; Pascale, 2011; Arnøy, 2013 a,b; Gallagher, 2015; Hanafi, 2015) predominantly used the CML-IA baseline method (Guinée et al, 2002). To enable direct comparison of the environmental impact results with other run-of-river schemes, this study also adopted the CML-IA baseline method, version 4.4 (CML, 2015). Table 3.7 shows the environmental impact categories addressed in this study (Guinée et al, 2002).

Table 3.7. LCIA impact categories considered in this study.

Impact categories	Abbreviations	Unit	Description (Guinée et al, 2002)
Global warming potential	GWP	kg CO_2 eq.	The enhanced climate change due to greenhouse gas (GHG) emissions to the air
Acidification potential	AP	kg SO_2 eq.	The enhanced acidification due to emissions of acidifying pollutants to the air
Human toxicity potential	HTP	kg 1,4 dichlorobenzene (1,4-DCB) eq.	The impacts on human heath due to emissions of toxic substances to the air, soil and water
Ozone depletion potential	ODP	kg CFC-11 eq.	Depletion of the stratospheric ozone layer due to ozone layer-depleting pollutants emissions to the air, soil and water
Photochemical oxidation potential	POCP	kg C_2H_4 eq.	Photo-oxidant formation due to emissions of pollutants (VOCs, CO) to the air
Eutrophication potential	EP	kg PO_4 eq.	The impacts of enhancing nutrient levels in the environment due to emissions of nutrients to the air, soil, and water
Terrestrial ecotoxicity potential	TETP	kg 1,4 dichlorobenzene (1,4-DCB) eq.	The impacts on terrestrial ecosystems due to emissions of toxic substance to air, soil and water
Freshwater aquatic ecotoxicity potential	FAETP	kg 1,4 dichlorobenzene (1,4-DCB) eq.	The impacts on freshwater aquatic ecosystems due to emissions of toxic substances to air, soil and water
Marine aquatic ecotoxicity potential	MAETP	kg 1,4 dichlorobenzene (1,4-DCB) eq.	The impacts on marine aquatic ecosystems due to emissions of toxic substances to air, soil and water
Abiotic resource depletion potential	ARDP	kg antimony (Sb) eq.	Depletion of non-living natural resources (i.e. metals and minerals)
Fossil resource depletion potential	FRDP	MJ	Depletion of fossil fuels (energy resources)

3.2.4.2 Classification and characterization

Once the impact categories have been selected, the classification step, which entails sorting the LCI results to the selected impact categories. For instance, the acidifying substances, including nitrogen oxide (NO_x) and sulphur dioxide (SO_2), emitted throughout the lifecycle of MHP installations are assigned to the impact category of acidification potential. This task was followed by the characterization step, which involves quantifications of the inventory results within each impact category. With the aid of the LCA software OpenLCA v1.6 in combination with Ecoinvent v.3.2 database, these two steps of LCIA were performed. Since the CML-IA baseline method is a midpoint approach, the characterization results presented are based on the environmental-related impacts in the mid-stage of the environmental mechanism. As the previous LCA studies focused solely on the environmental impacts at the midpoint level, the endpoint impacts, such as loss of species and human health risks, are not considered in this study. Figure 3.3 (adapted from Kim *et al.,* 2016) illustrates a schematic diagram of the LCA of a MHP installation and the method in which the LCIA was conducted.

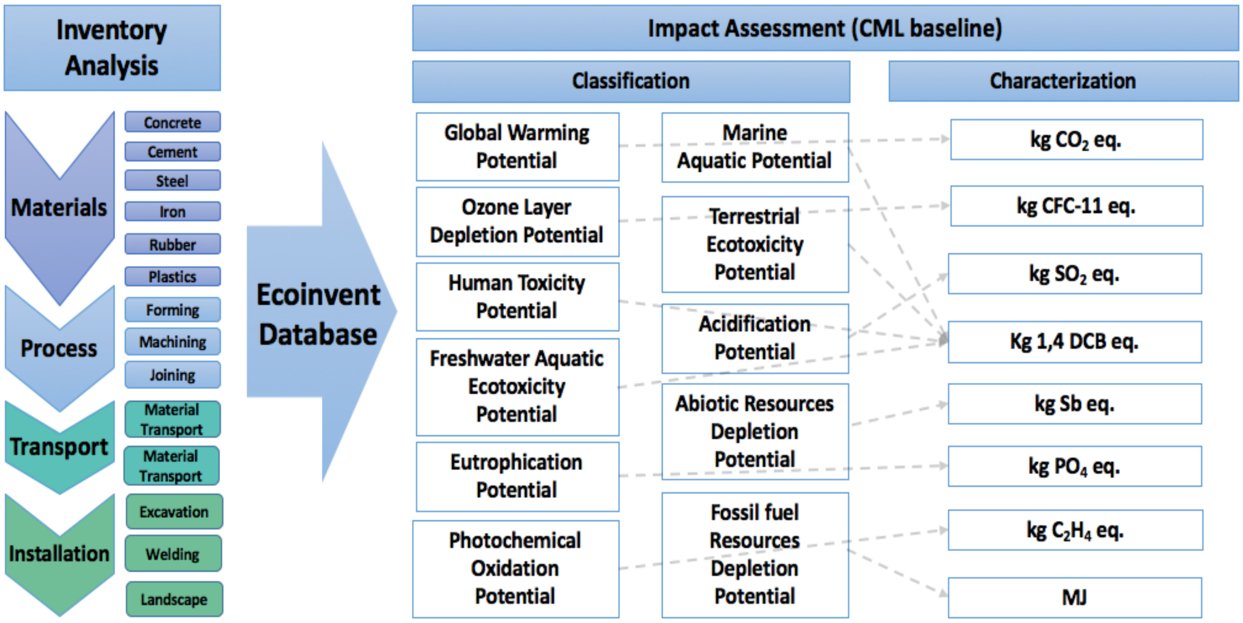

Figure 3.3. LCIA process map for MHP installation.

3.2.4.3 Normalization of LCIA

An optional element of LCA, a normalization of the impact categories was undertaken to evaluate the environmental performance of each MHP scheme. A reference value used for the normalization step is based on the average annual environmental impact of the 25 European Union nations obtained from CML characterization database (2015). This normalization of the impact categories assessed allows to compare the outcomes and impacts of each of these impact categories.

3.2.5 Interpretation and analyses of LCA results

The results of the LCA for each scheme were summarized in in a spreadsheet to enable further analysis of all investigated MHP installations. In order to identify similarities and differences in terms of the main contributors to eleven environmental impacts considered between the sites, a comparison of results of each scheme was conducted. The graphical representations of total individual scheme environmental impacts of the five sections (Intake, Penstock, Powerhouse, M&E and Site Visits) are prepared to determine which scheme sections are the greatest contributing source of environmental burdens. In a similar manner, a breakdown of the main contributors (categorized as Concrete & Aggregate, Metals, Plastics, Processes, Transport, Wood and others) to each environmental impact category. This contribution analysis allows to identify the potential improvements for MHP designs and explore the opportunities for mitigating the environmental impacts in the construction process of installing MHP plants in the future.

3.3 Key assumptions and limitations

Due to data gaps and data quality constraints involved in the LCI phase, a number of assumptions were made in order to facilitate the LCA study. The listed assumptions (see Table 3.9) were based on consultation with contractors, designers and developers, and with an aid of Ecoinvent v.3.2 via OpenLCA v.1.6 (Ecoinvent, 2015), the impact category data for the listed items were obtained.

The flowing limitations have been taken into consideration when undertaking this LCA study:

- Since several assumptions were made to compute the environmental impacts of each MHP installation, this limits the accuracy that can be acquired from the results of this LCA study;
- Although the system boundaries were clearly defined, identifying impact associated with some complex items, such as control panel and generator are limited and hence can possibly alter the results obtained;
- As presented in Table 3.2, the actual data were not available at all the MHP case studies, and hence, some data has been replicated, such as the size of turbine, based on the actual data obtained.

As stated in the ISO 14040 guideline (ISO, 2006a), since limitations associated with LCI data collection can hardly be avoided, it is important to present and enclose the limitations that are involved in conducting LCAs, which in turn enhances transparency of the report.

Table 3.8. Assumptions made during the LCA process.

Category	Items	Assumptions
Raw materials	Door cladding	Plywood (softwood) products
	Drainage and gutter pipes	Assumed to be polyvinyl chloride (PVC) pipes
	General stone	Limestone used for facing power house or weir
	HV-cable	Consists of bare copper cable
	LV-cable	3-core copper steel wired armored (SWA) cable
	Sensing cable	5-core copper steel wired armored (SWA) cable
	Weir gate	Weir gate boards are made of hardwoods
Construction process	Burial depth for cables	Trench depth – average of 1m Trench width – 0.3m wider than penstock diameter
	Burial depth for penstock	Trench depth – average of 1m with a trench width Trench width – average of 0.3m wide
	Electricity usage	Electricity consumption is based on the UK electricity generation in 2015 when the MHP were constructed
	Soil and rock excavation	Rock excavation work impacts twice as much of soil excavation work
	Storage of construction equipment (Location)	Construction equipment is stored within 75km away from each site
	Energy consumption for manufacturing turbine	Energy consumed in both Turgo and crossflow turbine productions are considered to be the same
Transportation	Pre-construction visits	Each MHP site involved a total of 15 construction site visits during construction period with an average of 100km each way.
	Concrete transportation	Concrete is transported from the closest concrete plant.
	Raw materials and component parts transportation	An average of 200km transportation distance of major items to suppliers is assumed.
	Site workers transportation	Assumed to be 60km round trip per day for 6 months
	Load factors (outward and return journeys)	Bases on the weight of freight carried, three load factors are considered: empty (0% load), average laden (50% load), full laden (100% load)
MHP operation condition	Capacity factor	The values for capacity factor used in each assessment were calculated based on the annual energy output during the 2015 operation.
	50 years energy output	Annual energy output from each MHP scheme assumed to remain the same output for 50 years lifetime operation.

Chapter 4 Results and discussion

This chapter presents the results and discussion of the LCA associated with the eleven MHP projects. The results of site No. 4, No.11, and No.14 were omitted from the analysis as discussed in the previous chapter. For the sake of simplicity, the following five relevant impact categories from the CML-IA baseline method (CML, 2015) 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 (Axpo, 2012; Gallagher et al., 2015; Hanafi and Riman, 2015; Suwanit and Gheewala, 2011) 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. The results of the rest of impact categories assessed are included in Appendices.

4.1 Contribution analysis

The purpose of this contribution analysis is to identify where the majority of each environmental impact originates within MHP installations and explore the possible alternative materials and potential improvements for MHP designs. The results of selected environmental impact categories are presented in the following two manners:

i. contribution of raw materials and activities to LCA results;
ii. contribution of each component to LCA results.

Within each result, site numbers are enumerated in ascending order of hydraulic head.

4.1.1 Breakdown of environmental impacts by raw materials and activities

In each environmental impact category, the results along with the contribution of each raw material and activities are expressed in terms of:

a. mass-based unit (except for FRDP with energy-based unit);
b. functional unit (per kWh electricity generated).

These two impact-metrics were chosen in order to represent the cumulative environmental impacts and to evaluate the environmental performance of each MHP installation. Following to each of those figures, the top five individual contributors for each impact category and the main contributor of each MHP component are presented in order of percentage contribution in table form.

Global Warming Potential

As can be seen in Figure 4.1a*,* expressed as mass-based functional unit, site No. 3 and site No. 10 contribute the highest and lowest GWP, respectively. In terms of materials and key activities, plastics are the main contributors of GWP among the sites analyzed. This was mainly due to the highest GWP contributor, high-density polyethylene (HDPE) plastics, which are used to manufacture the penstock – a crucial component of MHP projects as presented in Table 5.1. Thus, as presented in Figure 4.1a, plastics accounts for 41% (range 27 - 50%) of the total GWP associated with the MHP installations. The second and third highest GWP contributors, "formwork" and "floor slab" are constructed of reinforced concrete 32/40 with mean contributions of 12.0% and 8.8%, respectively. This reflects concrete and aggregates category to be one of the highest GWP impact, which accounts for an average of 34% (range 24 – 44%) of the GWP impact. With 5.6% mean contribution, reinforcement steel mainly used to strengthen the concrete walls and slabs is the fourth item in the list. Transport of raw materials and MHP components to suppliers contributes 5.1% of the overall GWP impact. Since wood related products are considered as carbon sequestration, they are presented as negative GWP, which is responsible for an average of -2% (range -1 to -7%) of the GWP impact.

Figure 4.1b demonstrates that site No. 1 and No. 13 contribute the highest and lowest GWP values per kWh electricity generated, respectively. Since sites No. 1 and No. 13 generate the least and greatest amounts of energy respectively, there is a strong correlation between GWP values per kWh and energy output of a MHP scheme – the higher the electricity produced, the lower the GWP burden. Although site No. 3 resulted in the highest GWP impact of one mass-based unit, due to its high electricity production, the GWP impact per kWh associated with site No. 3 turned out to be one of the lowest. As such, site No. 1 installation has the worst environmental performance in terms of GWP per functional unit, whereas site No. 13 has the least GWP impact per functional unit.

As demonstrated in the results summary for each MHP installation in Appendix 2, the mean and standard deviation for overall GWP associated with the eleven projects was 111.2 ± 30.2 t CO_2 eq. This indicated that even a small range of installed capacity of MHP scheme from 70 to 100kW can result in a notable difference in terms of GWP burdens.

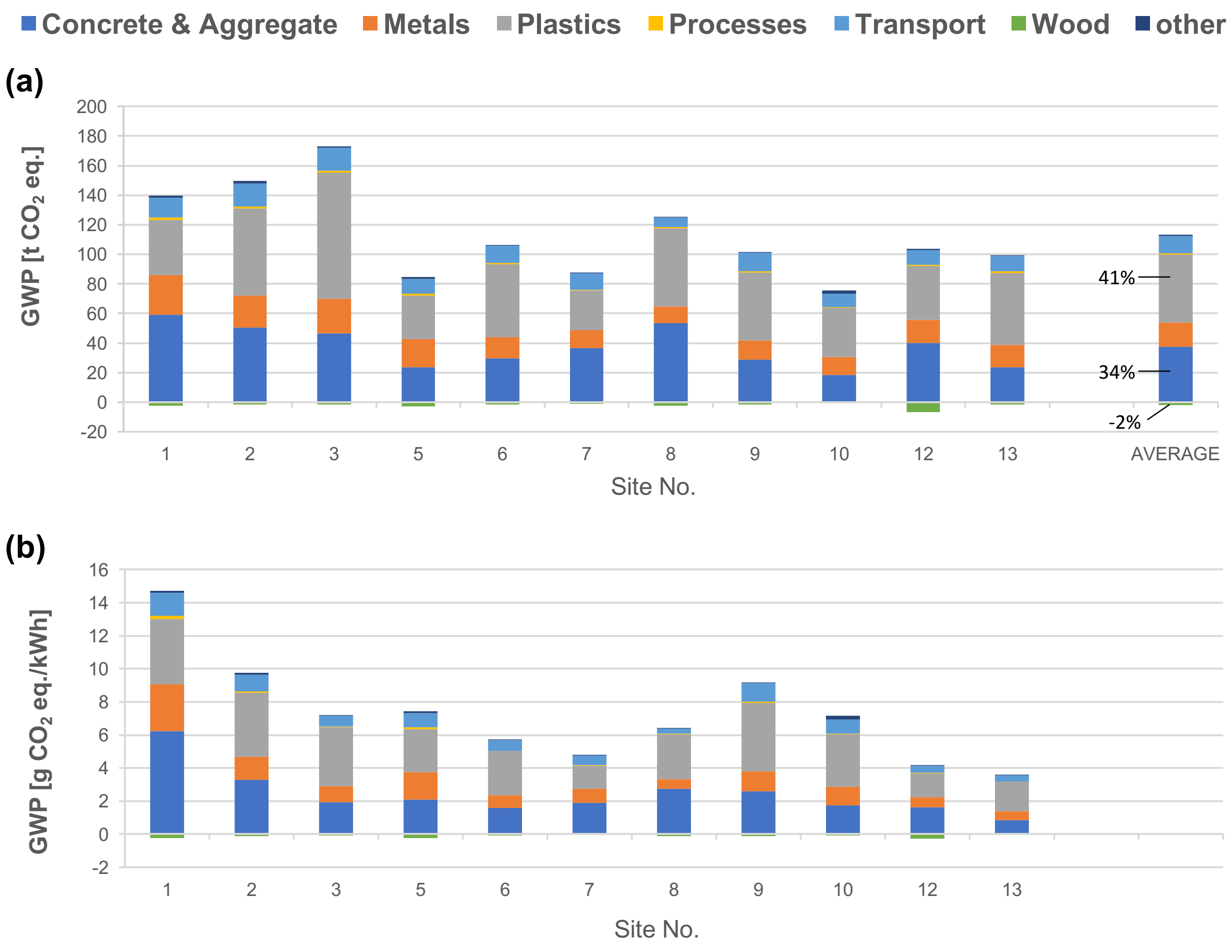

Figure 4.1. Breakdown of global warming potential by raw materials and activities of each MHP project (a) expressed as t CO_2 eq. and (b) expressed as g CO_2 eq. per kWh.

Table 4.1. Top five Individual GWP impact contributors.

Item	**Mean**	**Max**	**Min**
HDPE	38.9%	48.1%	25.6%
Formwork	12.0%	35.2%	6.3%
Floor slab	8.8%	14.2%	4.5%
Reinforcement steel	5.6%	14.1%	2.7%
Transport to suppliers	5.1%	13.4%	1.5%

Acidification Potential

In the case of AP, the mean and standard deviation for acidification impact associated with the eleven MHP installations was 483.9 ± 149.2 kg SO_2 eq., and as such, a significant amount of variation was found between the MHP case studies. Figure 4.2a presents, the metal-related items contribute the highest impact with mean contribution of 42% (range 29 – 69%), followed by plastics contributing 31% (range 19 – 46%) to the overall AP emissions. As the figure shows, AP based on per unit mass associated with site No. 6 installation is significant compared with the rest of MHP installations. This is primarily driven by excessive use of metal related items, particularly HV and sensing cables. The details of this aspect are described later in this chapter under the heading “Human Toxicity Potential”, which shows a more prominent result.

Although site No. 6 installation showed the greatest impact of one mass-based functional unit, as Figure 4.2b shows, the AP impact per kWh associated with site No. 1 installation surpassed the one associated with site No. 6. Thus, the installation of site No. 1 resulted in the worst environmental performance in terms of AP impact per kWh. On the other hand, site No. 7 installation showed the best environmental performance in terms of AP impact both per unit mass and per kWh.

Similar to the result found in GWP, Table 4.2 presents that HDPE is the highest AP contributor that has a mean contribution of 29.7% of the acidification emissions of the MHP investigated. Sensing cable, which is used for the purpose of supplying mains electricity, is the second on the list with 18.7% mean contribution. Generator, a key component of MHP projects, is the fourth item in the list that contributes 5.5% of the total acidification emissions, followed by reinforcement steel that strengthens the concrete with a mean contribution of 5.1%. Although HDPE is the main contributor to AP, metal-related items are in general responsible for the majority of the AP impact.

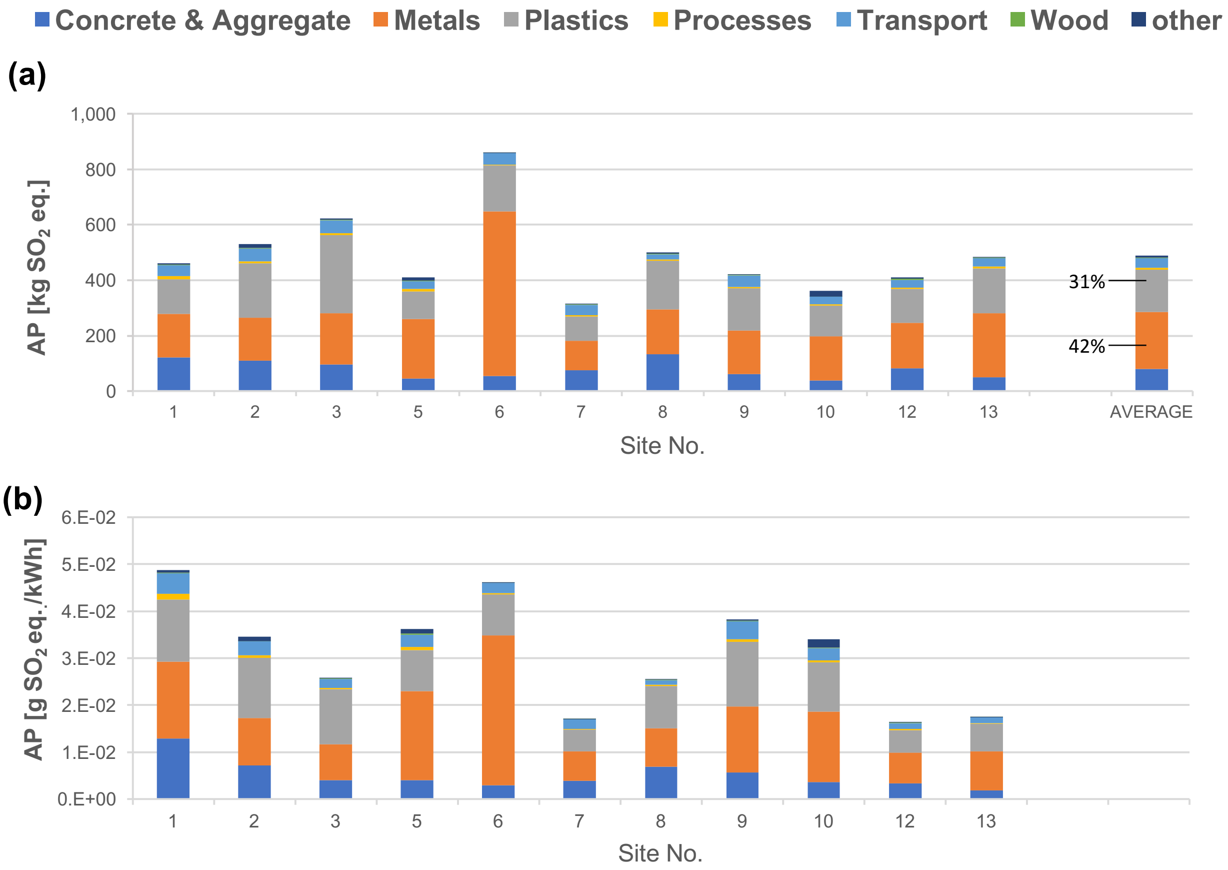

Figure 4.2. Breakdown of acidification potential by raw materials and activities of each MHP project (a) expressed as kg SO_2 eq. and (b) expressed as g SO_2 eq. per kWh.

Table 4.2. Top five individual AP impact contributors.

Item	Mean	Max	Min
HDPE	29.7%	44.0%	18.2%
Sensing cable	18.7%	27.4%	9.5%
Formwork	9.7%	23.5%	1.6%
Generator	5.5%	7.3%	2.2%
Reinforcement Steel	5.1%	7.3%	2.3%

Human Toxicity Potential

Figure 4.3a shows that site No. 6 installation has by far the highest HTP impact based on per unit mass. This is primarily due to the requirement of a long-distance cable connection. Since site No. 6 project involved with an upgrade of nearly 3 km of single–phase HV cable to three-phase HV cable, which is assumed to be a bare copper cable, the site made a significant impact on HTP. The results also show that the largest contribution to HTP, at a mean of 91% (range 86 – 98%), predominately comes from metals, which contain the load of toxic substances to human health.

This also reflects the top five individual items contributing to HTP as presented in Table 4.3, and all five individual items are the manufacture of metal products. Sensing cable is clearly the main contributor to HTP with 43.5% mean contribution. Second to sensing cable at a mean of 17.6% is HV and LV cables, and generator is third on the list that has a mean contribution of 10.1%. Coanda screen and turbine case, both made of stainless steel construction, are fourth and fifth on the list, contributing 5.3% and 3.3% of the total HTP burdens, respectively.

In terms of HTP per kWh, more variation was observed between the MHP case studies due to the difference in the amount of electricity produced at each site. However, HTP associated with site No. 6 remained by far the highest compared with other MHP installations. The mean and standard deviation for HTP associated with the eleven MHP installations was 213.2 ± 158.3 t 1,4-DCB eq. (see Appendix 2) with a significant standard deviation. However, excluding the result of site No.6 installation, the mean and standard deviation turned out to be 166.6 ± 34.8 t 1,4-DCB eq. with a small standard deviation. This suggested that MHP installation involving a distant grid connection causes significant impact on HTP.

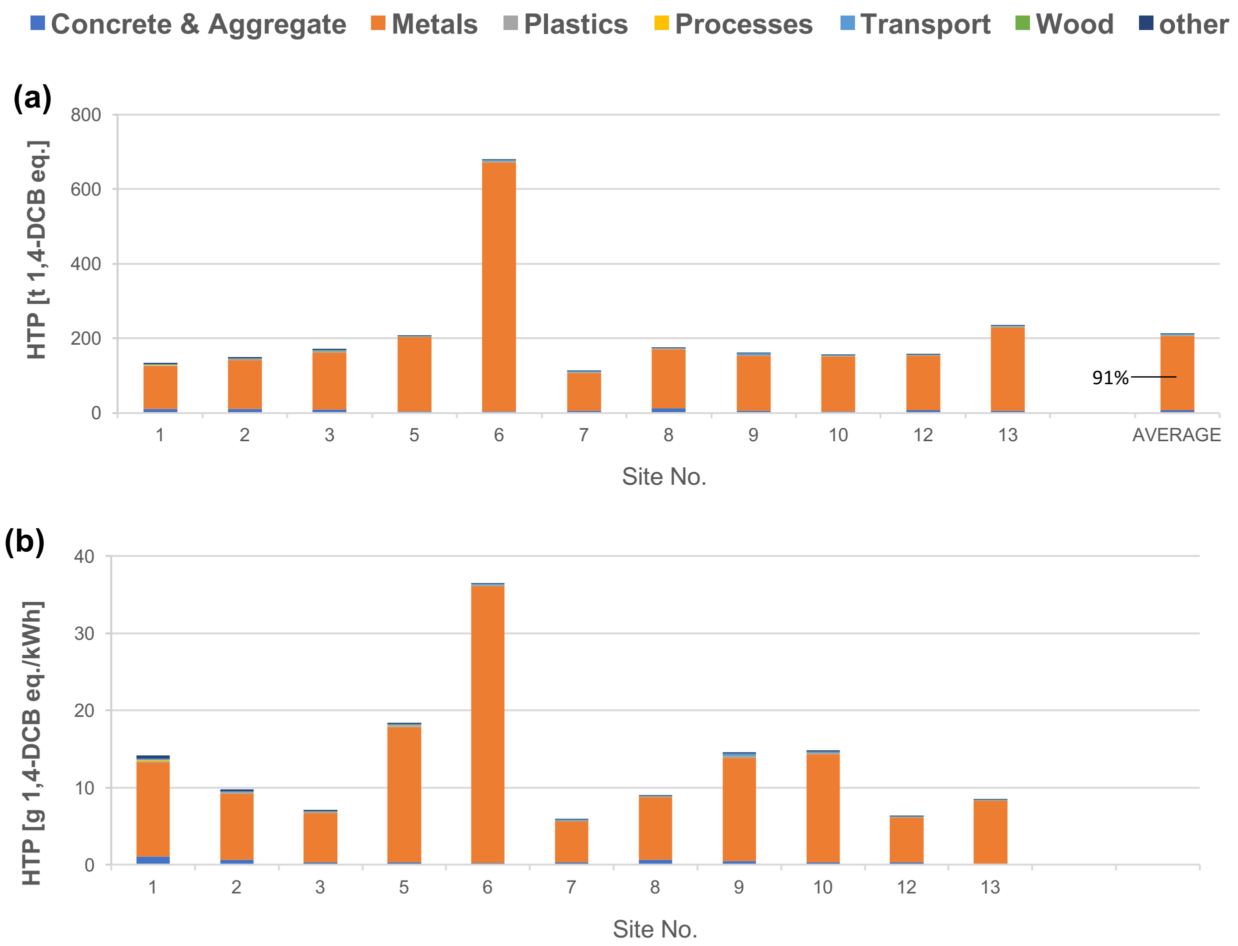

Figure 4.3. Breakdown of human toxicity potential by raw materials and activities of each MHP project (a) expressed as t 1,4-DCB eq. and (b) expressed as g 1,4-DCB eq. per kWh.

Table 4.3. Top five individual HTP impact contributors.

Item	Mean	Max	Min
Sensing cable	43.5%	61.3%	12.4%
HV & LV cables	17.6%	79.2%	4.2%
Generator	10.1%	18.3%	2.0%
Coanda screen	5.3%	8.2%	2.4%
Turbine case	3.3%	5.3%	0.7%

Abiotic Resource Depletion Potential

As demonstrated in Figure 4.4a, metal-related items predominantly responsible for the ARDP impact associated with all MHP installations, especially for site No. 6 project. As previously discussed, an upgrade of thousand meters long cable connection caused a significant impact on ARDP with the installation of site No. 6. Although the rest of MHP installations show the relatively similar amount of ARDP burden, the mean and standard deviation for ARDP impact resulted in 1097.8 ± 531.9 g Sb eq. (see Appendix 2) with a high standard deviation due to the result for site No.6.

Similar to the result seen with HTP, the vast majority of ARDP is caused by the consumption of metals with mean contribution of 94% (79 – 98%), which are manufactured by nonrenewable natural resources such as minerals and fossil fuels. This also leads the top five individual items contributing to ARDP to be the metal-related items (Table 4.4). Sensing cable, which requires for supplying mains electricity, is by far the main contributor to ARDP with 59.4% mean contribution. Second to sensing cable at a mean of 14.5% is HV and LV cables, and generator is third on the list that has a mean contribution of 6.9%. Casing for draft tube and turbine, both products of stainless steel, have mean contributions of 2.9% and 1.5% to the overall ARDP burden.

Figure 4.4b, the result of ARDP per kWh electricity generated, shows more variation between the MHP case studies. ARDP associated with site No. 6 remained the highest compared with other MHP installations. Although site No. 13 installation contributes the second highest impact on ARDP per unit mass, the result of ARDP per functional unit shows that site No.13 has one of the lowest impact. Since site No. 7 installation has the least impact on ARDP both per unit mass and per functional unit, it has the best environmental performance for ARDP. On the other hand, site No.6 installation contributes the highest impact on ARDP, and hence it shows the worst environmental performance for ARDP.

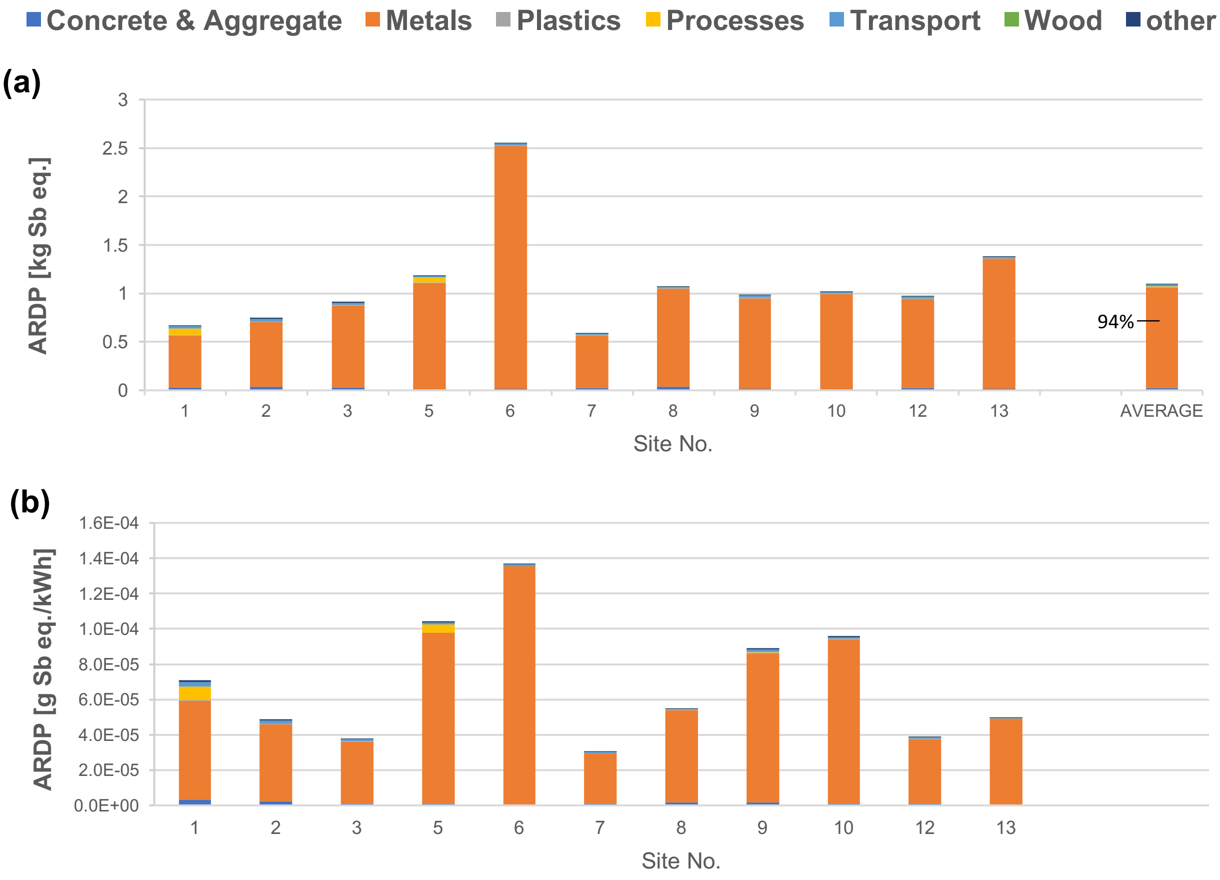

Figure 4.4. Breakdown of abiotic resource depletion by raw materials and activities of each MHP project (a) expressed as kg Sb eq. and (b) expressed as g Sb eq. per kWh.

Table 4.4. Top five Individual ARDP impact contributors.

Item	Mean	Max	Min
Sensing cable	59.4%	75.9%	25.6%
HV & LV cables	14.5%	67.3%	1.1%
Generator	6.9%	12.8%	1.9%
Draft tube casing	2.9%	3.3%	2.5%
Turbine case	1.5%	3.3%	0.4%

Fossil Resource Depletion Potential

As can be seen in Figure 4.5a and Figure 4.5b, the overall trends observed in the result of FRDP expressed as per unit mass and per kWh are analogous to the result found in GWP. The installation of site No. 3 and No. 13 have the highest and lowest impact on FRDP per mass-based unit, respectively. In terms of materials and key activities, plastics accounts for a more significant portion at a mean of 70% (range 57 – 77%) of the overall FRDP emissions as shown in Figure 4.5a.

Table 4.5 indicates that the main cause of FRDP in the MHP case studies is HDPE plastics (67.4%), which were mostly used for manufacturing the penstock. Second to HDPE at a mean of 6.5% is the transport of raw materials and MHP components to suppliers as the transport sector depends on fossil fuel recourses. “Formwork”, mainly used of reinforced concrete 32/40, is the third item in the list with mean contributions of 5.4%. Reinforcement steel used to strengthen the concrete walls and slabs is the fourth item on the list with 4.9% mean contribution. Lastly, sensing cable, use of bare copper cable, contributes 3.2% of the overall FRDP burdens.

Similar to the result seen with GWP, Figure 4.5b demonstrates that, while site No. 13 generates the highest electricity has the least impact on FRDP, the lowest electricity generation site No.1 has the greatest impact of FRDP. As such, a correlation between environmental impact per functional unit and electricity generation was also observed in the case of FRDP. Taking into these factors into consideration, in terms of FRDP per functional unit, the installation of site No. 7 and No. 1 have the best and worst environmental performance, respectively.

The mean and standard deviation for overall FRDP associated with the eleven MHP projects was 2158041 ± 651210 MJ (see Appendix 2). This implied that even a small range of installed capacity of MHP scheme from 70 to 100kW can result in a notable difference in terms of FRDP burdens.

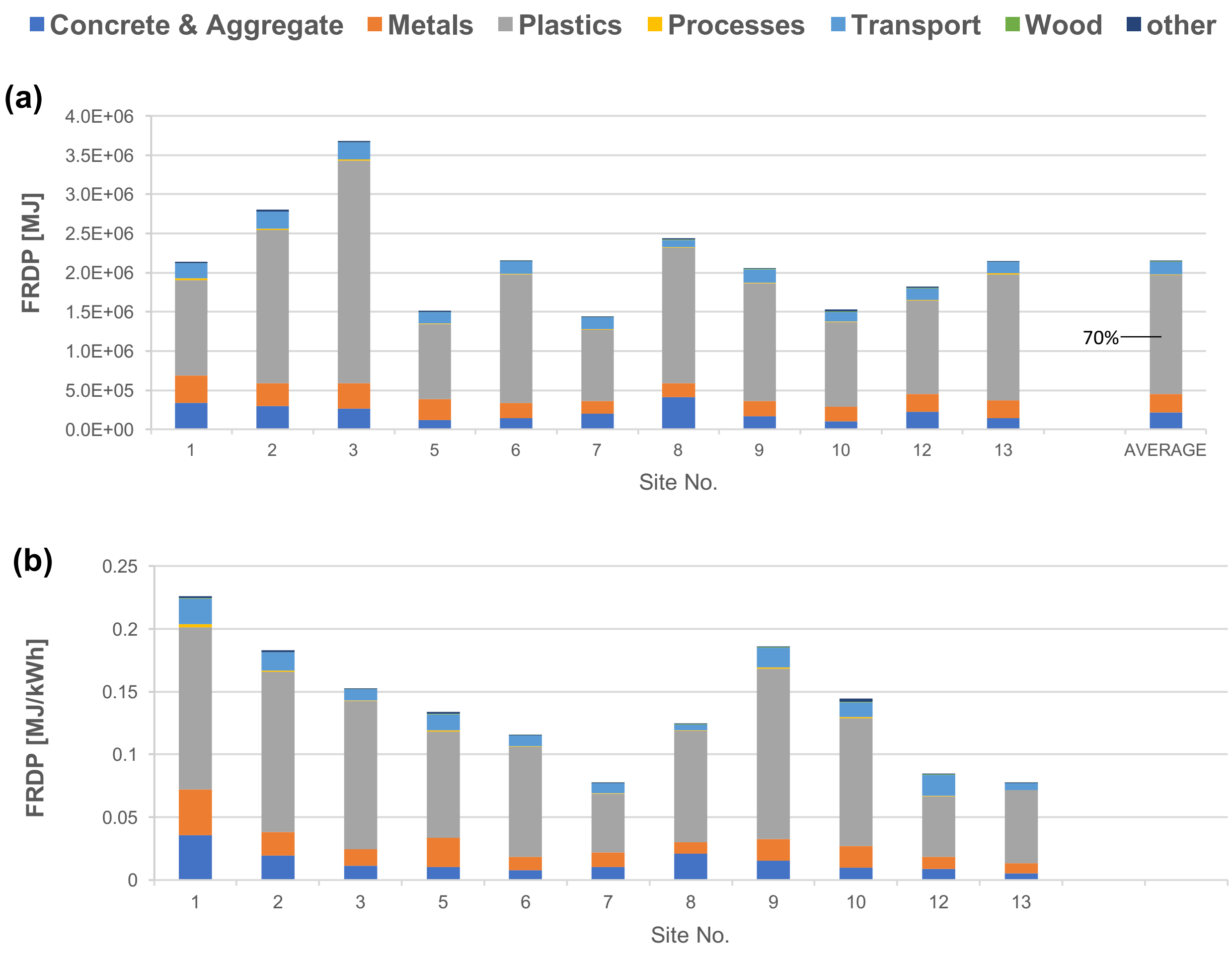

Figure 4.5. Breakdown of fossil resource depletion by raw materials and activities of each MHP project (a) expressed as MJ and (b) expressed as MJ per kWh.

Table 4.5. Top five individual FRDP impact contributors.

Item	Mean	Max	Min
HDPE	67.4%	76.0%	55.6%
Transport to suppliers	6.5%	22.1%	2.4%
Formwork	5.4%	14.8%	2.0%
Reinforcement steel	4.9%	8.7%	1.1%
Sensing cable	3.2%	4.5%	1.4%

4.1.2 Breakdown of environmental impacts by MHP components

Global Warming Potential

Figure 4.6a shows that penstock is responsible for almost half at a mean of 42% (range 28 – 52%) of the total GWP associated with the MHP installations. As previously stated, plastics are the main contributors of GWP for the MHP case studies, and HDPE is the most significant individual contributor to GWP. Since the penstock used for the MHP case studies are HDPE pipe, this led HDPE, which has a mean contribution of 25.1%, to be the main GWP contributor within penstock (see Table 4.6). In addition, the result indicates that the penstock of lower head MHP installations contributes to GWP more than higher head MHP installations.

Second to the penstock is the powerhouse with 23% (range 9 – 42%) mean contribution, followed by the intake with 21% (range 5 – 38%) mean contribution. These two components caused a major impact on GWP, primarily due to the use of concrete-related materials; the second and third highest GWP contributors, “formwork” and “floor slab” were mainly involved to construct and secure the intake and the powerhouse. Consequently, those two items are the main contributors of intake and powerhouse sections, respectively. Table 4.6 shows that the top GWP contributors of M&E and site visit sections, sensing cable and transportation used by site workers, are insignificant with mean contributions of 2.8% and 1.8%, respectively.

As can be seen in Figure 4.6b, the GWP impact tends to decrease as the head of the MHP scheme increases. The possible factors responsible for this trend include different construction environments and component requirements. For instance, since the river bed at upstream contains more boulders and rocks, high head sites can possibly construct more natural types of intake systems that require less intake construction. As such, a smaller amount of concrete and aggregate products is required during intake construction at high head sites, which are one of the highest GWP contributors.

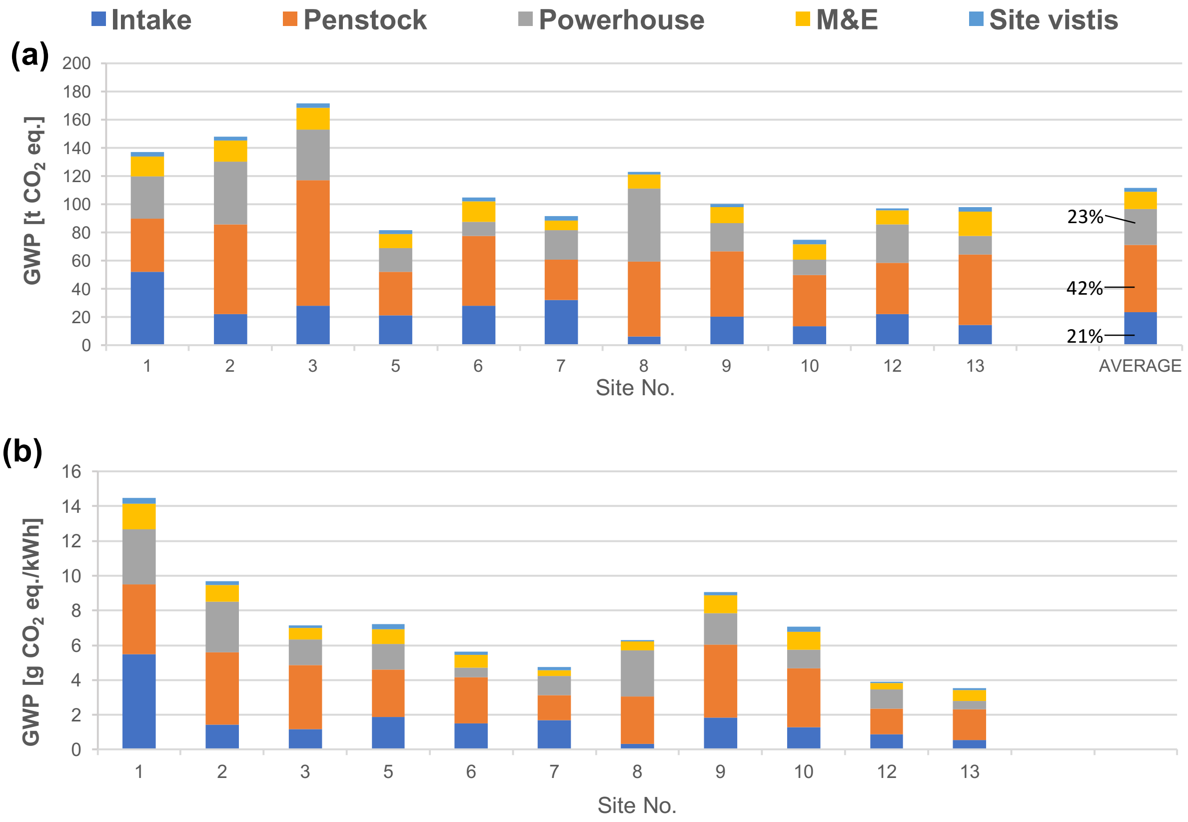

Figure 4.6. Breakdown of global warming potential by components of each MHP project (a) expressed as t CO_2 eq. and (b) expressed as g CO_2 eq. per kWh

Table 4.6. Top GWP impact contributors of each MHP component.

Component	Material / Process	Mean	Max	Min
Intake	Formwork	6.3%	14.2%	1.5%
Penstock	HDPE	25.1%	48.0%	12.3%
Powerhouse	Floor slab	9.2%	34.0%	4.8%
M&E	Sensing cable	2.8%	4.2%	1.4%
Site visits	2 vans daily visit for 6 months (60km round trip)	1.8%	3.0%	0.5%

Acidification Potential

Figure 4.7a demonstrates that the AP burdens are mainly caused by M&E with mean contribution of 37% (range 24 – 69%) materials and penstock that has a mean contribution of 33% (range 19 – 47%) section. As previously discussed, this is due to the products used in those two sections contain a number of acidifying compounds. While sensing cable is primarily responsible for the high AP impact generated by M&E materials with 17.4% mean contribution, the main AP contributor of penstock, HDPE has equally high AP impact at a mean of 17.1% (see Table 4.7). Although “Formwork” is the main AP contributors of both intake and powerhouse sections with 3.0% and 6.4% mean contribution, respectively, the AP burdens generated by this item is significantly less compared to that of sensing cable and HDPE.

Except site No. 6 installation that involves a long-distance bare copper cable connection, the AP impact contributed by M&E stay almost the same for each MHP installation. Whereas standard deviation for the M&E’s AP impact associated with the eleven projects was ± 138.9 kg SO_2 eq., without taking site No.6 into consideration, a significant lower standard deviation was found ± 39.2 kg SO_2 eq. This suggested that a significant reduction for the AP impact associated with M&E materials can hardly be expected except the installation of site No. 6.

As presented in Figure 4.7b, the AP impact per kWh associated with site No. 1 installation surpassed the one associated with site No. 6. Since the AP result per kWh fails to indicate the high impact associated with site No.6 installation demonstrated in Figure 4.7a, presenting the results based on these two different units helped to evaluate the environmental performances of each MHP installation.

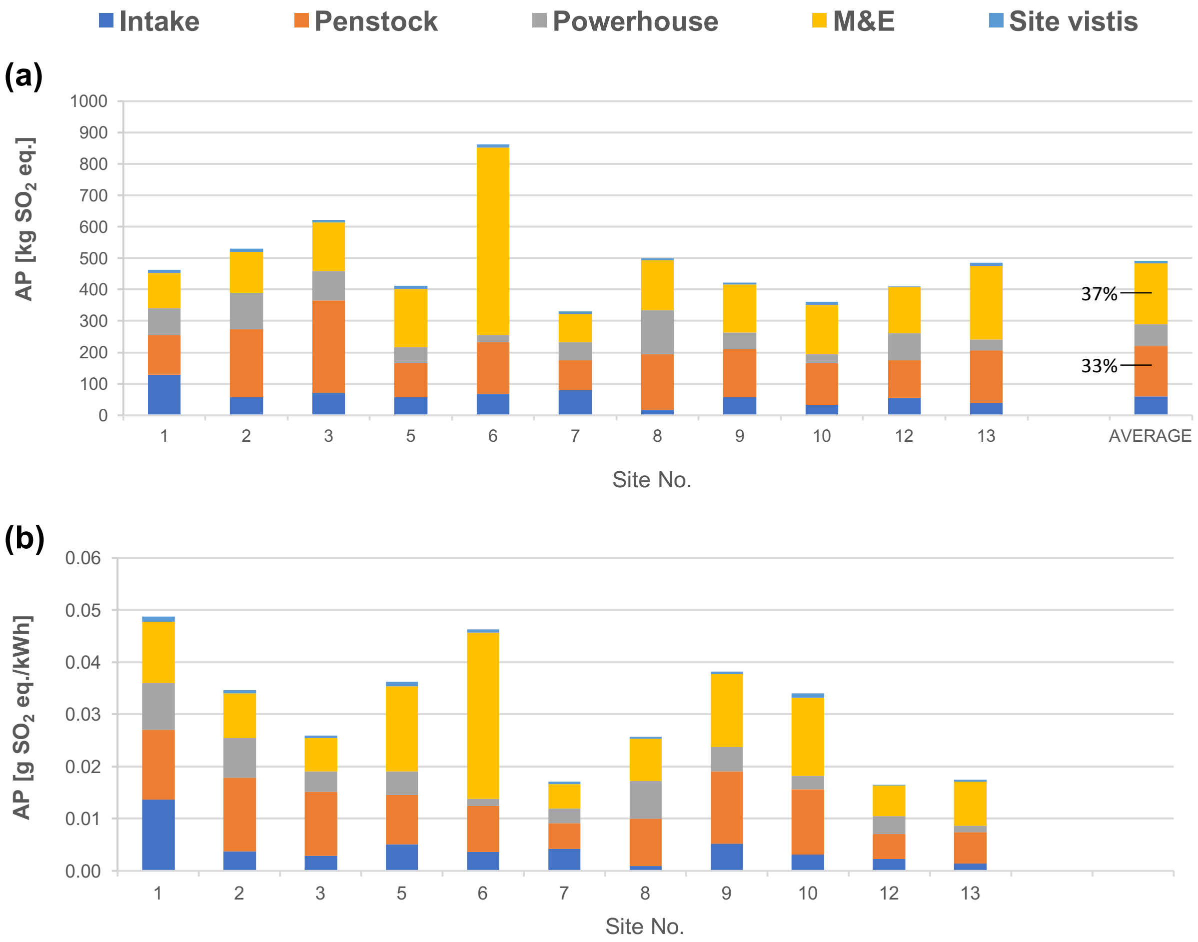

Figure 4.7. Breakdown of acidification potential by components of each MHP project (a) expressed as kg SO_2 eq. and (b) expressed as g CO_2 eq. per kWh

Table 4.7. Top AP impact contributors of each MHP component.

Component	**Material / Process**	**Mean**	**Max**	**Min**
Intake	Formwork	3.0%	8.5%	0.7%
Penstock	HDPE	17.1%	44.0%	8.0%
Powerhouse	Formwork	6.4%	22.7%	1.8%
M&E	Sensing cable	17.4%	27.4%	6.9%
Site visits	2 vans daily visit for 6 months (60km round trip)	1.3%	2.3%	0.2%

Human Toxicity Potential

As can be seen in Figure 4.8a, M&E equipment accounts for a significant portion at a mean of 82% (range 65 – 97%) of the overall HTP impact. As discussed in the previous section, the top five individual HTP impact contributors are all metal-related items (Sensing cable, HV and LV cables, generator, Coanda screen, and turbine case), and all of these five individual items belong to the M&E category. Thus, the majority of impact in HTP per unit mass is generated from M&E materials. As presented in Table 4.8, the vast majority of HTP impact is caused by the M&E leading contributor, sensing cable at a mean of 42.8%, whilst the rest of main contributors of each component have less than 4% mean contribution to the overall HTP burdens.

Due to the difference in the amount of electricity produced at each site, more variation was seen between the MHP case studies in terms of HTP per kWh. Although site No. 6 scheme generates above the average annual energy output of the MHP case studies, the impact on HTP per kWh associated with site No. 6 remained by far the highest compared with other MHP installations.

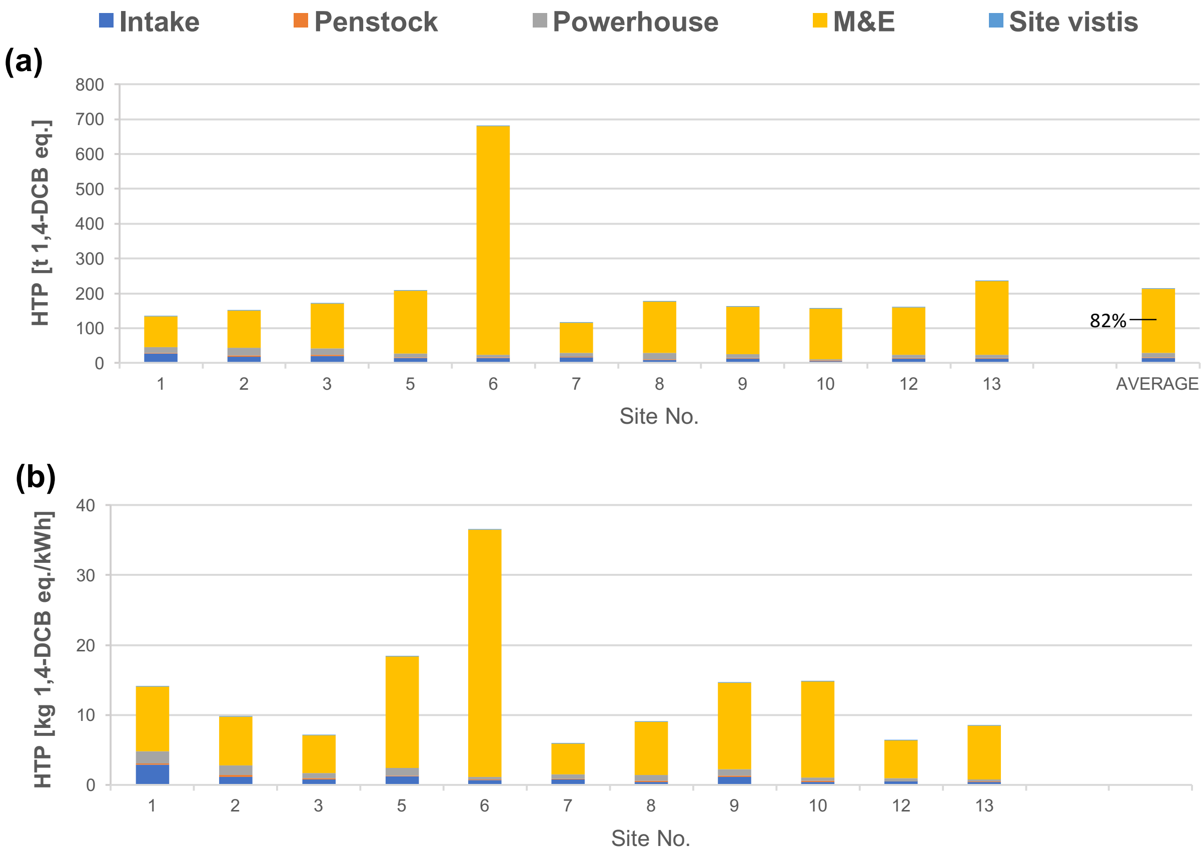

Figure 4.8. Breakdown of human toxicity potential by components of each MHP project (a) expressed as t 1,4-DCB eq. and (b) expressed as t 1,4-DCB eq. per kWh

Table 4.8. Top HTP impact contributors of each MHP component

Component	**Material / Process**	**Mean**	**Max**	**Min**
Intake	Coanda screen	3.9%	8.2%	1.5%
Penstock	HDPE	0.7%	2.0%	0.2%
Powerhouse	Outfall screen	2.4%	4.3%	0.4%
M&E	Sensing cable	42.8%	61.3%	12.4%
Site visits	2 vans daily visit for 6 months (60km round trip)	0.1%	0.2%	0.0%

Abiotic Resource Depletion Potential

The trends seen in Figures 4.9a and 4.9b are similar to the one found in the results of HTP. As shown in Figure 4.9a, M&E equipment accounts for a significant portion at a mean of 90% (range 71 – 98%) of the overall ARDP impact. This is primarily due to the top three individual items contributing to ARDP are the metal-related items (see Table 4.4), and these items are manufactured by nonrenewable natural resources such as minerals and fossil fuels.

Figure 4.9b demonstrates the result of ARDP per kWh electricity generated and shows the installation of site No.6 has the highest impact on ARDP due to an upgrade of thousand meters long bare copper cable. As it was previously mentioned, site No. 7 installation has the best environmental performance for ARDP because of its least ARDP impact while the installation of site No.6 shows the worst environmental performance due to its significant impact on ARDP.

As shown in Table 4.9, the main ARDP contributor of M&E, sensing cable accounts for predominately high percentages of the total ARDP burdens at a mean of 58.7%, whereas the other leading ARDP contributors of each MHP component account for significantly low contribution to ARDP with less than 2% mean contribution.

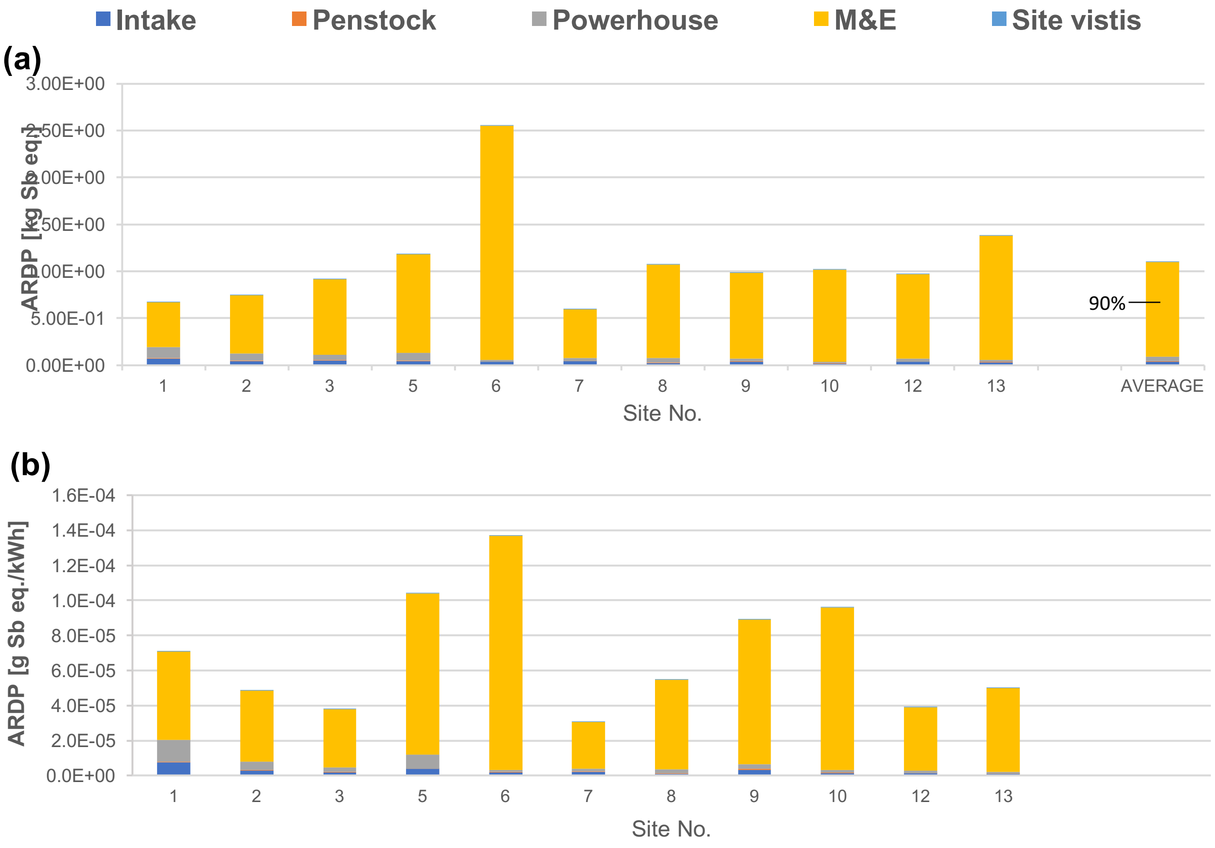

Figure 4.9. Breakdown of abiotic resource depletion potential by components of each MHP project (a) expressed as kg Sb eq. (b) expressed as g Sb eq. per kWh.

Table 4.9. Top ARDP impact contributors of each MHP component.

Component	Material / Process	Mean	Max	Min
Intake	Coanda screen	1.2%	3.2%	0.3%
Penstock	HDPE	0.2%	0.6%	0.0%
Powerhouse	Outfall screen	0.8%	1.7%	0.2%
M&E	Sensing cable	58.7%	75.9%	25.6%
Site visits	2 vans daily visit for 6 months (60km round trip)	0.0%	0.2%	0.0%

Fossil Resource Depletion Potential

Similar to the trend seen in the GWP results, the penstock of lower head schemes contributes to FRDP more than higher head schemes. In general, higher head MHP installations consists of long penstocks with relatively thick pipe walls for higher pressure resistance, and hence, the opposite trend was initially expected to occur. However, as opposed to expectation, the results imply that a larger dimeter pipe used at lower head schemes (due to high flow rate) likely leads to a greater impact on FRDP as well as GWP.

In terms of the impact associated with the MHP components, the penstock accounts for a significant portion at a mean of 70% (range 57 – 78%) of the overall emissions as shown in Figure 4.10a. This is due to the fact that the leading contributor of the penstock, HDPE plastics are made with non-renewable fossil fuel resources. As indicated in the table 4.10, HDPE responsible for notably high FRDP impact with a mean contribution of 43.7%.

Although the powerhouse and the intake are responsible for the second and third highest FRDP contributors, their contribution to FRDP is minor compared with the impact caused by the penstock. As such, the main FRDP contributors of intake and powerhouse sections – steel reinforcement contained in intake configurations and formwork required for the powerhouse construction – resulted in insignificant contributions to FRDP at a mean of 2.1% and 3.9%, respectively.

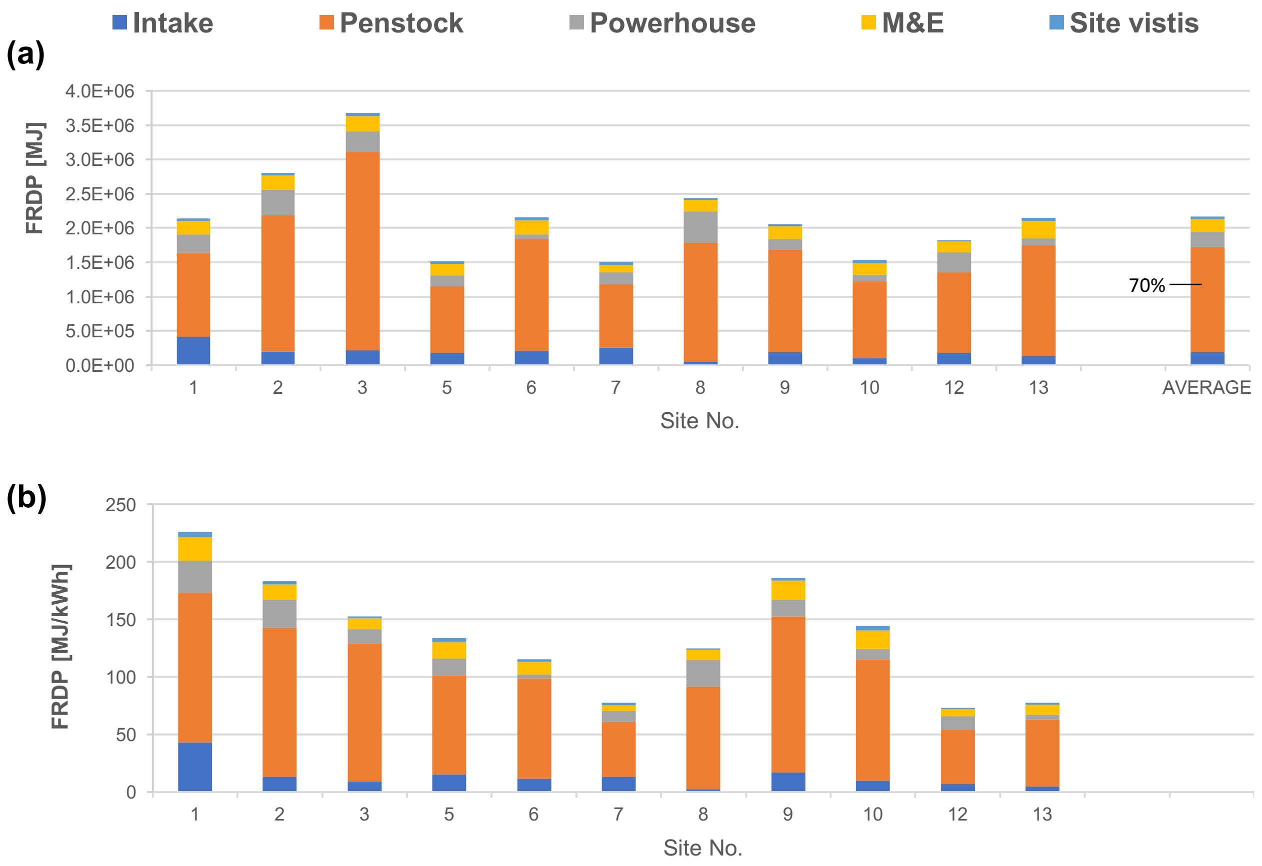

Figure 4.10. Breakdown of fossil resources depletion potential by components of each MHP project (a) expressed as MJ (b) expressed as MJ/kWh.

Table 4.10. Top FRDP impact contributors of each MHP component.

Component	**Material / Process**	**Mean**	**Max**	**Min**
Intake	Reinforcement steel	2.1%	5.9%	0.4%
Penstock	HDPE	43.7%	75.9%	25.3%
Powerhouse	Formwork	3.9%	14.8%	1.3%
M&E	Sensing cable	2.9%	4.5%	1.2%
Site visits	2 vans daily visit for 6 months (60km round trip)	1.3%	2.0%	0.4%

4.1.3 Normalized environmental impact categories for the MHP installations

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 (CML, 2015). The normalized results are presented based on two characteristics: installed capacity and types of turbines (see Figure 4.11 and Figure 4.13). The normalized values for each of those two characteristics are also presented with a range of maximum and minimum values in Figure 4.12 and Figure 4.14.

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. Figure 4.12 indicates the ranges of normalized results for the four representative MHP installations; while 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 4.11, while the 90 kW MHP schemes have the highest contribution to the majority of impact categories, 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. 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.

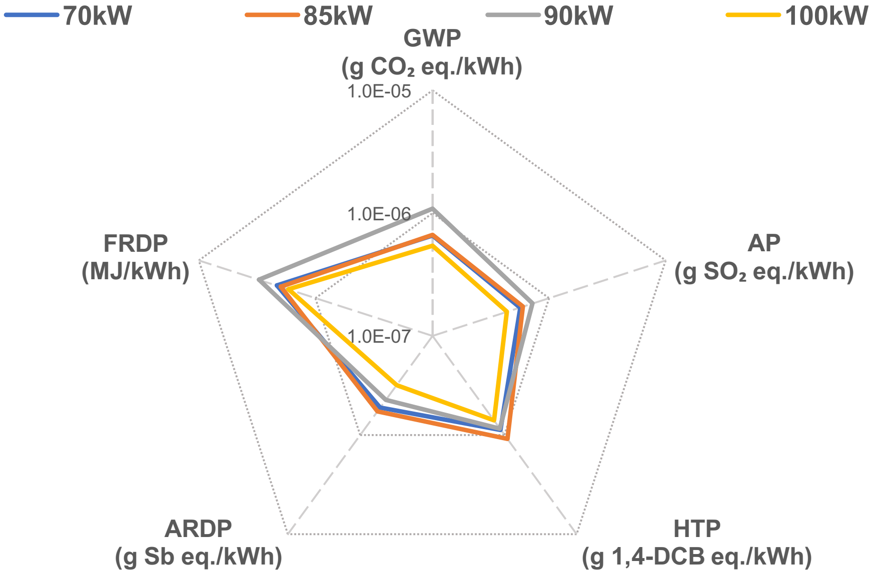

Figure 4.11. Normalized impact category results of MHP case studies with respect to installed capacity (expressed as per kWh).

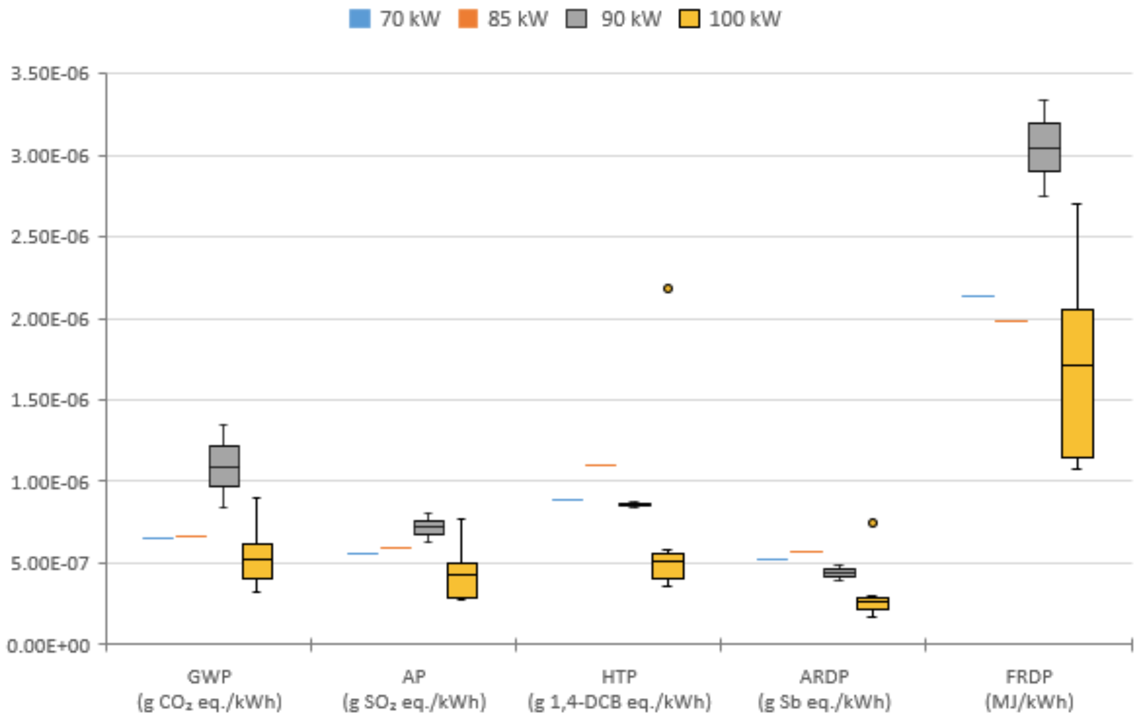

Figure 4.12. Normalized results for each of MHP installation based on installed capacity.

To investigate further environmental behavior of the MHP case studies, the normalized environmental impact potential with respect to the types of turbine installed also presented in Figure 4.13. The results are plotted based on the average values of each impact category for the crossflow and Turgo MHP schemes. Figure 4.14 represents a range of values for the mean of each scheme; the mean of crossflow schemes is based on the three projects, whilst the mean of Turgo schemes are based on the eight MHP installations.

As can be seen from 4.13, the crossflow turbine MHP installations have higher GWP, AP and FRDP impact contributions than the MHP sites installed with Turgo turbine. This is primarily 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.

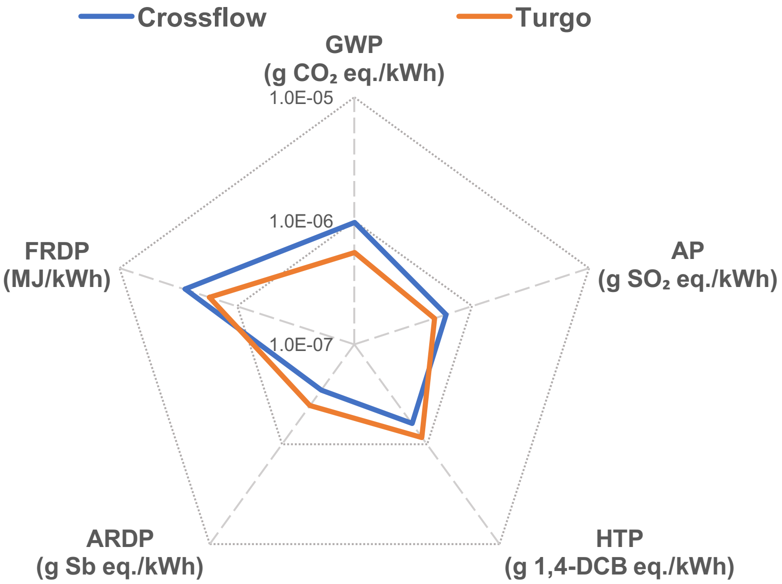

Figure 4.13. Normalized impact category results of MHP case studies with respect to installed turbine type (expressed as per kWh).

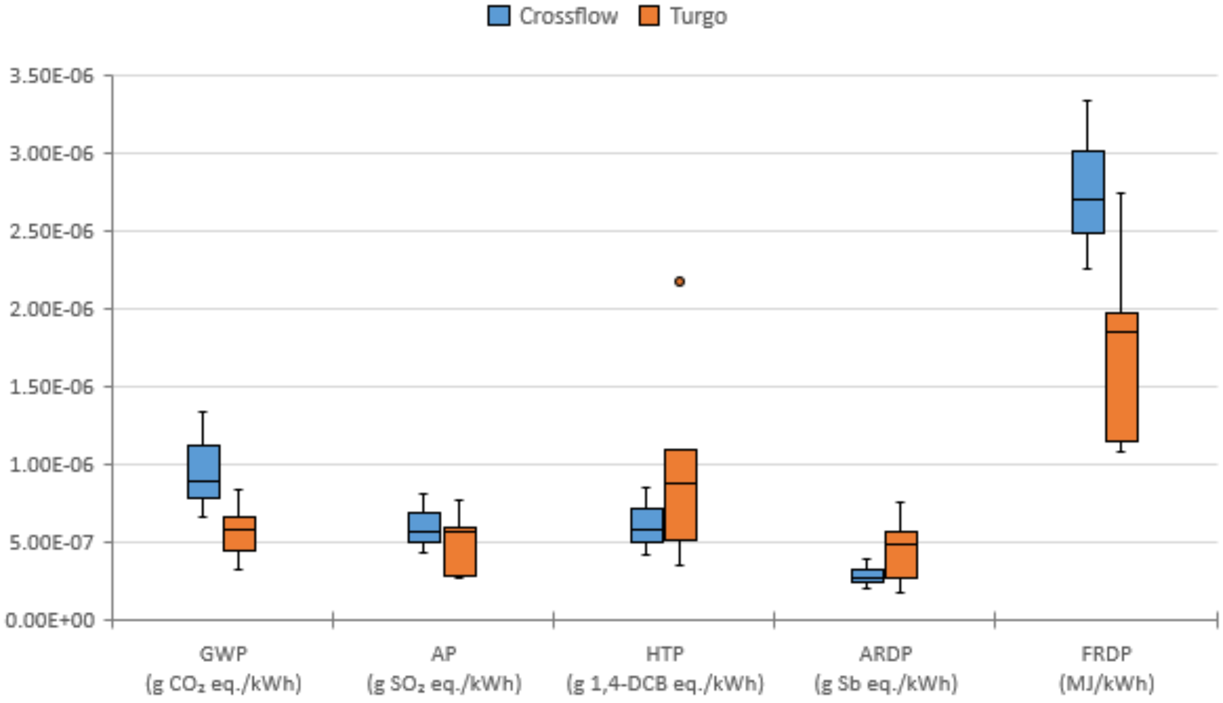

Figure 4.14. Normalized results for each of MHP installation based on installed turbines.

4.2 Comparison of LCA results with previous research findings

In order to compare the results of this study with previous run-of-river LCA studies (see Table 4.11), Figure 4.15 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.

Table 4.11. Comparative previous LCA studies of run-of-river HP projects.

Location	Installed Capacity	Impact Categories Considered	Authors (Year)
Norway	52.5 MW	GWP, AP, EP, ODP POCP, Waste	Arnøy and Modahl (2013a)
Norway	130 MW	GWP, AP, EP, ODP POCP, Waste	Arnøy and Modahl (2013b)
Switzerland	50 MW	GWP, AP, EP, ODP POCP, FRDP	Axpo (2012)
North Wales, UK	50 – 650 kW	GWP, AP, HTP, ARDP, FRDP	Gallagher *et al*. (2015)
India	50 – 3000 kW	GWP	Varun *et al.* (2008)
Simalungun, Indonesia	9 MW	GWP, ADP, AP, FAETP, HTP, POCP, FRDP, ODP, MAETP, EP, TETP	Hanafi and Riman (2015)
Thailand	1.25 – 5.1 MW	GWP, ARDP, AP, FAETP, HTP, POCP, FRDP	Suwanit and Gheewala (2011)
Thailand	3 kW	GWP, Ecotoxicity, ODP, AP, EP, POCP, Resource depletion	Pascale *et al*. (2011)

In comparison to other run-of-river schemes, the results of five selected environmental impact categories investigated in this study were generally low as illustrated in Figure 4.15. 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 with 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 (Arnøy and Modahl 2013a, b; AXPO, 2011). As some HP installations are located in developing countries (Suwanit and Gheewala, 2011; Varun, 2008; Pacale, 2011) 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 (Suwanit and Gheewala, 2011) used steel penstock pipes that causes less impact on FRDP or GWP but higher impact on AP or ARDP compared with HDPE pipes. Hence, the trend shown in the figure was observed.

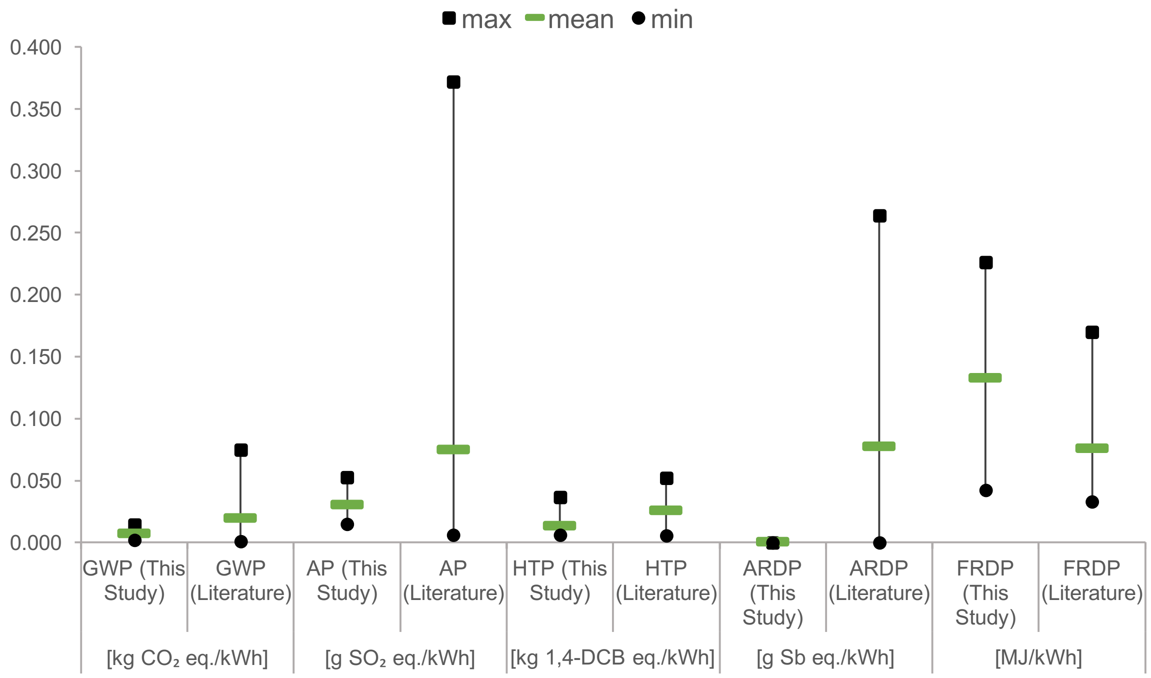

Figure 4.15. Comparison of results with previous run-of-river HP LCA studies (expressed per kWh generated).

4.3 Environmental impacts with respect to head and flow variations

Figure 4.16 represent 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.

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 a crossflow 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.

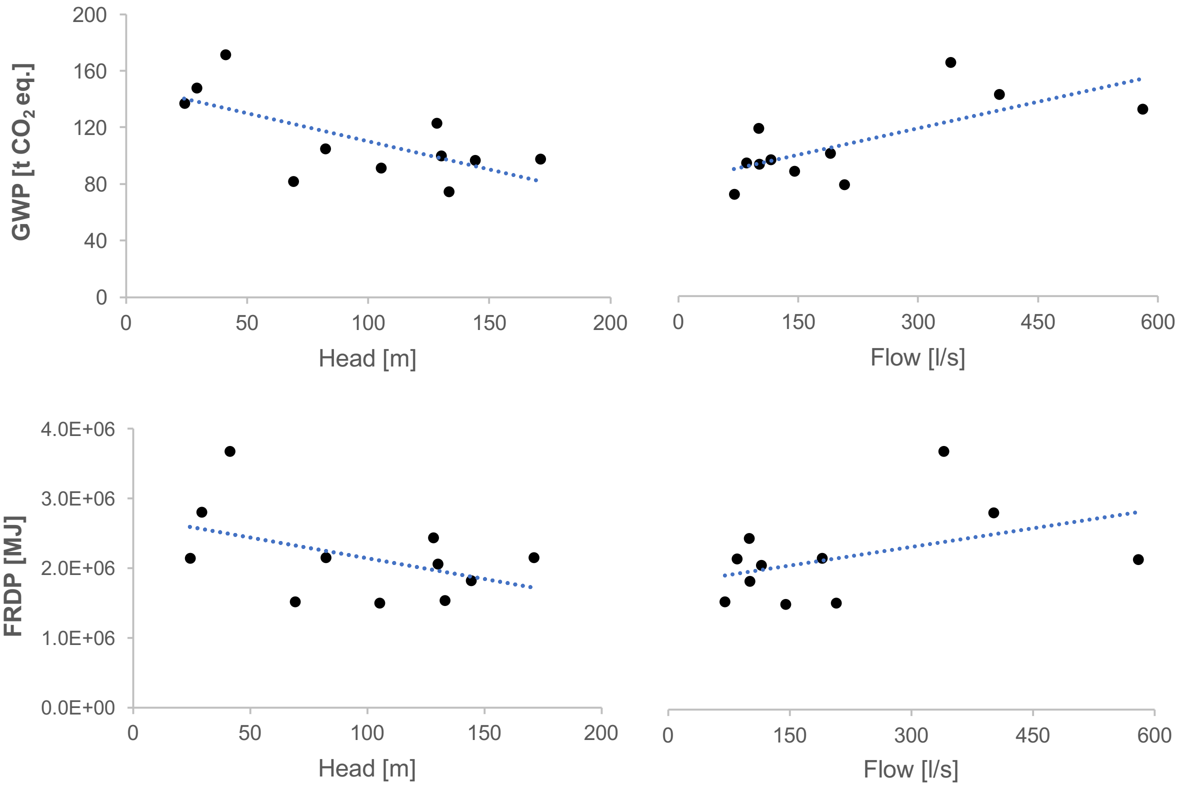

Figure 4.16. Selected environmental impacts vs. head and flow of MHP installation.

4.4 Environmental impacts with respect to 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 4.17 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 4.17.

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.

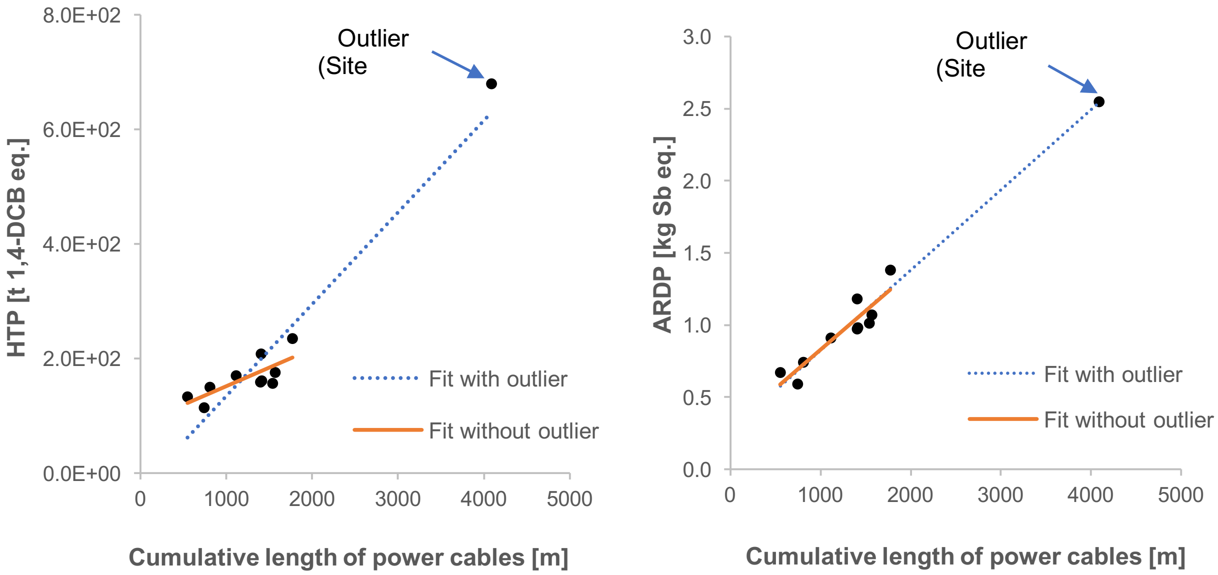

Figure 4.17. Selected environmental impacts vs. cumulative length of power cables at each MHP site with best-fit lines including and excluding outlier (site No.6 scheme).

4.5 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.

4.5.1 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 (2004), 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.

4.5.2 Underground and 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 (CETC, 2004), 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 (2008), 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 (AWWA) (2006) 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 (Gilroy, 1985). In addition, to reduce the visual impact of the above-ground penstock installation, the use of grass-covered penstock, or the reforestation of excavated areas can be an effective solution that allows the penstock to match with the natural environment (Ramos, 2009).

4.5.3 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.

4.6 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 4.12 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). The main purpose of this work 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 4.12. 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 4.13 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 4.13 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.

Table 4.13. Results of impact categories for MHP projects based on sensitivity analysis scenarios.

Scenario	Impact Categories	% Change in Impact Categories		
		Site No. 1 (Low Head)	Site No. 3 (Med Head)	Site No. 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%

Chapter 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 (ISO, 2006a). 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). Transportation have a major impact on ozone depletion potential (ODP) (see Appendix 3), whilst the impact caused by transport-related processes are insignificant for other environmental impact categories.

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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Appendices

Appendix 1: Environmental impact characterization factors

(Swiss Center for Life Cycle Inventories, 2015)

Materials & Processes	Category	Description	Ecoinvent Database name	Units	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
					kg CO2 eq.	kg SO2 eq.	kg 1,4-DCB eq.	kg CFC-11 eq.	kg C2H4 eq.	kg PO4 eq.	kg 1,4-DCB eq.	kg 1,4-DCB eq.	kg 1,4-DCB eq.	kg Sb eq.	MJ
Aluminium	Metals	Aluminium for turbine and manifolds etc	1.0 kg aluminium, production mix, cast alloy, at plant	kg	3.13E+00	1.45E-02	2.83E+00	2.16E-07	1.12E-03	6.00E-03	3.66E-02	2.08E+00	9.46E+03	2.37E-05	3.26E+01
Bitumen	Other	Bitumen	1.0 kg bitumen	kg	5.71E-01	5.65E-03	3.07E-01	4.61E-07	3.40E-04	9.00E-04	3.08E-03	8.76E-02	4.30E+02	5.38E-07	5.08E+01
Car Medium	Transport	Vehicle used for	1.0 km operation, passenger car,	km	6.35E-02	1.10E-04	5.08E-03	9.51E-09	9.92E-06	2.22E-05	1.10E-04	1.19E-03	5.43E+00	4.14E-09	8.55E-01
Cargo Ship	Transport	Assemblies transported by	1.0 t*km transport, transoceanic freight	tkm	1.08E-02	2.40E-04	4.28E-03	1.22E-09	7.58E-06	2.58E-05	2.80E-05	1.17E-03	4.63E+00	1.14E-09	1.45E-01
Cast Iron	Metals	General Cast Iron	1.0 kg cast iron, at plant	kg	1.52E+00	5.77E-03	8.18E-01	5.32E-08	8.70E-04	3.15E-03	7.19E-02	1.34E+00	2.38E+03	7.35E-07	2.04E+01
Concrete 16/20	Concrete &	Lower spec concrete used	1.0 m3 concrete, normal, at plant	m^3	2.66E+02	4.40E-01	2.79E+01	8.82E-06	1.63E-02	1.09E-01	6.03E-01	1.16E+01	3.09E+04	1.00E-04	1.02E+03
Concrete 32/40	Concrete & Aggregate	RC concrete without the steel	1.0 m3 concrete, exacting, at plant	m^3	3.30E+02	5.41E-01	3.34E+01	1.07E-05	2.03E-02	1.32E-01	7.29E-01	1.38E+01	3.71E+04	1.30E-04	1.26E+03
Concrete block	Concrete & Aggregate	Concrete blocks used for turbine house 215x440 dense hollow	1.0 kg concrete block, at plant	m^2	1.23E-01	2.40E-04	3.40E-02	4.44E-09	1.06E-05	7.99E-05	7.80E-04	1.37E-02	3.19E+01	1.74E-07	5.69E-01
Control panel	Other	Control panel for turbine	1.0 kg steel, converter, low-alloyed, at plant & 1.0 kg assembly, LCD module	kg	3.73E+00	1.34E-07	8.25E-07	1.60E-06	3.03E-03	6.61E-01	1.57E-06	1.29E-02	2.33E-02	5.09E-02	1.93E-03
Copper	Metals	Copper used	1.0 kg Copper wire	kg	3.64E+00	5.55E-01	6.50E+02	2.85E-07	2.12E-02	2.14E+00	2.14E+00	1.45E+02	4.10E+05	2.07E-03	4.24E+01
Diesel	Other	Diesel used on site for construction	1.0 MJ diesel, burned in diesel	MJ	8.84E-02	9.10E-04	9.76E-03	1.09E-08	2.96E-05	2.00E-04	9.68E-05	1.99E-03	1.02E+01	9.08E-09	1.20E+00
Drainage Pipe	Plastics	PVC pipes for drainage	1.0 kg polyvinylchloride, emulsion polymerised, at plant	kg	2.52E+00	6.65E-03	4.70E-01	1.33E-09	3.30E-04	1.25E-03	1.21E-02	1.10E-01	3.71E+02	1.25E-05	5.08E+01
Ductile Iron	Metals	Ductile cast iron pipes	1.0 kg cast iron, at plant	kg	1.52E+00	5.77E-03	8.18E-01	5.32E-08	8.70E-04	3.15E-03	7.19E-02	1.34E+00	2.38E+03	7.35E-07	2.04E+01
Electric Motor	Metals	diesel generator system model (Original)	1.0 kg of diesel generator system model (Original)	kg	2.20E+00	1.99E-02	1.44E+01	1.11E-07	1.42E-03	4.70E-02	7.94E-02	4.24E+00	1.27E+04	5.05E-05	2.65E+01
Electricity	Processes	Used for certain tasks	1 kWh, electricity, production mix GB (Original)	kWh	4.63E-01	1.80E-03	1.40E-01	1.31E-08	7.07E-05	6.10E-04	1.33E-03	8.85E-02	4.71E+02	6.40E-08	5.49E+00
Fill material	Concrete &	Crushed gravel for fill	1.0 kg gravel, crushed, at mine	kg	4.44E-03	2.54E-05	3.55E-03	4.89E-10	1.12E-06	9.47E-06	7.90E-05	1.68E-03	4.27E+00	1.95E-08	5.47E-02
Formwork for Concrete Walls	Concrete & Aggregate	Formwork for reinforced concrete walles	1.0 m3concrete, sole plate and foundation, at plant + 65 kg/m3 RC steel	m^3	2.58E+02	6.62E-01	6.48E+01	1.09E-05	6.54E-02	2.95E-01	2.47E+00	7.48E+01	1.48E+05	1.80E-04	2.00E+03
Formwork for Concrete Slabs	Concrete & Aggregate	Formwork for reinforced concrete bases	1.0 m3concrete, sole plate and foundation, at plant + 100 kg/m3 RC steel	m^3	3.10E+02	8.41E-01	8.58E+01	1.30E-05	9.39E-02	4.06E-01	3.55E+00	1.09E+02	2.12E+05	2.20E-04	2.66E+03
Formwork for Concrete Walls C32/40	Concrete & Aggregate	Formwork for reinforced concrete walles	1.0 m3concrete, sole plate and foundation, at plant + 65 kg/m3 RC steel	m^3	2.58E+02	6.62E-01	6.48E+01	1.09E-05	6.54E-02	2.95E-01	2.47E+00	7.48E+01	1.48E+05	1.80E-04	2.00E+03
Formwork for reinforced concrete bases	Concrete & Aggregate	Formwork for reinforced concrete bases	1.0 m3concrete, sole plate and foundation, at plant + 100 kg/m3 RC steel	m^3	3.10E+02	8.41E-01	8.58E+01	1.30E-05	9.39E-02	4.06E-01	3.55E+00	1.09E+02	2.12E+05	2.20E-04	2.66E+03
Galvanising Steel	Processes	Zinc coat for galvenising steel	1.0 m2 zinc coating, pieces	m^2	6.21E+00	5.61E-02	1.33E+01	7.83E-07	2.11E-03	2.59E-02	2.23E-01	6.04E+00	1.66E+04	6.90E-04	7.64E+01
General Stone	Concrete & Aggregate	Natural stone used for facing turbine house or weir	1.0 kg limestone, milled, packed, at plant	kg	2.34E-02	1.00E-04	1.36E-02	2.32E-09	4.23E-06	3.62E-05	1.60E-04	6.01E-03	1.64E+01	3.15E-08	2.54E-01
GRP (injection moulded)	Plastics	Glass fibre reinforced plastic injection moulded pipes	1.0 kg glass fibre reinforced plastic, polyamide, injection moulding, at plant	kg	8.78E+00	3.19E-02	1.07E+00	7.56E-07	1.47E-03	8.16E-03	1.02E-02	6.63E-01	2.02E+03	7.01E-06	1.16E+02
Gutter Pipe	Plastics	PVC gutters and downpipes	1.0 kg polyvinylchloride, emulsion polymerised	kg	2.52E+00	6.65E-03	4.70E-01	1.33E-09	3.30E-04	1.25E-03	1.21E-02	1.10E-01	3.71E+02	1.25E-05	5.08E+01
Hardwood	Wood	Sawnwood air dried hardwood	1.0 m3 sawn timber, hardwood, planed	m^3	-1.09E+03	5.35E-01	4.61E+01	8.39E-06	4.41E-02	2.47E-01	9.43E-01	3.57E+01	9.88E+04	1.60E-04	1.20E+03
HDPE	Plastics	High Density Polyethylene used for pipes	1.0 kg polyethylene, HDPE, granulate, at plant	kg	1.97E+00	6.53E-03	8.00E-02	7.02E-10	6.20E-04	5.40E-04	1.50E-04	2.95E-02	1.02E+02	6.18E-08	6.66E+01

HGV >32t (dedicated load) 0% laden	Transport	Dedicated Transport using HGV >32 metric ton	1.0 v*km operation, lorry >32t, EURO5	km	9.85E-01	2.69E-03	7.39E-02	1.47E-07	8.23E-05	5.80E-04	1.04E-03	1.91E-02	8.54E+01	6.42E-08	1.32E+01
HGV >32t (dedicated load) 100% laden	Transport	Dedicated Transport using HGV >32 metric ton	1.0 v*km operation, lorry >32t, EURO5	km	9.85E-01	2.69E-03	7.39E-02	1.47E-07	8.23E-05	5.80E-04	1.04E-03	1.91E-02	8.54E+01	6.42E-08	1.32E+01
HGV >32t (dedicated load) average laden	Transport	Dedicated Transport using HGV >32 metric ton	1.0 v*km operation, lorry >32t, EURO5	km	9.85E-01	2.69E-03	7.39E-02	1.47E-07	8.23E-05	5.80E-04	1.04E-03	1.91E-02	8.54E+01	6.42E-08	1.32E+01
HGV >32t (shared load)	Transport	Transport using HGV >32 metric ton	1.0 t*km transport, lorry >32t, EURO5	tkm	1.07E-01	3.30E-04	1.85E-02	1.76E-08	1.42E-05	9.17E-05	3.30E-04	1.03E-02	2.83E+01	3.24E-07	1.63E+00
HGV 16-32t (dedicated load) 0% laden	Transport	Dedicated Transport using HGV 16-32 metric ton	1.0 v*km operation, lorry 16-32t, EURO5	km	8.02E-01	2.15E-03	6.15E-02	1.20E-07	6.69E-05	4.70E-04	8.70E-04	1.57E-02	6.97E+01	5.21E-08	1.08E+01
HGV 16-32t (dedicated load) 100% laden	Transport	Dedicated Transport using HGV 16-32 metric ton	1.0 v*km operation, lorry 16-32t, EURO5	km	8.02E-01	2.15E-03	6.15E-02	1.20E-07	6.69E-05	4.70E-04	8.70E-04	1.57E-02	6.97E+01	5.21E-08	1.08E+01
HGV 16-32t (dedicated load) average laden	Transport	Dedicated Transport using HGV 16-32 metric ton	1.0 v*km operation, lorry 16-32t, EURO5	km	8.02E-01	2.15E-03	6.15E-02	1.20E-07	6.69E-05	4.70E-04	8.70E-04	1.57E-02	6.97E+01	5.21E-08	1.08E+01
HGV 16-32t (shared load)	Transport	Transport using HGV 16-32 metric ton	1.0 t*km transport, lorry 16-32t, EURO5	tkm	1.68E-01	5.00E-04	2.66E-02	2.65E-08	2.07E-05	1.30E-04	4.70E-04	1.41E-02	4.00E+01	4.68E-07	2.46E+00
HGV 3.5-7.5t (dedicated load) 0% laden	Transport	Dedicated Transport using HGV 3.5-7.5 metric ton	1.0 v*km operation, lorry 3.5-7.5t, EURO5	km	3.70E-01	9.20E-04	3.20E-02	5.41E-08	3.03E-05	2.00E-04	4.40E-04	7.29E-03	3.24E+01	2.36E-08	4.86E+00
HGV 3.5-7.5t (dedicated load) 0% laden	Transport	Dedicated Transport using HGV 3.5-7.5 metric ton	1.0 v*km operation, lorry 3.5-7.5t, EURO5	km	3.70E-01	9.20E-04	3.20E-02	5.41E-08	3.03E-05	2.00E-04	4.40E-04	7.29E-03	3.24E+01	2.36E-08	4.86E+00
HGV 3.5-7.5t (dedicated load)	Transport	Dedicated Transport using HGV 3.5-7.5 metric ton	1.0 v*km operation, lorry 3.5-7.5t, EURO5	km	3.70E-01	9.20E-04	3.20E-02	5.41E-08	3.03E-05	2.00E-04	4.40E-04	7.29E-03	3.24E+01	2.36E-08	4.86E+00
HGV 3.5-7.5t (shared load)	Transport	Transport using HGV 3.5-7.5 metric ton	1.0 t*km transport, lorry 3.5-7.5t, EURO5	tkm	4.74E-01	1.37E-03	9.11E-02	7.18E-08	6.08E-05	3.90E-04	1.55E-03	4.85E-02	1.37E+02	2.02E-06	6.80E+00
HGV 7.5-16t (dedicated load) 0% laden	Transport	Dedicated Transport using HGV 7.5-16 metric ton	1.0 v*km operation, lorry 7.5-16t, EURO5	km	6.17E-01	1.62E-03	4.89E-02	9.15E-08	5.10E-05	3.50E-04	6.30E-04	1.18E-02	5.36E+01	3.99E-08	8.23E+00
HGV 7.5-16t (dedicated load) 100% laden	Transport	Dedicated Transport using HGV 7.5-16 metric ton	1.0 v*km operation, lorry 7.5-16t, EURO5	km	6.17E-01	1.62E-03	4.89E-02	9.15E-08	5.10E-05	3.50E-04	6.30E-04	1.18E-02	5.36E+01	3.99E-08	8.23E+00
HGV 7.5-16t (dedicated load) average laden	Transport	Dedicated Transport using HGV 7.5-16 metric ton	1.0 v*km operation, lorry 7.5-16t, EURO5	km	6.17E-01	1.62E-03	4.89E-02	9.15E-08	5.10E-05	3.50E-04	6.30E-04	1.18E-02	5.36E+01	3.99E-08	8.23E+00
HGV 7.5-16t (shared load)	Transport	Transport using HGV 7.5-16 metric ton	1.0 t*km transport, lorry 7.5-16t, EURO5	tkm	2.25E-01	6.60E-04	3.45E-02	3.51E-08	2.65E-05	1.70E-04	5.80E-04	1.74E-02	5.06E+01	6.17E-07	3.25E+00
LGV up to 3.5t (dedicated load)	Transport	Dedicated Transport using small and medium sized van	1.0 v*km operation, van < 3,5t	km	2.88E-01	9.70E-04	2.67E-02	4.23E-08	1.20E-04	2.10E-04	2.90E-04	5.79E-03	2.59E+01	2.15E-08	3.87E+00
LGV up to 3.5t (dedicated load)	Transport	Dedicated Transport using small and medium sized van	1.0 v*km operation, van < 3,5t	km	2.88E-01	9.70E-04	2.67E-02	4.23E-08	1.20E-04	2.10E-04	2.90E-04	5.79E-03	2.59E+01	2.15E-08	3.87E+00
LGV up to 3.5t (dedicated load)	Transport	Dedicated Transport using small and medium sized van	1.0 v*km operation, van < 3,5t	km	2.88E-01	9.70E-04	2.67E-02	4.23E-08	1.20E-04	2.10E-04	2.90E-04	5.79E-03	2.59E+01	2.15E-08	3.87E+00
LGV up to 3.5t (shared load)	Transport	Transport using small and medium sized van	1.0 t*km transport, van <3.5t	tkm	1.55E+00	5.53E-03	7.26E-01	2.18E-07	8.80E-04	1.76E-03	9.01E-03	2.45E-01	6.67E+02	3.61E-06	2.15E+01
LCD Display	Other	Liquid crystal display for turbine control panel	1.0 kg assembly, LCD module	kg	3.60E+01	2.13E-01	7.19E+01	1.59E-06	8.24E-03	1.64E-01	4.35E-01	1.24E+01	5.93E+05	1.90E-04	3.47E+02
Metal Welding	Processes	General Welding	1.0 m welding, arc, steel	m	1.24E-01	5.00E-04	9.05E-01	5.65E-09	5.49E-05	3.10E-04	9.94E-02	1.32E-01	2.56E+02	1.24E-06	1.52E+00
Mortar	Concrete & Aggregate	Mortar used for grouting, screed or block work	1.0 kg cement mortar, at plant	kg	1.96E-01	3.30E-04	2.19E-02	8.21E-09	1.32E-05	8.37E-05	4.20E-04	9.75E-03	2.71E+01	5.18E-08	9.01E-01

Penstock 200mm	Metals	Penstock used on pipes	1.0 kg wallmounted gate, total	Nr	3.48E+00	1.60E-02	3.88E+01	1.69E-07	1.14E-03	5.08E-03	1.32E+00	6.63E+00	7.30E+03	8.25E-05	6.64E+01
Penstock 300mm	Metals	Penstock used on pipes	1.0 kg wallmounted gate, total	Nr	3.48E+00	1.60E-02	3.88E+01	1.69E-07	1.14E-03	5.08E-03	1.32E+00	6.63E+00	7.30E+03	8.25E-05	6.64E+01
Penstock 400mm	Metals	Penstock used on pipes	1.0 kg wallmounted gate, total	Nr	3.48E+00	1.60E-02	3.88E+01	1.69E-07	1.14E-03	5.08E-03	1.32E+00	6.63E+00	7.30E+03	8.25E-05	6.64E+01
Penstock 600mm	Metals	Penstock used on pipes	1.0 kg wallmounted gate, total	Nr	3.48E+00	1.60E-02	3.88E+01	1.69E-07	1.14E-03	5.08E-03	1.32E+00	6.63E+00	7.30E+03	8.25E-05	6.64E+01
Petrol	Other	Unleaded petrol for on-site equipment such as generators etc	1.0 kg petrol, unleaded, at regional storage	kg	7.07E-01	7.90E-03	3.42E-01	4.73E-07	5.20E-04	1.01E-03	3.22E-03	9.17E-02	4.67E+02	3.48E-07	5.33E+01
Plywood	Wood	Plywood for electrical mounting boards	1.0 m3 plywood, indoor use, at plant	m³	-6.54E+02	2.69E+00	2.68E+02	5.44E-05	2.41E-01	1.21E+00	6.45E+00	1.53E+02	4.49E+05	1.32E-03	7.83E+03
Power Cables 185mm2	Metals	Underground SWA cables	1.0 m cable, three-conductor cable, at plant	m	2.45E+00	7.68E-02	7.49E+01	1.07E-07	3.09E-03	8.58E-02	2.42E-01	2.24E+01	6.22E+04	5.80E-04	5.31E+01
Power Cables 95mm2	Metals	Underground SWA cables	1.0 m cable, three-conductor cable, at plant	m	2.45E+00	7.68E-02	7.49E+01	1.07E-07	3.09E-03	8.58E-02	2.42E-01	2.24E+01	6.22E+04	5.80E-04	5.31E+01
Reinforced Concrete Floors C32/40	Concrete & Aggregate	100kg/m3 of RC steel	1.0 m3concrete, sole plate and foundation, at plant + 100 kg/m3 RC steel	m³	3.10E+02	8.41E-01	8.58E+01	1.30E-05	9.39E-02	4.06E-01	3.55E+00	1.09E+02	2.12E+05	2.20E-04	2.66E+03
Reinforced Concrete Walls C32/40	Concrete & Aggregate	65kg/m3 of RC steel	1.0 m3concrete, sole plate and foundation, at plant + 65 kg/m3 RC steel	m³	2.58E+02	6.62E-01	6.48E+01	1.09E-05	6.54E-02	2.95E-01	2.47E+00	7.48E+01	1.48E+05	1.80E-04	2.00E+03
Reinforcement Steel	Metals	Reinforcing Steel bars	1.0 kg reinforcing steel, at plant	kg	1.48E+00	5.09E-03	5.99E-01	6.00E-08	8.10E-04	3.18E-03	3.07E-02	9.83E-01	1.83E+03	1.09E-06	1.90E+01
Rock Excavation 0.25-1m	Processes	Excavating rock for foundations	1.0 m3 excavation, hydraulic digger (twice as much for rock exc.)	m³	1.07E+00	8.00E-03	1.80E-01	1.30E-07	2.20E-04	1.92E-03	3.68E-03	6.86E-02	2.07E+02	2.81E-07	1.48E+01
Rock Excavation 1-2m	Processes	Excavating rock for trenches	1.0 m3 excavation, hydraulic digger (twice as much for rock exc.)	m³	1.07E+00	8.00E-03	1.80E-01	1.30E-07	2.20E-04	1.92E-03	3.68E-03	6.86E-02	2.07E+02	2.81E-07	1.48E+01
Sensing Cables 2.5mm2	Metals	Underground SWA cables	1.0 m cable, three-conductor cable, at plant	m	2.45E+00	7.68E-02	7.49E+01	1.07E-07	3.09E-03	8.58E-02	2.42E-01	2.24E+01	6.22E+04	5.80E-04	5.31E+01
Seperating Fabrics	Plastics	Used to seperate aggregate from ground like teram (polypropolene)	1.0 kg polypropylene, granulate, at plant	kg	1.99E+00	6.20E-03	6.74E-02	5.31E-10	4.20E-04	6.70E-04	1.20E-04	2.56E-02	8.43E+01	7.30E-08	6.58E+01
Sheet Steel	Metals	Sheet steel for general use	1.0 kg steel, converter, low-alloyed, at plant	kg	2.09E+00	8.27E-03	1.02E+01	5.78E-08	1.19E-03	4.89E-03	3.31E-01	2.34E+00	3.58E+03	3.21E-05	2.53E+01
Slate Tiles	Concrete & Aggregate	Natural stone plate slate used for roofing	1.0 kg fibre cement roof slate, at plant	kg	6.98E-01	1.73E-03	2.88E-01	4.17E-08	1.20E-04	6.90E-04	4.02E-03	1.30E-01	3.53E+02	1.59E-06	5.54E+00
Softwood	Wood	Sawnwood air dried softwood	1.0 m3 sawn timber, softwood, planed, air dried, at plant	m³	-7.30E+02	4.89E-01	3.85E+01	7.98E-06	4.47E-02	2.11E-01	7.56E-01	2.97E+01	8.13E+04	1.30E-04	1.12E+03
Soil Excavation 0.25-1m	Processes	Excavation of top soil and soil for foundations and tracks	1.0 m3 excavation, hydraulic digger	m³	5.35E-01	4.00E-03	8.98E-02	6.51E-08	1.10E-04	9.60E-04	1.84E-03	3.43E-02	1.03E+02	1.40E-07	7.40E+00
Soil Excavation 1-2m	Processes	Excavation of soil for trenches	1.0 m3 excavation, hydraulic digger	m³	5.35E-01	4.00E-03	8.98E-02	6.51E-08	1.10E-04	9.60E-04	1.84E-03	3.43E-02	1.03E+02	1.40E-07	7.40E+00
Stainless Steel	Metals	Stainless steel for general use	1.0 kg steel, converter, chromium steel 18/8, at plant	kg	4.47E+00	2.34E-02	7.74E+01	2.08E-07	1.55E-03	8.88E-03	2.63E+00	1.31E+01	1.41E+04	1.50E-04	5.10E+01
Steel (cast or block)	Metals	General steel used is turbine components for example	1.0 kg steel, low-alloyed, at plant	kg	1.76E+00	6.74E-03	6.75E+00	7.47E-08	8.80E-04	4.02E-03	2.36E-01	2.05E+00	3.08E+03	2.06E-05	2.21E+01
Steel Machining	Processes	General metal working for steel product manufacturing	1.0 kg chromium steel product manufacturing, average metal working	kg	2.54E+00	1.03E-02	1.82E+01	1.83E-07	5.50E-04	5.17E-03	6.18E-01	3.81E+00	4.88E+03	3.53E-05	2.85E+01
Steel Pipe	Metals	General steel pipe per weight	1.0 kg drawing of pipes, steel	kg	4.32E-01	1.07E-03	1.26E-01	3.30E-08	9.27E-05	7.10E-04	3.31E-03	3.42E-01	4.32E+02	3.06E-06	3.06E+00
Transformer	Metals	Transformer for grid connection	1.0 kg transformer, high voltage use, at plant	Nr	5.42E+00	3.27E-02	7.01E+00	4.62E-07	1.32E-03	1.65E-02	4.76E-02	3.57E+00	9.53E+03	2.20E-04	7.64E+01
Waterstop Concrete Seal	Plastics	Used as sealant between concrete joints (PVC)	1.0 kg synthetic rubber, at plant	kg	2.61E+00	1.07E-02	1.11E+00	6.42E-07	5.90E-04	3.70E-03	1.41E-02	6.15E-01	1.83E+03	7.51E-05	7.65E+01

Appendix 2: Overall environmental impacts of MHP case studies

site	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	t CO_2 eq.	kg SO_2 eq.	t 1,4-DCB eq.	g CFC-11 eq.	kg C_2H_4 eq.	kg PO_4 eq.	t 1,4-DCB eq.	t 1,4-DCB eq.	kt 1,4-DCB eq.	g Sb eq.	MJ
1	137.1	462.1	134.0	5.8	39.5	248.8	2.5	51.5	122.8	670.8	2139975
2	148.1	530.5	150.0	5.8	42.8	260.9	2.4	52.1	129.5	745.8	2805704
3	171.5	622.7	171.2	5.5	51.9	290.3	2.4	59.2	149.1	913.3	3677902
5	81.8	411.0	208.5	3.7	28.2	379.3	2.0	62.6	165.7	1181.5	1518693
6	137.8	861.7	680.1	3.7	60.1	1984.5	3.3	163.8	453.7	2549.5	2154635
7	91.6	315.7	113.4	3.9	28.3	181.5	1.7	39.5	96.7	590.3	1443452
8	123.6	499.7	176.2	4.0	41.2	301.4	2.0	69.9	176.7	1070.1	2437668
9	100.1	422.3	161.2	3.9	33.1	233.6	1.7	50.9	132.9	982.6	2055068
10	74.9	361.0	157.0	3.1	24.9	227.3	1.3	49.1	131.4	1016.1	1532347
12	97.0	410.5	159.1	4.3	29.6	239.1	1.7	52.9	136.2	973.5	1824612
13	97.8	484.6	235.1	3.6	33.8	394.5	1.9	69.9	185.5	1382.4	2148390
Min.	74.9	315.7	113.4	3.1	24.9	181.5	1.3	39.5	96.7	590.3	1443452
Max.	171.5	861.7	680.1	5.8	60.1	1984.5	3.3	163.8	453.7	2549.5	3677902
Mean	114.7	489.3	213.2	4.3	37.6	431.0	2.1	65.6	170.9	1097.8	2158041
Median	100.1	462.1	161.2	3.9	33.8	260.9	2.0	52.9	136.2	982.6	2139975
Stdev	30.8	149.2	158.3	1.0	10.9	519.2	0.5	33.8	97.2	531.9	651210

Appendix 3: Summary of LCA results with relative contribution of each site

Site No.1 Overall LCA Results

INSTALLATION DETAILS				
Site	1		Turbine Power	90 kW
Scheme Type	Low Head		Capacity Factor	24%
Head	24 m		Annual Output	189431 kWh
Flow	580 l/s		50yr Output	9471550 kWh
Turbine Type	Crossflow			

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

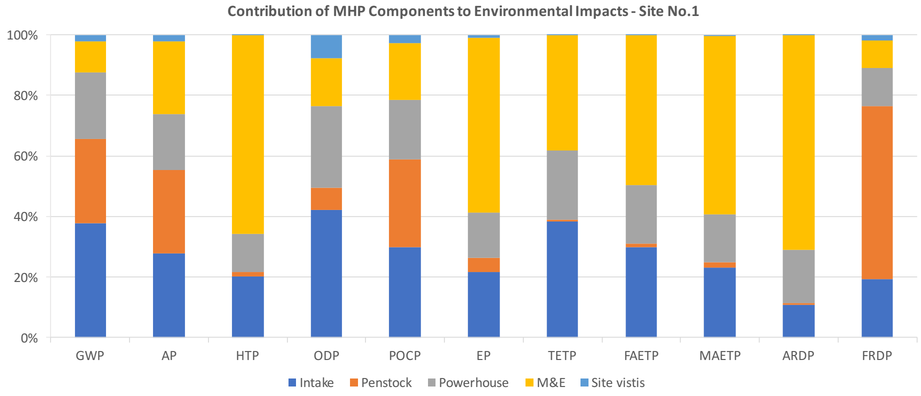
sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	5.20E+04	1.29E+02	2.73E+04	2.47E-03	1.19E+01	5.40E+01	9.71E+02	1.54E+04	2.83E+07	7.23E-02	4.11E+05
Penstock	3.80E+04	1.27E+02	1.75E+03	4.33E-04	1.14E+01	1.20E+01	8.35E+00	6.36E+02	2.20E+06	3.45E-03	1.23E+06
Powerhouse	3.00E+04	8.50E+01	1.71E+04	1.57E-03	7.84E+00	3.69E+01	5.77E+02	1.00E+04	1.94E+07	1.19E-01	2.64E+05
M&E	1.40E+04	1.12E+02	8.76E+04	9.20E-04	7.41E+00	1.44E+02	9.61E+02	2.54E+04	7.27E+07	4.76E-01	1.95E+05
Site vistis	3.10E+03	9.63E+00	2.74E+02	4.57E-04	1.03E+00	2.08E+00	3.34E+00	6.15E+01	2.76E+05	2.23E-04	4.16E+04
Total	1.37E+05	4.62E+02	1.34E+05	5.85E-03	3.95E+01	2.49E+02	2.52E+03	5.15E+04	1.23E+08	6.71E-01	2.14E+06

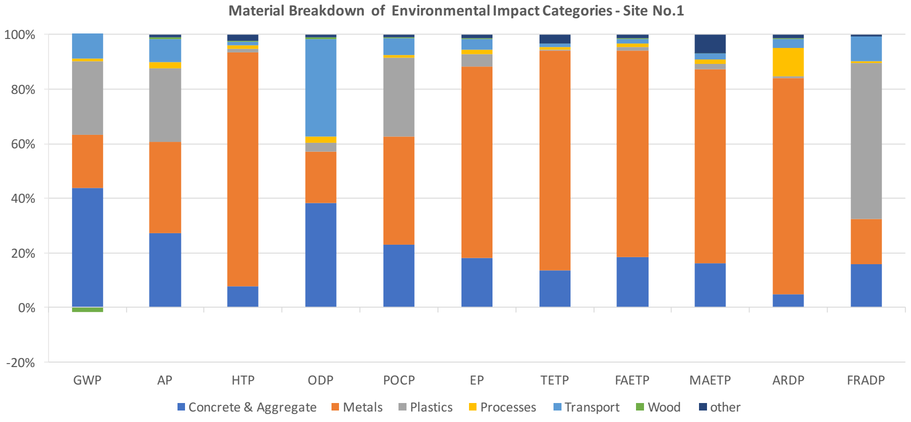
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	6.24E+00	1.29E-02	1.08E+00	2.32E-07	9.51E-04	4.69E-03	3.55E-02	9.95E-01	2.07E+03	3.30E-06	3.55E-02
Metals	2.82E+00	1.64E-02	1.21E+01	1.16E-07	1.65E-03	1.84E-02	2.15E-01	4.12E+00	9.24E+03	5.61E-05	3.69E-02
Plastics	3.95E+00	1.32E-02	1.82E-01	1.97E-08	1.21E-03	1.23E-03	6.70E-04	7.30E-02	2.46E+02	4.32E-07	1.29E-01
Processes	1.81E-01	1.29E-03	1.70E-01	1.80E-08	4.39E-05	4.63E-04	2.85E-03	7.88E-02	2.40E+02	7.52E-06	2.31E-03
Transport	1.43E+00	4.25E-03	1.97E-01	2.21E-07	2.53E-04	1.06E-03	3.13E-03	8.66E-02	2.62E+02	2.29E-06	2.03E-02
Wood	-2.50E-01	2.16E-04	1.81E-02	3.74E-09	1.96E-05	9.39E-05	3.82E-04	1.29E-02	3.58E+01	7.01E-08	5.29E-04
other	1.05E-01	5.40E-04	3.53E-01	6.75E-09	4.34E-05	3.49E-04	8.91E-03	7.56E-02	8.76E+02	1.06E-06	1.45E-03
Total	1.45E+01	4.88E-02	1.41E+01	6.17E-07	4.17E-03	2.63E-02	2.66E-01	5.44E+00	1.30E+04	7.08E-05	2.26E-01

MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	formwork	HDPE	Generator	Coanda screen B-1200 & B-1050	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	35114.29326	1.17E+02	3.10E+04	6.46E-04	1.11E+01	7.98E+01	3.73E+02	9.29E+03	2.58E+07	2.40E-01	1.19E+06
% of total	25%	25%	23%	11%	28%	32%	15%	18%	21%	36%	56%
Main contributor for each env. impact	Concrete for walls and slabs	formwork	Generator	Concrete for walls and slabs	Reinforcement Steel	Sensing cable	Turbine casing and runner	Generator	Generator	Generator	Reinforcement Steel
Amount	1.95E+04	3.91E+01	2.45E+04	6.33E-04	5.37E+00	3.55E+01	2.36E+02	7.22E+03	2.17E+07	8.59E-02	1.26E+05
% of total	14%	8%	18%	11%	14%	14%	9%	14%	18%	13%	6%
Main contributor for each env. impact	formwork	Generator	Coanda screen B-1200 & B-1050	Transport to suppliers	formwork	Reinforcement Steel	Draft tube casing	Reinforcement Steel	Reinforcement Steel	Galvenise sheet steel	formwork
Amount	1.53E+04	3.38E+01	1.10E+04	5.70E-04	3.86E+00	2.11E+01	2.32E+02	6.52E+03	1.21E+07	7.04E-02	1.18E+05
% of total	11%	7%	8%	10%	10%	8%	9%	13%	10%	10%	6%


Contribution of MHP Components to Environmental Impacts - Site No.1


Material Breakdown of Environmental Impact Categories - Site No.1

Site No.2 Overall LCA Results

INSTALLATION DETAILS

Site	2	Turbine Power	100 kW
Scheme Type	Low Head	Capacity Factor	35%
Head	29 m	Annual Output	306369 kWh
Flow	401 l/s	50yr Output	15318450 kWh
Turbine Type	Crossflow		

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	2.20E+04	5.65E+01	1.82E+04	1.01E-03	5.16E+00	2.26E+01	6.33E+02	7.37E+03	1.28E+07	4.39E-02	1.97E+05
Penstock	6.38E+04	2.17E+02	3.46E+03	9.25E-04	1.90E+01	2.38E+01	3.62E+01	1.70E+03	4.93E+06	7.88E-03	1.99E+06
Powerhouse	4.43E+04	1.16E+02	2.15E+04	2.47E-03	9.45E+00	4.67E+01	7.00E+02	1.19E+04	2.31E+07	6.97E-02	3.70E+05
M&E	1.49E+04	1.31E+02	1.07E+05	9.40E-04	8.15E+00	1.66E+02	1.02E+03	3.11E+04	8.85E+07	6.24E-01	2.07E+05
Site vistis	3.10E+03	9.63E+00	2.74E+02	4.57E-04	1.03E+00	2.08E+00	3.34E+00	6.15E+01	2.76E+05	2.23E-04	4.16E+04
Total	1.48E+05	5.30E+02	1.50E+05	5.80E-03	4.28E+01	2.61E+02	2.39E+03	5.21E+04	1.30E+08	7.46E-01	2.81E+06

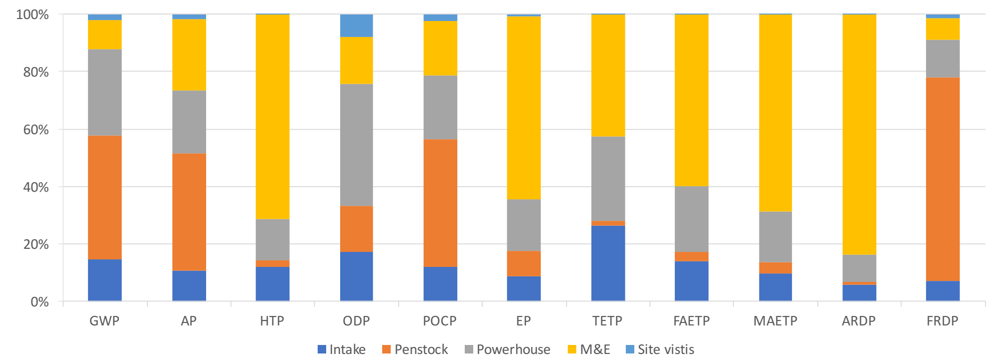
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	3.30E+00	7.22E-03	6.87E-01	1.32E-07	5.08E-04	2.65E-03	2.02E-02	5.56E-01	1.18E+03	2.23E-06	1.96E-02
Metals	1.40E+00	1.01E-02	8.55E+00	5.81E-08	8.59E-04	1.20E-02	1.27E-01	2.66E+00	6.27E+03	4.38E-05	1.87E-02
Plastics	3.86E+00	1.28E-02	1.73E-01	1.28E-08	1.19E-03	1.15E-03	5.91E-04	6.69E-02	2.27E+02	3.89E-07	1.28E-01
Processes	7.68E-02	4.72E-04	1.82E-02	6.68E-09	1.44E-05	1.25E-04	3.44E-04	8.99E-03	3.94E+01	5.81E-08	1.01E-03
Transport	1.01E+00	2.98E-03	1.33E-01	1.56E-07	1.66E-04	7.40E-04	2.13E-03	5.86E-02	1.78E+02	1.55E-06	1.43E-02
Wood	-1.01E-01	9.71E-05	8.38E-03	1.72E-09	8.78E-06	4.25E-05	1.80E-04	5.76E-03	1.62E+01	3.38E-08	2.44E-04
other	1.25E-01	9.49E-04	2.24E-01	1.07E-08	4.65E-05	3.52E-04	5.57E-03	4.79E-02	5.48E+02	6.60E-07	1.61E-03
Total	9.67E+00	3.46E-02	9.79E+00	3.79E-07	2.79E-03	1.70E-02	1.56E-01	3.40E+00	8.46E+03	4.87E-05	1.83E-01

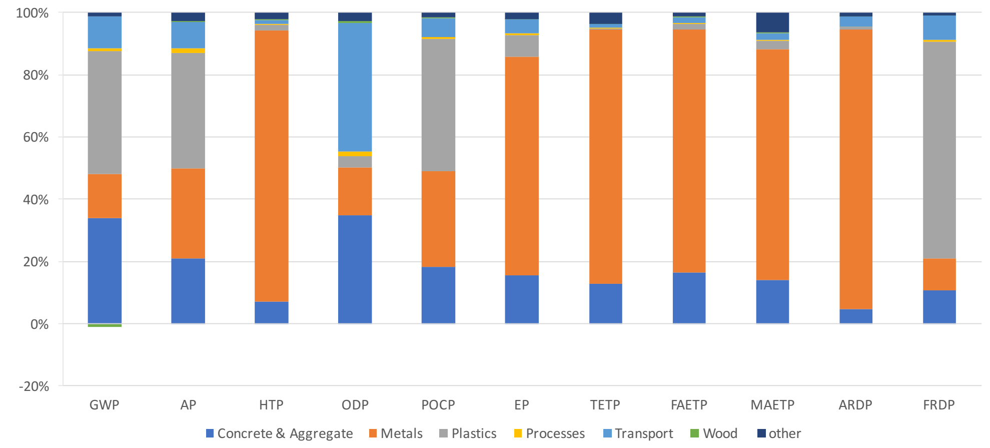
MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	Transport to suppliers	HDPE	Generator	Coanda screen D-1800	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	56619.52323	1.88E+02	4.89E+04	7.29E-04	1.79E+01	7.98E+01	2.58E+02	1.47E+04	4.06E+07	3.79E-01	1.92E+06
% of total	38%	35%	33%	13%	42%	31%	11%	28%	31%	51%	68%
Main contributor for each env. impact	Floor slab	Sensing cable	Generator	Formwork	Formwork	Sensing cable	Turbine casing and runner	Generator	Generator	LV Cable	Formwork
Amount	1.16E+04	5.02E+01	2.45E+04	4.57E-04	3.29E+00	5.60E+01	2.36E+02	7.22E+03	2.17E+07	8.99E-02	9.34E+04
% of total	8%	9%	16%	8%	8%	21%	10%	14%	17%	12%	3%
Main contributor for each env. impact	Formwork	Generator	LV Cable	Floor slab	RC Steel	630 Pipe SDR 26	Draft tube casing	Formwork	LV Cable	Generator	Transport to suppliers
Amount	1.09E+04	3.38E+01	1.16E+04	3.76E-04	2.84E+00	1.53E+01	2.32E+02	3.83E+03	9.64E+06	8.59E-02	6.75E+04
% of total	7%	6%	8%	6%	7%	6%	10%	7%	7%	12%	2%

Contribution of MHP Components to Environmental Impacts - Site No.2



Material Breakdown of Environmental Impact Categories - Site No.2



Site No.3 Overall LCA Results

INSTALLATION DETAILS

Site	3	Turbine Power	100 kW
Scheme Type	Medium Head	Capacity Factor	55%
Head	41 m	Annual Output	481315 kWh
Flow	340 l/s	50yr Output	24065750 kWh
Turbine Type	Crossflow		

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

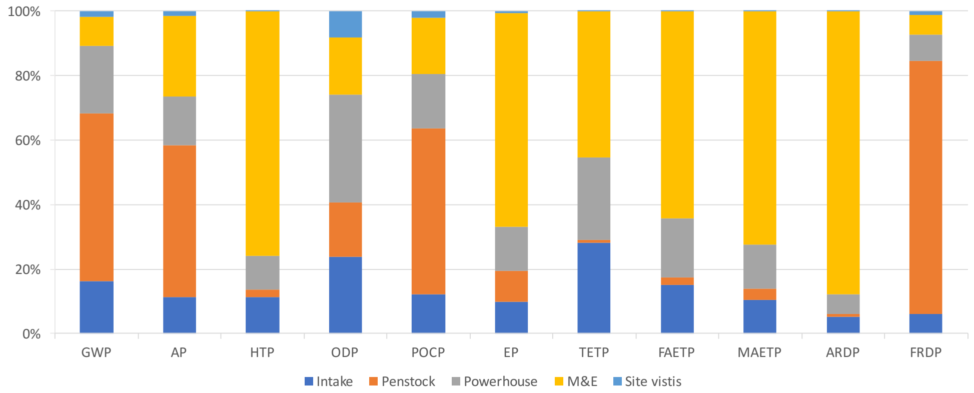
sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	2.79E+04	6.97E+01	1.94E+04	1.32E-03	6.32E+00	2.88E+01	6.83E+02	8.87E+03	1.57E+07	4.77E-02	2.21E+05
Penstock	8.91E+04	2.95E+02	4.07E+03	9.29E-04	2.67E+01	2.74E+01	1.88E+01	1.47E+03	5.11E+06	8.84E-03	2.89E+06
Powerhouse	3.57E+04	9.40E+01	1.78E+04	1.83E-03	8.71E+00	3.99E+01	6.18E+02	1.07E+04	2.04E+07	5.42E-02	3.05E+05
M&E	1.57E+04	1.55E+02	1.30E+05	9.75E-04	9.11E+00	1.92E+02	1.09E+03	3.80E+04	1.08E+08	8.02E-01	2.24E+05
Site vistis	3.10E+03	9.63E+00	2.74E+02	4.57E-04	1.03E+00	2.08E+00	3.34E+00	6.15E+01	2.76E+05	2.23E-04	4.16E+04
Total	1.72E+05	6.23E+02	1.71E+05	5.52E-03	5.19E+01	2.90E+02	2.42E+03	5.92E+04	1.49E+08	9.13E-01	3.68E+06

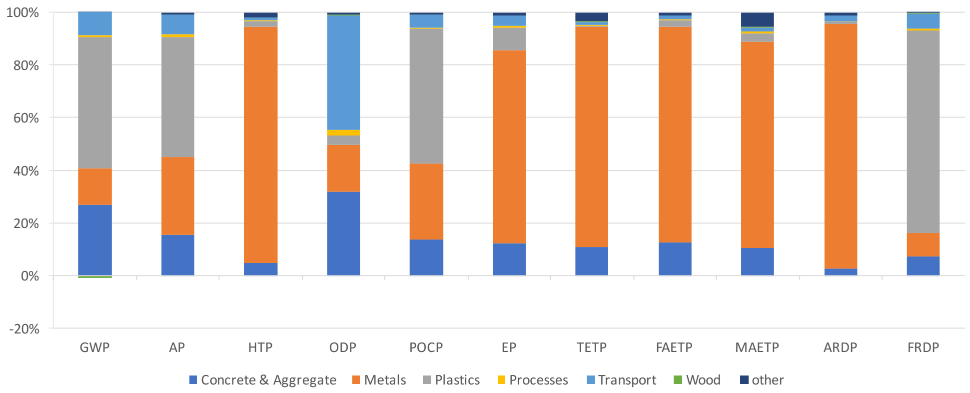
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	1.93E+00	4.03E-03	3.45E-01	7.30E-08	2.98E-04	1.47E-03	1.11E-02	3.13E-01	6.55E+02	1.07E-06	1.12E-02
Metals	9.84E-01	7.60E-03	6.38E+00	4.07E-08	6.22E-04	8.85E-03	8.37E-02	2.01E+00	4.85E+03	3.52E-05	1.34E-02
Plastics	3.54E+00	1.18E-02	1.56E-01	8.51E-09	1.10E-03	1.04E-03	5.06E-04	5.91E-02	2.02E+02	3.30E-07	1.18E-01
Processes	4.88E-02	3.00E-04	1.15E-02	4.24E-09	9.11E-06	7.94E-05	2.17E-04	5.67E-03	2.50E+01	3.18E-08	6.39E-04
Transport	6.47E-01	1.89E-03	8.05E-02	9.95E-08	1.04E-04	4.61E-04	1.26E-03	3.36E-02	1.05E+02	8.39E-07	9.10E-03
Wood	-6.37E-02	6.14E-05	5.29E-03	1.09E-09	5.55E-06	2.69E-05	1.14E-04	3.64E-03	1.02E+01	2.14E-08	1.54E-04
other	4.13E-02	2.12E-04	1.39E-01	2.11E-09	1.69E-05	1.38E-04	3.50E-03	2.96E-02	3.44E+02	4.16E-07	5.08E-04
Total	7.13E+00	2.59E-02	7.11E+00	2.29E-07	2.15E-03	1.21E-02	1.00E-01	2.46E+00	6.19E+03	3.79E-05	1.53E-01

MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	Formwork	HDPE	Sensing cable	Coanda screen D-1800	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	82520.02962	2.74E+02	7.11E+04	4.57E-04	2.60E+01	8.15E+01	3.29E+02	2.13E+04	5.91E+07	5.51E-01	2.79E+06
% of total	48%	44%	42%	8%	50%	28%	14%	36%	40%	60%	76%
Main contributor for each env. impact	Floor slab	Sensing cable	Generator	Transport to suppliers	Formwork	Generator	Turbine casing and runner	Generator	Generator	LV Cable	Formwork
Amount	1.16E+04	7.30E+01	2.45E+04	4.36E-04	3.29E+00	7.98E+01	2.36E+02	7.22E+03	2.17E+07	9.57E-02	9.34E+04
% of total	7%	12%	14%	8%	6%	28%	10%	12%	15%	10%	3%
Main contributor for each env. impact	Formwork	Generator	LV Cable	Floor slab	RC Steel	630 Pipe SDR 26	Draft tube casing	Formwork	LV Cable	Generator	RC Steel
Amount	1.09E+04	3.38E+01	1.24E+04	3.76E-04	3.00E+00	2.26E+01	2.32E+02	3.83E+03	1.03E+07	8.59E-02	7.02E+04
% of total	6%	5%	7%	7%	6%	8%	10%	6%	7%	9%	2%


Contribution of MHP Components to Environmental Impacts - Site No.3


Material Breakdown of Environmental Impact Categories - Site No.3

Site No.5 LCA Results

INSTALLATION DETAILS				
Site	5		Turbine Power	85 kW
Scheme Type	Medium Head		Capacity Factor	30%
Head	60 m		Annual Output	226863 kWh
Flow	207 l/s		50yr Output	11343150 kWh
Turbine Type	Turgo			

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	2.14E+04	5.72E+01	1.40E+04	1.09E-03	4.99E+00	2.35E+01	4.57E+02	7.12E+03	1.59E+07	4.49E-02	1.77E+05
Penstock	3.09E+04	1.08E+02	1.47E+03	5.23E-04	9.17E+00	1.14E+01	7.20E+00	5.17E+02	1.84E+06	2.07E-03	9.74E+05
Powerhouse	1.65E+04	5.15E+01	1.26E+04	1.04E-03	4.39E+00	2.15E+01	4.09E+02	5.90E+03	1.14E+07	8.80E-02	1.63E+05
M&E	9.96E+03	1.85E+02	1.80E+05	6.13E-04	8.64E+00	3.21E+02	1.09E+03	4.90E+04	1.36E+08	1.05E+00	1.63E+05
Site vistis	3.10E+03	9.63E+00	2.74E+02	4.57E-04	1.03E+00	2.08E+00	3.34E+00	6.15E+01	2.76E+05	2.23E-04	4.16E+04
Total	8.18E+04	4.11E+02	2.08E+05	3.72E-03	2.82E+01	3.79E+02	1.97E+03	6.26E+04	1.66E+08	1.18E+00	1.52E+06

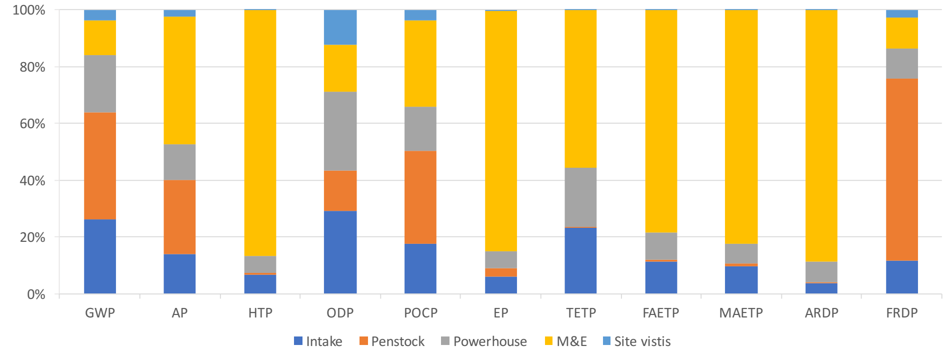
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	2.09E+00	4.04E-03	3.14E-01	7.77E-08	2.32E-04	1.27E-03	8.56E-03	2.25E-01	5.01E+02	1.01E-06	1.04E-02
Metals	1.66E+00	1.90E-02	1.75E+01	7.44E-08	1.21E-03	3.00E-02	1.56E-01	5.11E+00	1.33E+04	9.67E-05	2.34E-02
Plastics	2.61E+00	8.71E-03	1.23E-01	1.62E-08	7.94E-04	8.37E-04	4.67E-04	5.04E-02	1.69E+02	2.98E-07	8.45E-02
Processes	9.33E-02	6.88E-04	1.17E-01	9.69E-09	2.38E-05	2.57E-04	2.43E-03	4.93E-02	1.40E+02	4.62E-06	1.19E-03
Transport	8.79E-01	2.62E-03	1.08E-01	1.35E-07	1.69E-04	6.34E-04	1.67E-03	4.41E-02	1.39E+02	1.05E-06	1.24E-02
Wood	-2.39E-01	2.02E-04	1.69E-02	3.49E-09	1.83E-05	8.80E-05	3.55E-04	1.21E-02	3.36E+01	6.51E-08	4.94E-04
other	1.17E-01	9.74E-04	1.55E-01	1.15E-08	4.24E-05	3.10E-04	3.80E-03	3.31E-02	3.74E+02	4.49E-07	1.56E-03
Total	7.21E+00	3.62E-02	1.84E+01	3.28E-07	2.49E-03	3.34E-02	1.73E-01	5.52E+00	1.46E+04	1.04E-04	1.34E-01

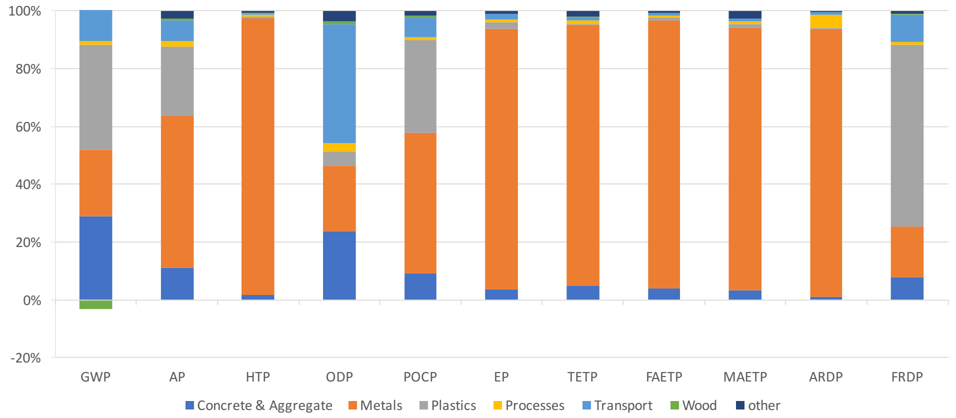
MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	Sensing cable	Sensing cable	2 vans each day for 6 months (60km round trip)	HDPE	HV cable	Sensing cable	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	27378.04138	8.65E+01	8.43E+04	3.30E-04	8.64E+00	1.47E+02	2.72E+02	2.53E+04	7.01E+07	6.53E-01	9.27E+05
% of total	33%	21%	40%	9%	31%	39%	14%	40%	42%	55%	61%
Main contributor for each env. impact	Floor slab	HDPE	HV cable	Transport to suppliers	Sensing cable	Sensing cable	Turbine case	HV cable	HV cable	LV Cable	Sensing cable
Amount	7.15E+03	9.10E+01	4.48E+04	3.01E-04	3.48E+00	9.66E+01	1.58E+02	1.00E+04	2.83E+07	1.62E-01	5.97E+04
% of total	9%	22%	21%	8%	12%	25%	8%	16%	17%	14%	4%
Main contributor for each env. impact	Concrete Transport Empty	Meter Cubicle GRP	Poles	Concrete transport (empty)	RC Steel transport 60% (empty)	Control pannel casing	Manifold pipe	Poles	Poles	Meter Cubicle GRP	RC Steel transport 60% (empty)
Amount	6.96E+03	3.83E+01	2.10E+04	2.32E-04	2.37E+00	4.50E+01	1.58E+02	6.29E+03	1.74E+07	1.43E-01	5.55E+04
% of total	9%	9%	10%	6%	8%	12%	8%	10%	11%	12%	4%

Contribution of MHP Components to Environmental Impacts - Site No.5



Material Breakdown of Environmental Impact Categories - Site No.5



Site No.6 Overall LCA Results

INSTALLATION DETAILS				
Site	6		Turbine Power	100 kW
Scheme Type	High Head		Capacity Factor	42%
Head	82 m		Annual Output	372776 kWh
Flow	190 l/s		50yr Output	18638800 kWh
Turbine Type	Turgo			

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

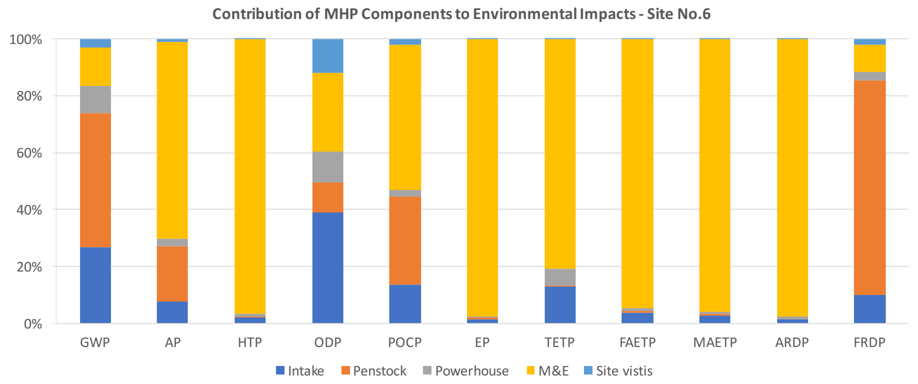
sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	2.80E+04	6.74E+01	1.36E+04	1.49E-03	6.62E+00	2.50E+01	4.29E+02	6.36E+03	1.22E+07	3.72E-02	2.13E+05
Penstock	4.96E+04	1.65E+02	2.16E+03	4.02E-04	1.51E+01	1.50E+01	7.44E+00	7.76E+02	2.72E+06	1.79E-03	1.63E+06
Powerhouse	9.95E+03	2.31E+01	6.66E+03	4.25E-04	1.21E+00	6.68E+00	2.05E+02	1.63E+03	3.00E+06	1.95E-02	6.65E+04
M&E	1.43E+04	5.96E+02	6.57E+05	1.05E-03	2.49E+01	1.93E+03	2.68E+03	1.55E+05	4.34E+08	2.49E+00	2.08E+05
Site vistis	3.10E+03	9.63E+00	2.74E+02	4.57E-04	1.03E+00	2.08E+00	3.34E+00	6.15E+01	2.76E+05	2.23E-04	4.16E+04
Total	1.05E+05	8.62E+02	6.80E+05	3.83E-03	4.88E+01	1.98E+03	3.32E+03	1.63E+05	4.52E+08	2.55E+00	2.15E+06

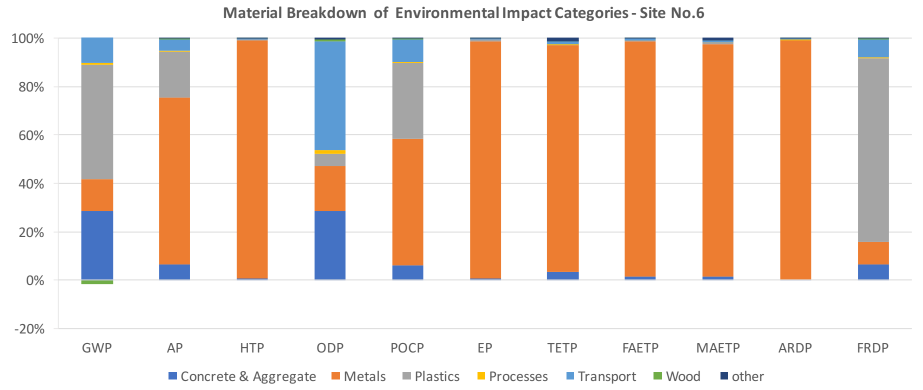
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	1.60E+00	2.96E-03	2.17E-01	5.84E-08	1.60E-04	8.90E-04	5.84E-03	1.48E-01	3.35E+02	6.99E-07	7.61E-03
Metals	7.56E-01	3.18E-02	3.59E+01	3.83E-08	1.37E-03	1.04E-01	1.67E-01	8.49E+00	2.34E+04	1.35E-04	1.07E-02
Plastics	2.66E+00	8.85E-03	1.20E-01	1.03E-08	8.19E-04	8.06E-04	4.10E-04	4.70E-02	1.59E+02	2.60E-07	8.76E-02
Processes	3.46E-02	2.29E-04	1.82E-02	3.48E-09	6.85E-06	6.00E-05	6.03E-04	5.51E-03	1.58E+01	6.19E-08	4.61E-04
Transport	6.37E-01	2.14E-03	1.70E-01	9.24E-08	2.43E-04	5.64E-04	2.14E-03	5.58E-02	1.63E+02	8.00E-07	8.72E-03
Wood	-8.20E-02	7.98E-05	6.90E-03	1.42E-09	7.22E-06	3.49E-05	1.49E-04	4.72E-03	1.33E+01	2.79E-08	2.01E-04
other	2.73E-02	1.44E-04	8.94E-02	1.14E-09	1.10E-05	9.07E-05	2.26E-03	1.91E-02	2.22E+02	2.68E-07	3.04E-04
Total	5.63E+00	4.62E-02	3.65E+01	2.05E-07	2.62E-03	1.06E-01	1.78E-01	8.77E+00	2.43E+04	1.37E-04	1.16E-01

MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	400 Pipe SDR 26	HV cable	HV cable	2 vans each day for 6 months (60km round trip)	HV cable	HV cable	HV cable	HV cable	HV cable	HV cable	HDPE
Amount	4603.67397	4.60E+02	5.38E+05	3.30E-04	1.76E+01	1.77E+03	1.77E+03	1.20E+05	3.40E+08	1.72E+00	1.60E+06
% of total	4%	53%	79%	9%	36%	90%	53%	74%	75%	67%	74%
Main contributor for each env. impact	Concrete for walls and slabs	HDPE	HV cable	HV cable	HDPE	Generator	Turbine case	Generator	Generator	Generator	400 Pipe SDR 26
Amount	6.99E+03	1.57E+02	8.43E+04	2.36E-04	1.29E+01	4.50E+01	1.58E+02	4.07E+03	1.22E+07	4.84E-02	1.67E+04
% of total	7%	18%	12%	6%	27%	2%	5%	2%	3%	2%	1%
Main contributor for each env. impact	HDPE	400 Pipe SDR 26	Generator	Formwork	Reinforcement Steel	400 Pipe SDR 26	Coanda screen D-1800	Reinforcement Steel	Control Panel	LV Cable	Formwork
Amount	4.71E+04	8.39E+01	1.38E+04	2.36E-04	1.71E+00	4.50E+01	1.29E+02	2.08E+03	4.13E+06	2.90E-02	5.97E+04
% of total	45%	10%	2%	6%	4%	2%	4%	1%	1%	1%	3%


Contribution of MHP Components to Environmental Impacts - Site No.6


Material Breakdown of Environmental Impact Categories - Site No.6

Site No.7 Overall LCA results

INSTALLATION DETAILS			
Site	7	Turbine Power	100 kW
Scheme Type	High Head	Capacity Factor	44%
Head	105 m	Annual Output	386446 kWh
Flow	145 l/s	50yr Output	19322300 kWh
Turbine Type	Turgo		

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

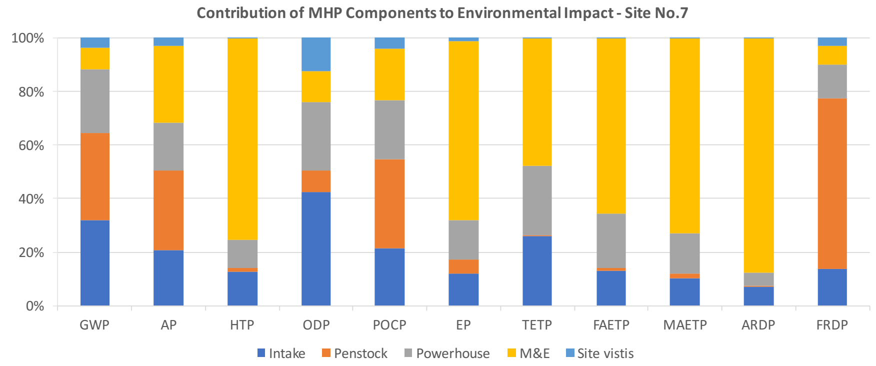
sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	2.78E+04	6.51E+01	1.46E+04	1.57E-03	5.52E+00	2.07E+01	4.24E+02	4.76E+03	9.37E+06	4.19E-02	1.98E+05
Penstock	2.83E+04	9.44E+01	1.25E+03	2.92E-04	8.52E+00	8.76E+00	4.85E+00	4.48E+02	1.57E+06	1.08E-03	9.19E+05
Powerhouse	2.08E+04	5.66E+01	1.21E+04	9.43E-04	5.72E+00	2.55E+01	4.26E+02	7.32E+03	1.37E+07	3.04E-02	1.80E+05
M&E	7.04E+03	9.01E+01	8.53E+04	4.28E-04	4.97E+00	1.15E+02	7.78E+02	2.39E+04	6.61E+07	5.17E-01	1.04E+05
Site vistis	3.10E+03	9.63E+00	2.74E+02	4.57E-04	1.03E+00	2.08E+00	3.34E+00	6.15E+01	2.76E+05	2.23E-04	4.16E+04
Total	8.70E+04	3.16E+02	1.13E+05	3.69E-03	2.58E+01	1.72E+02	1.64E+03	3.65E+04	9.11E+07	5.90E-01	1.44E+06

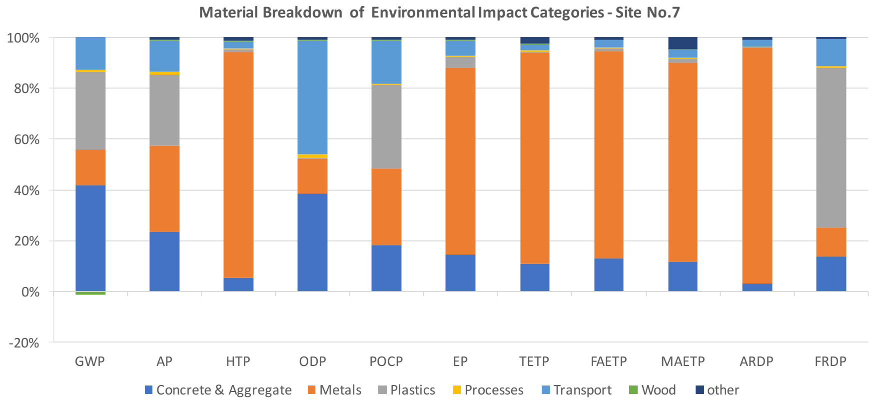
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	1.89E+00	3.86E-03	3.25E-01	7.38E-08	2.46E-04	1.31E-03	9.17E-03	2.51E-01	5.49E+02	1.03E-06	1.03E-02
Metals	6.19E-01	5.51E-03	5.22E+00	2.63E-08	4.01E-04	6.50E-03	7.04E-02	1.53E+00	3.69E+03	2.83E-05	8.59E-03
Plastics	1.39E+00	4.61E-03	5.98E-02	5.10E-10	4.35E-04	3.87E-04	2.08E-04	2.15E-02	7.43E+01	1.51E-07	4.69E-02
Processes	3.10E-02	1.81E-04	1.80E-02	2.48E-09	5.78E-06	5.05E-05	5.82E-04	5.93E-03	1.99E+01	5.20E-08	3.99E-04
Transport	5.89E-01	1.99E-03	1.60E-01	8.54E-08	2.30E-04	5.26E-04	2.01E-03	5.27E-02	1.53E+02	7.65E-07	8.08E-03
Wood	-4.63E-02	4.90E-05	4.30E-03	8.82E-10	4.43E-06	2.15E-05	9.39E-05	2.89E-03	8.15E+00	1.78E-08	1.25E-04
other	2.66E-02	1.41E-04	8.65E-02	1.61E-09	1.09E-05	8.74E-05	2.18E-03	1.85E-02	2.15E+02	2.59E-07	3.49E-04
Total	4.50E+00	1.63E-02	5.87E+00	1.91E-07	1.33E-03	8.88E-03	8.46E-02	1.89E+00	4.71E+03	3.06E-05	7.47E-02

MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	2 vans each day for 6 months (60km round trip	HDPE	Sensing cable	Coanda screen D-1800	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	26467.78181	8.79E+01	5.54E+04	3.30E-04	8.35E+00	6.35E+01	1.93E+02	1.66E+04	4.60E+07	4.29E-01	8.96E+05
% of total	30%	28%	49%	9%	32%	37%	12%	46%	51%	73%	62%
Main contributor for each env. impact	Concrete for walls and slabs	Sensing cable	Generator	Screeding	RC Steel	Generator	Sensing cable	Generator	Generator	Generator	RC Steel
Amount	6.70E+03	5.69E+01	1.38E+04	2.65E-04	2.84E+00	4.50E+01	1.79E+02	4.07E+03	1.22E+07	4.84E-02	6.64E+04
% of total	8%	18%	12%	7%	11%	26%	11%	11%	13%	8%	5%
Main contributor for each env. impact	Floor slab	Generator	Turbine case	Concrete for walls and slabs	Sensing cable	Formwork	Turbine case	Formwork	Control Panel	Turbine case	Formwork
Amount	5.48E+03	1.91E+01	5.69E+03	2.22E-04	2.29E+00	6.75E+00	1.58E+02	1.81E+03	4.13E+06	9.00E-03	4.42E+04
% of total	6%	6%	5%	6%	9%	4%	10%	5%	5%	2%	3%


Contribution of MHP Components to Environmental Impact - Site No.7


Material Breakdown of Environmental Impact Categories - Site No.7

Site No.8 Overall LCA Results

INSTALLATION DETAILS

Site	8	Turbine Power	100 kW
Scheme Type	High Head	Capacity Factor	45%
Head	128 m	Annual Output	390000 kWh
Flow	100 l/s	50yr Output	19500000 kWh
Turbine Type	Turgo		

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

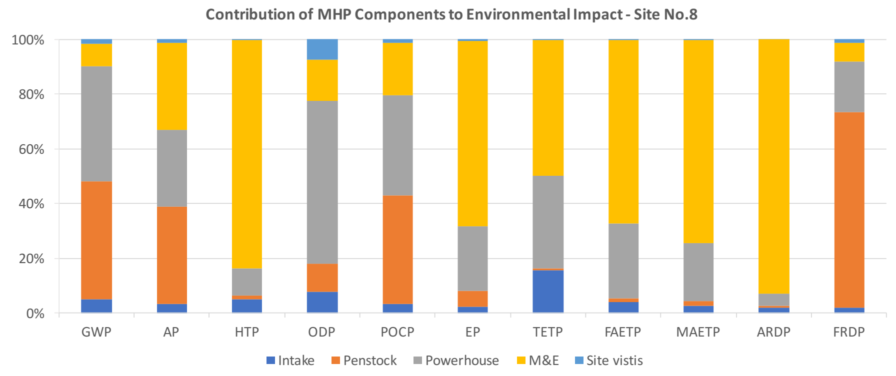
sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	6.27E+03	1.69E+01	9.03E+03	3.13E-04	1.31E+00	6.35E+00	3.07E+02	2.51E+03	3.92E+06	1.95E-02	5.10E+04
Penstock	5.31E+04	1.77E+02	2.45E+03	4.12E-04	1.61E+01	1.63E+01	1.20E+01	8.90E+02	3.06E+06	6.74E-03	1.74E+06
Powerhouse	5.16E+04	1.41E+02	1.74E+04	2.41E-03	1.48E+01	6.51E+01	6.73E+02	1.74E+04	3.36E+07	4.77E-02	4.54E+05
M&E	1.01E+04	1.59E+02	1.47E+05	6.18E-04	7.67E+00	1.87E+02	9.79E+02	4.26E+04	1.18E+08	9.96E-01	1.69E+05
Site vistis	2.00E+03	5.95E+00	1.72E+02	2.96E-04	5.70E-01	1.28E+00	2.24E+00	3.95E+01	1.77E+05	1.42E-04	2.69E+04
Total	1.23E+05	5.00E+02	1.76E+05	4.05E-03	4.05E+01	2.76E+02	1.97E+03	6.34E+04	1.59E+08	1.07E+00	2.44E+06

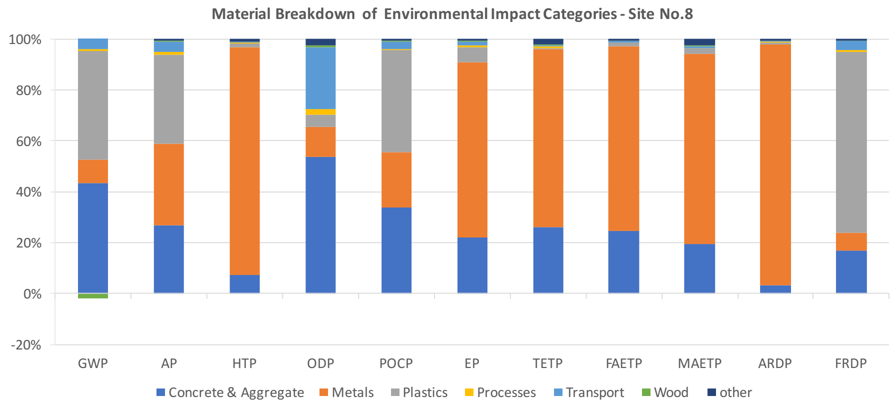
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	2.75E+00	6.89E-03	6.69E-01	1.11E-07	7.04E-04	3.12E-03	2.65E-02	8.03E-01	1.58E+03	1.78E-06	2.11E-02
Metals	5.75E-01	8.21E-03	8.09E+00	2.50E-08	4.52E-04	9.77E-03	7.06E-02	2.35E+00	6.10E+03	5.20E-05	8.96E-03
Plastics	2.70E+00	8.98E-03	1.25E-01	9.86E-09	8.29E-04	8.20E-04	5.26E-04	4.80E-02	1.63E+02	3.81E-07	8.88E-02
Processes	4.43E-02	2.90E-04	1.93E-02	4.37E-09	8.64E-06	7.52E-05	6.10E-04	6.20E-03	1.96E+01	3.00E-08	5.90E-04
Transport	3.28E-01	9.64E-04	3.96E-02	5.03E-08	6.00E-05	2.31E-04	6.09E-04	1.57E-02	5.04E+01	3.60E-07	4.60E-03
Wood	-1.15E-01	1.02E-04	8.65E-03	1.78E-09	9.26E-06	4.45E-05	1.83E-04	6.07E-03	1.70E+01	3.39E-08	2.52E-04
other	3.13E-02	1.91E-04	8.82E-02	5.12E-09	1.38E-05	9.47E-05	2.19E-03	1.90E-02	2.16E+02	2.61E-07	7.36E-04
Total	6.31E+00	2.56E-02	9.04E+00	2.08E-07	2.08E-03	1.42E-02	1.01E-01	3.25E+00	8.14E+03	5.49E-05	1.25E-01

MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	Formwork	HDPE	Sensing cable	Formwork	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	49801.14035	1.65E+02	9.63E+04	1.76E-03	1.57E+01	1.10E+02	4.79E+02	2.89E+04	8.00E+07	7.46E-01	1.69E+06
% of total	40%	33%	55%	43%	39%	40%	24%	46%	50%	70%	69%
Main contributor for each env. impact	Formwork	Formwork	LV Cable	Transport to suppliers	Formwork	Formwork	Sensing cable	Formwork	Formwork	LV Cable	Formwork
Amount	4.19E+04	1.14E+02	1.95E+04	1.85E-04	1.27E+01	5.49E+01	3.11E+02	1.47E+04	2.86E+07	1.51E-01	3.60E+05
% of total	34%	23%	11%	5%	31%	20%	16%	23%	18%	14%	15%
Main contributor for each env. impact	Floor slab	Sensing cable	Formwork	Meter Cubicle GRP	Sensing cable	Generator	Coanda screen	LV Cable	LV Cable	Generator	Sensing cable
Amount	1.54E+04	9.88E+01	1.16E+04	1.74E-04	3.97E+00	4.50E+01	1.98E+02	5.84E+03	1.62E+07	4.84E-02	6.82E+04
% of total	12%	20%	7%	4%	10%	16%	10%	9%	10%	5%	3%


Contribution of MHP Components to Environmental Impact - Site No.8


Material Breakdown of Environmental Impact Categories - Site No.8

Site No.9 Overall LCA Results

INSTALLATION DETAILS				
Site	9		Turbine Power	90 kW
Scheme Type	High Head		Capacity Factor	28%
Head	130 m		Annual Output	220869 kWh
Flow	115 l/s		50yr Output	11043450 kWh
Turbine Type	Turgo			

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

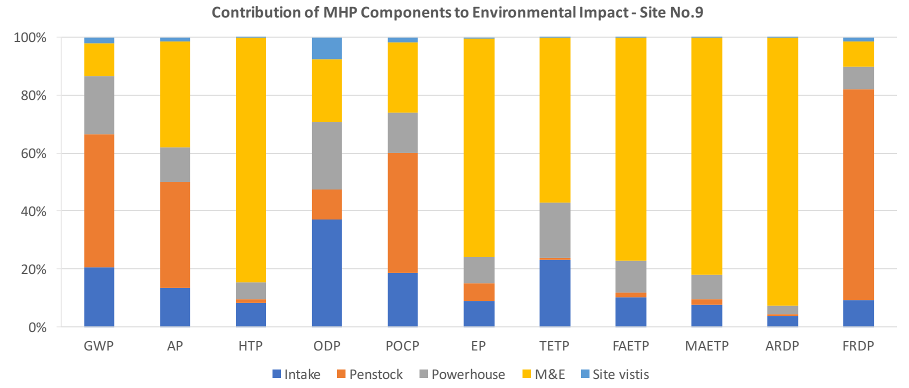
sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	2.04E+04	5.73E+01	1.32E+04	1.45E-03	6.11E+00	2.09E+01	3.84E+02	5.21E+03	1.03E+07	3.71E-02	1.91E+05
Penstock	4.62E+04	1.54E+02	2.19E+03	4.14E-04	1.38E+01	1.45E+01	1.27E+01	7.60E+02	2.66E+06	7.08E-03	1.49E+06
Powerhouse	2.00E+04	5.14E+01	9.40E+03	9.14E-04	4.57E+00	2.13E+01	3.18E+02	5.58E+03	1.08E+07	2.82E-02	1.59E+05
M&E	1.14E+04	1.54E+02	1.36E+05	8.43E-04	8.02E+00	1.76E+02	9.46E+02	3.93E+04	1.09E+08	9.10E-01	1.84E+05
Site vistis	2.00E+03	5.95E+00	1.72E+02	2.96E-04	5.70E-01	1.28E+00	2.24E+00	3.95E+01	1.77E+05	1.42E-04	2.69E+04
Total	1.00E+05	4.22E+02	1.61E+05	3.92E-03	3.31E+01	2.34E+02	1.66E+03	5.09E+04	1.33E+08	9.83E-01	2.06E+06

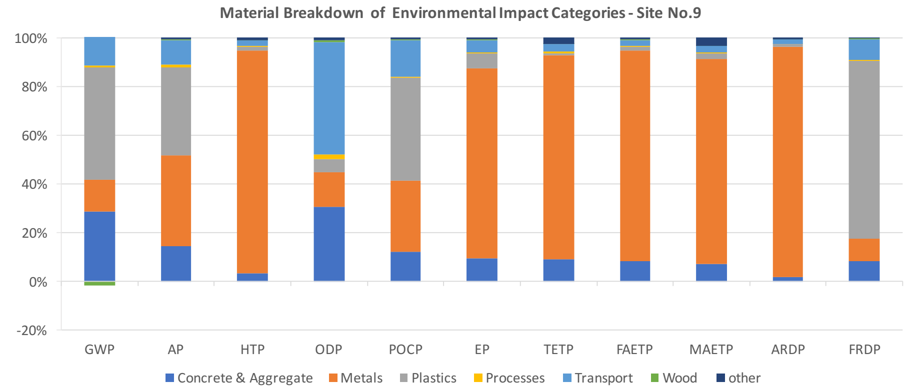
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	2.59E+00	5.61E-03	5.02E-01	1.08E-07	3.70E-04	1.97E-03	1.37E-02	3.91E-01	8.56E+02	1.51E-06	1.52E-02
Metals	1.19E+00	1.41E-02	1.33E+01	5.08E-08	8.66E-04	1.65E-02	1.26E-01	3.98E+00	1.02E+04	8.41E-05	1.77E-02
Plastics	4.17E+00	1.38E-02	2.05E-01	1.88E-08	1.26E-03	1.30E-03	1.12E-03	7.85E-02	2.65E+02	1.05E-06	1.36E-01
Processes	7.30E-02	4.77E-04	3.40E-02	7.17E-09	1.43E-05	1.25E-04	1.08E-03	1.09E-02	3.38E+01	1.08E-07	9.69E-04
Transport	1.13E+00	3.81E-03	3.42E-01	1.63E-07	4.48E-04	1.04E-03	4.32E-03	1.14E-01	3.26E+02	1.65E-06	1.55E-02
Wood	-1.37E-01	1.36E-04	1.18E-02	2.42E-09	1.23E-05	5.95E-05	2.55E-04	8.03E-03	2.26E+01	4.80E-08	3.44E-04
other	4.91E-02	2.73E-04	1.52E-01	3.99E-09	2.02E-05	1.58E-04	3.83E-03	3.26E-02	3.77E+02	4.55E-07	7.40E-04
Total	9.06E+00	3.82E-02	1.46E+01	3.55E-07	2.99E-03	2.12E-02	1.51E-01	4.61E+00	1.20E+04	8.90E-05	1.86E-01

MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	Formwork	HDPE	Sensing cable	Sensing cable	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	42576.54118	1.41E+02	9.63E+04	2.29E-04	1.34E+01	1.10E+02	3.11E+02	2.89E+04	8.00E+07	7.46E-01	1.44E+06
% of total	43%	33%	60%	6%	41%	47%	19%	57%	60%	76%	70%
Main contributor for each env. impact	Floor slab	Sensing cable	Generator	Floor slab	Sensing cable	Generator	Turbine case	Generator	Generator	HV cable	Sensing cable
Amount	5.78E+03	9.88E+01	1.38E+04	1.88E-04	3.97E+00	4.50E+01	1.58E+02	4.07E+03	1.22E+07	5.22E-02	6.82E+04
% of total	6%	23%	9%	5%	12%	19%	9%	8%	9%	5%	3%
Main contributor for each env. impact	Formwork	Generator	HV cable	Meter Cubicle GRP	Formwork	HV cable	Coanda screen D-1800	HV cable	HV cable	Generator	Formwork
Amount	5.44E+03	1.91E+01	6.74E+03	1.74E-04	1.65E+00	7.72E+00	1.55E+02	2.02E+03	5.60E+06	4.84E-02	4.67E+04
% of total	5%	5%	4%	4%	5%	3%	9%	4%	4%	5%	2%


Contribution of MHP Components to Environmental Impact - Site No.9


Material Breakdown of Environmental Impact Categories - Site No.9

Site No. 10 Overall LCA Results

INSTALLATION DETAILS			
Site	10	Turbine Power	70 kW
Scheme Type	High Head	Capacity Factor	35%
Head	133 m	Annual Output	212000 kWh
Flow	70 l/s	50yr Output	10600000 kWh
Turbine Type	Turgo		

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	8.56E+03	2.00E+01	3.86E+03	3.19E-04	2.01E+00	8.85E+00	1.45E+02	2.56E+03	4.69E+06	8.36E-03	6.21E+04
Penstock	4.03E+04	1.43E+02	2.94E+03	8.60E-04	1.17E+01	1.99E+01	5.25E+01	1.86E+03	4.70E+06	9.53E-03	1.15E+06
Powerhouse	8.55E+03	2.06E+01	3.88E+03	4.86E-04	1.41E+00	7.28E+00	1.18E+02	1.68E+03	3.40E+06	1.28E-02	6.51E+04
M&E	1.43E+04	1.68E+02	1.46E+05	9.50E-04	8.72E+00	1.89E+02	1.01E+03	4.30E+04	1.18E+08	9.85E-01	2.10E+05
Site vistis	2.96E+03	9.31E+00	2.73E+02	4.38E-04	1.02E+00	2.03E+00	3.40E+00	6.64E+01	2.81E+05	5.00E-04	4.00E+04
Total	7.47E+04	3.60E+02	1.57E+05	3.05E-03	2.49E+01	2.27E+02	1.32E+03	4.91E+04	1.31E+08	1.02E+00	1.53E+06

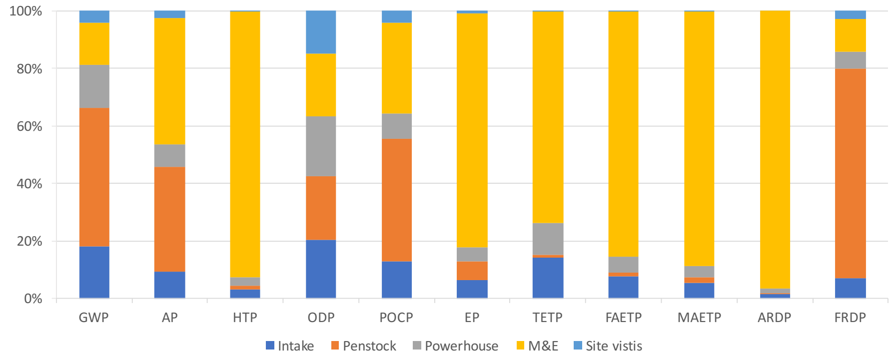
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	1.75E+00	3.62E-03	3.07E-01	6.79E-08	2.50E-04	1.27E-03	9.26E-03	2.59E-01	5.53E+02	9.62E-07	9.91E-03
Metals	1.12E+00	1.50E-02	1.40E+01	4.81E-08	8.67E-04	1.79E-02	1.08E-01	4.22E+00	1.11E+04	9.29E-05	1.71E-02
Plastics	3.15E+00	1.05E-02	1.52E-01	1.75E-08	9.55E-04	1.00E-03	7.25E-04	6.05E-02	2.03E+02	5.35E-07	1.02E-01
Processes	6.11E-02	4.05E-04	3.19E-02	6.18E-09	1.21E-05	1.05E-04	1.15E-03	9.32E-03	2.65E+01	5.17E-08	8.15E-04
Transport	8.57E-01	2.58E-03	1.14E-01	1.30E-07	1.89E-04	6.24E-04	1.67E-03	4.31E-02	1.37E+02	9.07E-07	1.20E-02
Wood	-7.50E-02	6.13E-05	5.10E-03	1.05E-09	5.57E-06	2.67E-05	1.06E-04	3.67E-03	1.02E+01	1.93E-08	1.49E-04
other	2.04E-01	1.86E-03	1.74E-01	2.11E-08	7.15E-05	5.12E-04	4.14E-03	3.71E-02	4.08E+02	4.88E-07	2.64E-03
Total	7.07E+00	3.41E-02	1.48E+01	2.92E-07	2.35E-03	2.14E-02	1.25E-01	4.63E+00	1.24E+04	9.59E-05	1.45E-01

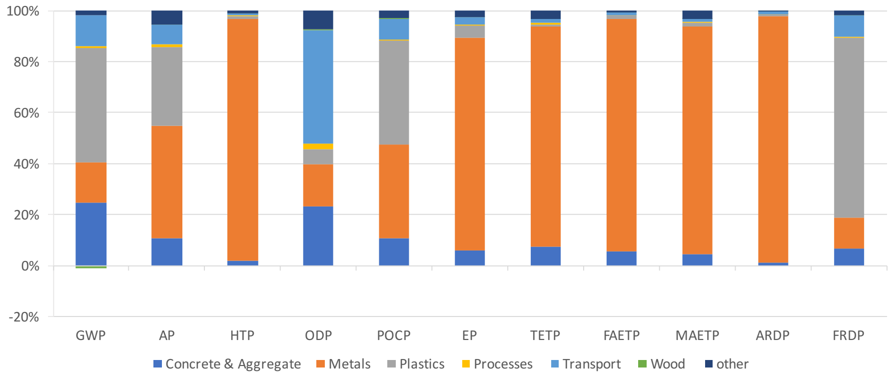
MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	Formwork	HDPE	Sensing cable	Sensing cable	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	42576.54118	1.41E+02	9.63E+04	2.29E-04	1.34E+01	1.10E+02	3.11E+02	2.89E+04	8.00E+07	7.46E-01	1.44E+06
% of total	43%	33%	60%	6%	41%	47%	19%	57%	60%	76%	70%
Main contributor for each env. impact	Floor slab	Sensing cable	Generator	Floor slab	Sensing cable	Generator	Turbine case	Generator	Generator	HV cable	Sensing cable
Amount	5.78E+03	9.88E+01	1.38E+04	1.88E-04	3.97E+00	4.50E+01	1.58E+02	4.07E+03	1.22E+07	5.22E-02	6.82E+04
% of total	6%	23%	9%	5%	12%	19%	9%	8%	9%	5%	3%
Main contributor for each env. impact	Formwork	Generator	HV cable	Meter Cubicle GRP	Formwork	HV cable	Coanda screen D-1800	HV cable	HV cable	Generator	Formwork
Amount	5.44E+03	1.91E+01	6.74E+03	1.74E-04	1.65E+00	7.72E+00	1.55E+02	2.02E+03	5.60E+06	4.84E-02	4.67E+04
% of total	5%	5%	4%	4%	5%	3%	9%	4%	4%	5%	2%

Contribution of MHP Components to Environmental Impact - Site No.10



Material Breakdown of Environmental Impact Categories - Site No.10



Site No.12 Overall LCA Results

INSTALLATION DETAILS				
Site	12		Turbine Power	100 kW
Scheme Type	High Head		Capacity Factor	57%
Head	144 m		Annual Output	499258 kWh
Flow	101 l/s		50yr Output	24962900 kWh
Turbine Type	Turgo			

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

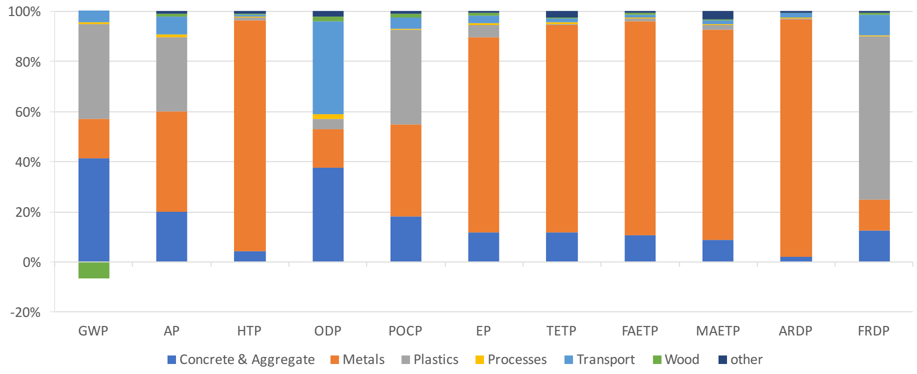
sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	2.22E+04	5.54E+01	1.24E+04	1.19E-03	4.57E+00	2.17E+01	4.20E+02	6.03E+03	1.12E+07	3.35E-02	1.82E+05
Penstock	3.62E+04	1.21E+02	1.64E+03	3.70E-04	1.09E+01	1.14E+01	6.97E+00	6.01E+02	2.08E+06	2.42E-03	1.18E+06
Powerhouse	2.75E+04	8.47E+01	1.00E+04	1.94E-03	6.79E+00	3.23E+01	3.32E+02	7.38E+03	1.51E+07	3.69E-02	2.87E+05
M&E	9.77E+03	1.46E+02	1.35E+05	6.04E-04	7.19E+00	1.73E+02	9.41E+02	3.89E+04	1.08E+08	9.00E-01	1.61E+05
Site vistis	1.36E+03	3.12E+00	1.21E+02	2.06E-04	1.77E-01	6.88E-01	2.21E+00	3.83E+01	1.46E+05	5.65E-04	1.86E+04
Total	9.70E+04	4.10E+02	1.59E+05	4.31E-03	2.96E+01	2.39E+02	1.70E+03	5.29E+04	1.36E+08	9.73E-01	1.82E+06

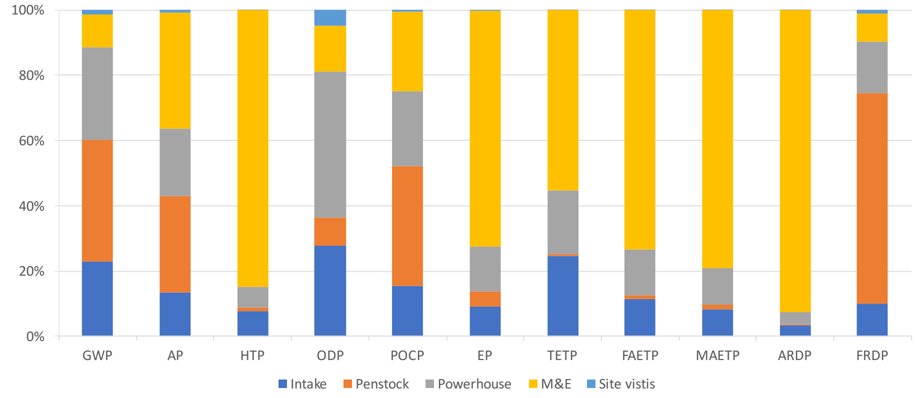
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	1.61E+00	3.32E-03	2.82E-01	6.48E-08	2.18E-04	1.14E-03	8.00E-03	2.24E-01	4.88E+02	8.42E-07	9.07E-03
Metals	6.20E-01	6.54E-03	5.86E+00	2.64E-08	4.34E-04	7.46E-03	5.65E-02	1.81E+00	4.58E+03	3.69E-05	9.04E-03
Plastics	1.46E+00	4.88E-03	6.84E-02	7.47E-09	4.47E-04	4.59E-04	2.72E-04	2.73E-02	9.18E+01	1.85E-07	4.77E-02
Processes	3.18E-02	2.01E-04	1.51E-02	2.95E-09	6.13E-06	5.35E-05	4.72E-04	4.98E-03	1.62E+01	4.24E-08	4.19E-04
Transport	4.05E-01	1.17E-03	5.84E-02	6.39E-08	5.50E-05	3.02E-04	9.86E-04	2.79E-02	8.16E+01	7.74E-07	5.87E-03
Wood	-2.62E-01	1.93E-04	1.56E-02	3.23E-09	1.76E-05	8.37E-05	3.17E-04	1.16E-02	3.21E+01	5.61E-08	4.56E-04
other	2.42E-02	1.45E-04	6.87E-02	3.85E-09	1.04E-05	7.36E-05	1.71E-03	1.48E-02	1.69E+02	2.04E-07	5.57E-04
Total	3.89E+00	1.64E-02	6.37E+00	1.73E-07	1.19E-03	9.58E-03	6.82E-02	2.12E+00	5.46E+03	3.90E-05	7.31E-02

MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	Transport to suppliers	HDPE	Sensing cable	Sensing cable	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	34050.01767	1.13E+02	8.54E+04	9.64E-04	1.07E+01	9.78E+01	2.75E+02	2.56E+04	7.09E+07	6.61E-01	1.15E+06
% of total	35%	28%	54%	22%	36%	41%	16%	48%	52%	68%	63%
Main contributor for each env. impact	Floor slab	Sensing cable	LV Cable	Formwork	Sensing cable	Generator	Turbine case	LV Cable	LV Cable	LV Cable	Sensing cable
Amount	7.36E+03	8.76E+01	1.95E+04	2.91E-04	3.52E+00	4.50E+01	1.58E+02	5.84E+03	1.62E+07	1.51E-01	6.05E+04
% of total	8%	21%	12%	7%	12%	19%	9%	11%	12%	15%	3%
Main contributor for each env. impact	Formwork	LV Cable	Generator	Mortar	Formwork	LV Cable	Coanda screen D-1800	Generator	Generator	Generator	Formwork
Amount	6.92E+03	2.00E+01	1.38E+04	2.67E-04	2.09E+00	2.23E+01	1.29E+02	4.07E+03	1.22E+07	4.84E-02	5.94E+04
% of total	7%	5%	9%	6%	7%	9%	8%	8%	9%	5%	3%


Contribution of MHP Components to Environmental Impact - Site No.12


Material Breakdown of Environmental Impact Categories - Site No.12

Site No.13 Overall LCA results

INSTALLATION DETAILS			
Site	13	Turbine Power	100 kW
Scheme Type	High Head	Capacity Factor	63%%
Head	171	Annual Output	553892 kWh
Flow	85	50yr Output	27694600 kWh
Turbine Type	Turgo		

TOTAL ENVIRONMENTAL IMPACTS OF EACH COMPONENT

sections	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Intake	1.47E+04	3.95E+01	1.20E+04	8.58E-04	3.39E+00	1.57E+01	4.04E+02	4.78E+03	8.52E+06	3.07E-02	1.30E+05
Penstock	4.97E+04	1.66E+02	2.25E+03	5.07E-04	1.50E+01	1.56E+01	9.55E+00	8.26E+02	2.85E+06	3.32E-03	1.62E+06
Powerhouse	1.31E+04	3.46E+01	9.08E+03	6.26E-04	2.96E+00	1.40E+01	2.99E+02	3.95E+03	7.39E+06	2.37E-02	1.08E+05
M&E	1.71E+04	2.34E+02	2.11E+05	1.13E-03	1.14E+01	3.47E+02	1.21E+03	6.03E+04	1.66E+08	1.32E+00	2.52E+05
Site vistis	3.19E+03	9.91E+00	2.89E+02	4.72E-04	1.04E+00	2.15E+00	3.62E+00	7.03E+01	3.00E+05	4.99E-04	4.30E+04
Total	9.78E+04	4.85E+02	2.35E+05	3.59E-03	3.38E+01	3.94E+02	1.93E+03	6.99E+04	1.86E+08	1.38E+00	2.15E+06

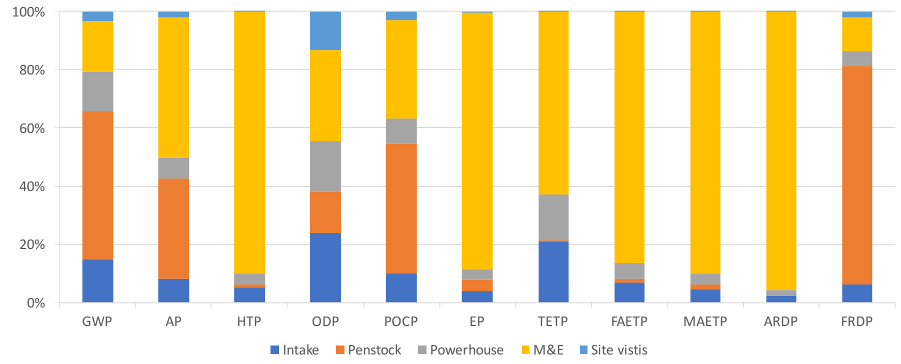
Material Breakdown (expressed per kWh generated over project 50-year lifespan)

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	g CO2 eq./kWh	g SO2 eq./kWh	g 1,4-dichlorobenzene eq./kWh	g CFC-11 eq./kWh	g ethylene eq./kWh	g PO4--- eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g 1,4-dichlorobenzene eq./kWh	g antimony eq./kWh	MJ/kWh
Concrete & Aggregate	8.55E-01	1.85E-03	1.67E-01	3.57E-08	1.26E-04	6.61E-04	4.67E-03	1.34E-01	2.91E+02	5.04E-07	5.10E-03
Metals	5.42E-01	8.26E-03	8.11E+00	2.34E-08	4.55E-04	1.26E-02	6.18E-02	2.32E+00	6.06E+03	4.86E-05	8.33E-03
Plastics	1.76E+00	5.86E-03	7.82E-02	6.89E-09	5.43E-04	5.32E-04	2.37E-04	3.09E-02	1.05E+02	1.37E-07	5.80E-02
Processes	3.53E-02	2.30E-04	1.48E-02	3.45E-09	6.87E-06	6.00E-05	4.48E-04	4.93E-03	1.60E+01	3.99E-08	4.69E-04
Transport	3.78E-01	1.14E-03	5.17E-02	5.81E-08	7.80E-05	2.80E-04	7.81E-04	2.09E-02	6.46E+01	4.83E-07	5.33E-03
Wood	-5.65E-02	5.45E-05	4.70E-03	9.66E-10	4.93E-06	2.39E-05	1.01E-04	3.23E-03	9.07E+00	1.90E-08	1.37E-04
other	1.94E-02	1.07E-04	6.05E-02	1.23E-09	7.87E-06	6.30E-05	1.52E-03	1.29E-02	1.50E+02	1.81E-07	2.56E-04
Total	3.53E+00	1.75E-02	8.49E+00	1.30E-07	1.22E-03	1.42E-02	6.96E-02	2.52E+00	6.70E+03	4.99E-05	7.76E-02

MAIN ENV. IMPACT CONTRIBUTORS

	GWP	AP	HTP	ODP	POCP	EP	TETP	FAETP	MAETP	ARDP	FRDP
	kg CO2 eq.	kg SO2 eq.	kg 1,4-dichlorobenzene eq.	kg CFC-11 eq.	kg ethylene eq.	kg PO4--- eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg 1,4-dichlorobenzene eq.	kg antimony eq.	MJ
Main contributor for each env. impact	HDPE	HDPE	Sensing cable	Transport to suppliers	HDPE	Sensing cable	Sensing cable	Sensing cable	Sensing cable	Sensing cable	HDPE
Amount	46509.46718	1.55E+02	1.18E+05	6.28E-04	1.47E+01	1.35E+02	3.80E+02	3.53E+04	9.78E+07	9.12E-01	1.58E+06
% of total	48%	32%	50%	17%	43%	34%	20%	50%	53%	66%	73%
Main contributor for each env. impact	Floor slab	Sensing cable	HV cable	2 vans each day for 6 months (60km round trip)	Sensing cable	HV cable	Turbine case	HV cable	HV cable	LV Cable	Sensing cable
Amount	4.73E+03	1.21E+02	3.74E+04	3.30E-04	4.86E+00	1.23E+02	1.58E+02	8.36E+03	2.36E+07	2.00E-01	8.34E+04
% of total	5%	25%	16%	9%	14%	31%	8%	12%	13%	14%	4%
Main contributor for each env. impact	Formwork	HV cable	LV Cable	Valve transport	RC Steel	Generator	Coanda screen D-1800	LV Cable	LV Cable	HV cable	RC Steel
Amount	4.45E+03	3.19E+01	2.58E+04	1.87E-04	1.64E+00	4.50E+01	1.29E+02	7.75E+03	2.15E+07	1.19E-01	3.85E+04
% of total	5%	7%	11%	5%	5%	11%	7%	11%	12%	9%	2%

Contribution of MHP Components to Environmental Impact - Site No.13



Material Breakdown of Environmental Impact Categories - Site No.13