

Article

Life Cycle Assessment of a Small Hydropower Plant in Iceland—A Case Study of a 9.9 MW Run-of-River Hydropower Plant

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Abstract

Decarbonizing the energy sector is central to limiting global average temperature to below 2 °C above pre-industrial levels, in line with the Paris Agreement. Hydropower plays a key role in renewable energy generation, yet environmental impacts vary depending on systems and site conditions. Small hydropower (<10 MW installed capacity) is often assumed to have lower environmental impacts, but evidence remains limited, especially in cold-climate regions. This study assesses the cradle-to-gate life cycle environmental impacts of a 9.9 MW run-of-river hydropower plant in Iceland, using life cycle assessment based on the CML-IA method. The study uses primary design and operator data and provides direct comparison with published Icelandic large hydropower life cycle assessments. The functional unit is 1 kWh of electricity generated over a 60-year lifetime. Results indicate a global warming potential of 4 g CO₂ equivalent per kWh, decreasing to 3 g CO₂ under a 100-year lifetime. Hot spot analysis shows that construction materials, particularly glass fibre reinforced plastic (GRP), concrete, and steel, dominate environmental impacts. Sensitivity analysis shows the influence of lifetime, capacity factor, and dam material. Indicative reservoir emission estimates highlight additional potential impacts even for small intake reservoirs. Overall, the studied system shows higher life cycle impacts per kWh compared to Icelandic large hydropower plants, highlighting the importance of site-specific assessment and careful interpretation of small hydropower (SHP) environmental performance.

Keywords: life cycle assessment; hydropower; environmental impact assessment; large hydropower; small hydropower



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1. Introduction

1.1. Background

Climate and environmental issues, such as rising global temperatures, loss of biodiversity and severe reduction in available land, are among the most pressing challenges of our times. The effort to hold the increase in global average temperature to well below 2 °C above pre-industrial levels, further pursuing to limit the temperature increase to 1.5 °C,

has become a recognized goal of nations worldwide through the Paris Agreement, as this would significantly reduce the risks and impacts of climate change [1]. This suggests the need for the decarbonization of the energy sector, as the burning of fossil fuels is the biggest producer of greenhouse gas (GHG) emissions globally [2]. As energy demand is rising, the transition to renewable energy production has thus become a key factor in achieving this goal, reflected, e.g., in the European Union's Sustainable Development Goals (SDGs) and the International Energy Agency's World Energy Outlook (WEO) [3,4].

Hydropower (HP) is one of the renewable energy sources that can contribute to the decarbonization of the energy sector [5]. It has technological and economic advantages compared to other renewable energy sources, such as often massive storage potential, flexibility, and the potential to be integrated with, e.g., wind or solar power [5]. Furthermore, HP is a reliable, versatile energy source [6]. In countries where HP is abundant, e.g., in Iceland and Norway, hydroelectricity, generated from HPs with storage, can be used as a base load energy source and the efficiency of converting HP into electricity can be up to 90% [7,8]. When energy consumption is low, the flow of water can be reduced, and energy can be conserved for times when the demand for power increases [8]. However, large hydropower (LHP) development, often utilizing large reservoirs, has been met with increasing opposition [9–11]. This is due to the significant environmental impacts associated with such development, such as the destruction of arable land, habitat and biodiversity loss, altered river ecosystems and potential high GHG emissions from reservoirs [12,13]. These concerns, along with the fact that many of the feasible options for LHP development have already been utilized [14], have prompted increasing interest in small hydropower (SHP) [6,10,15,16], sometimes with simplified policy and regulation processes to facilitate its development [5,17,18].

HP plants are generally defined and compared by their installed capacity. The most common definition for SHP, especially in Europe, is less than 10 MW [5,6,10]. SHP has sometimes been regarded as a more environmentally viable alternative to LHP, and sometimes even claimed as being 'green', having no or negligible environmental impacts [6,10]. The main reason for these claims is that most SHP operate as run-of-river (RoR) systems, rather than utilizing a reservoir [19]. RoR systems can be classified into three types: dam-toe, diversion weir, and pondage. Dam-toe systems integrate the powerhouse directly into the river channel, without diverting its flow. Diversion weir RoR systems divert river flow through a canal or penstock to generate electricity, and their generation largely depends on the natural flow conditions [5,14]. Pondage RoR systems use a small reservoir that allows for slight, short-term energy storage, increasing their generation capacity [5,14,20]. Although LHP and SHP share many of the same components (e.g., turbines, powerhouses, intake, penstocks), the design and configuration of the systems can vary significantly, particularly between RoR and storage HP. These differences influence operational characteristics and, consequently, environmental impacts. Despite these variations, many environmental impacts are driven by similar types of inputs, while overall differences are also influenced by scale, site conditions, and system configuration [10,15]. Although sometimes regarded as more environmentally viable than LHP, SHP can have severe and even irreversible impacts [14]. Additionally, some studies have pointed out that a single LHP development could have less negative environmental impacts than several SHP developments [14,18,21].

1.2. Life Cycle Assessment of Hydropower Plants

In recent years, life cycle assessment (LCA) has increasingly been used as a policy support tool in the energy sector [22]. Varun notes that assessing environmental impacts from the whole life cycle is essential when comparing different energy systems for decision-making purposes, making LCA an important tool for environmental evaluation [23]. Ac-

cordingly, several studies have used LCA to review and/or compare electricity generation options, for example, comparing fossil-based energy sources to renewables [24,25] or comparing the impacts from electricity generation of different renewable energy systems [5,19,23,26]. These studies consistently show that when comparing fossil-based energy systems to renewable systems using LCA, renewable systems tend to perform better from an environmental perspective [24,25]. However, when comparing different renewable energy systems, the results vary [23,26]. This is similarly true when comparing LHP and SHP. Several studies have reported that SHP, generally operating as RoR, exhibit lower life cycle environmental impacts than LHP, largely because they require smaller or no reservoirs, thereby avoiding reservoir-related emissions [19,23,25]. In contrast, other studies have concluded that due to economies of scale, LHPs usually have better environmental performance and lower GHG emissions compared to SHP [5,27].

These differences in results might stem from how the functional unit is defined, what LCA method is used, and the method chosen for allocation and/or the expansion of the system boundary, data applications, methodological choices and lack of standardization [19,25,28]. Additionally, HP is highly site-specific and very sensitive to changes in geographical locations, which might reflect inconsistent results [19,24,29,30].

SHP remains comparatively underrepresented in the literature. When SHP is included, it is often assessed within broader renewable energy comparisons rather than as a distinct category, limiting the specificity of conclusions regarding SHP performance [5,19,24,25]. Additionally, the definition of SHP varies, and although the most common definition is <10 MW, the installed capacity of SHP in these studies is sometimes up to 50 MW [19,25,30], which further reduces comparability between studies. Several HP LCAs are case studies, assessing the life cycle environmental impacts of a single or several plants [27,30–32], and only a limited number of studies apply the 10 MW threshold definition of SHP [31,32].

Furthermore, direct comparisons between SHP and LHP are often affected by inconsistencies in methodological choices, including differences in system boundaries, functional units, and inventory assumptions [19,24,28], as well as site-specific geographical and hydrological conditions [25,27,29]. As a result, it can be challenging to determine whether observed differences in environmental performance reflect true technological differences or methodological variability across studies. This highlights the need for additional case-specific and methodologically consistent LCAs of SHP to improve the robustness and comparability of results.

1.3. The Icelandic Context

Iceland is one of the leading countries in terms of harnessing and utilizing renewable energy, with about 99.4% of domestic energy production coming from renewable sources, with HP and geothermal energy being the main contributors to the energy mix [33]. Globally, Iceland has the highest total primary energy supply (TPES) derived from renewables in any national total energy budget, or approximately 85% [34]. In recent years, the domestic electricity production has fluctuated between 19 and 20 TWh annually, with close to 13 TWh being produced by LHP [35,36]. Most of the electricity produced is used in heavy industry, with about 70% being tied up in long-term contracts with the industry's power users, e.g., aluminum smelters [37]. Due to a growing population, increased business activity, and the intended energy transition, the demand for energy is on the rise [16].

In Iceland, all potential major energy options for the development of renewable energy are evaluated via the Master Plan for Nature Protection and Energy Utilization [38]. The Master Plan encompasses methodology, processes, and laws to reconcile the often competing interests between nature protection and energy utilization, and it is used for the planning and mapping out of potential major energy development, classifying the

options into three categories: energy utilization, on-hold, and protection [39,40]. All HP developments with installed capacity of 10 MW or higher are evaluated by the Master Plan because of their potential significant environmental and social impact and require an environmental impact assessment (EIA) [41]. An EIA assesses potential impacts of a development on, e.g., local hydrology, biodiversity, wildlife and cultural heritage [39,41]. SHPs are not subject to the Master Plan according to Icelandic law, nor do they require an environmental impact assessment (EIA), unless determined by the National Planning Agency. They do, however, have a notification obligation to the National Planning Agency and need to apply for applicable permits through the National Energy Regulatory, as well as through relevant municipalities [40]. The Icelandic Environment and Energy Agency has, since 2016, increasingly encouraged the development of SHP, as most of the LHP options in Iceland are either already utilized or under protection [42].

LCAs assessing the Icelandic energy sector remain limited, and studies focusing on local HP are particularly scarce. This is especially true regarding peer-reviewed research, where only one LCA on Icelandic HPs has been published [43]. The Icelandic consulting engineer firm EFLA has conducted several LCAs of hydropower plants operated by Landsvirkjun: Búðarhálsstöð (2018), Fljótsdalsstöð (2018), Blöndustöð (2019) and Búrfellsstöð II (2020) [44–47]. However, these studies are available primarily as technical reports, which limits their use in comparative academic synthesis. In 2025, Kjeld et al. published a peer-reviewed study based on these reports, exploring hydropower utilization in Iceland as a driving force for climate strategy and decarbonization [43]. Furthermore, peer-reviewed LCAs of Icelandic SHP remain virtually absent, highlighting a clear gap in the literature.

1.4. Research Objectives

In 2024, the global average temperature reached 1.55 °C above pre-industrial levels, exceeding the efforts of the Paris Agreement to limit the increase in temperature to 1.5 °C [1,2]. The same year, all sources of energy increased to meet the growing energy demand, including fossil fuels [4]. HP continues to play an important role in terms of transitioning to renewable energy, along with solar power, wind, bioenergy, and geothermal energy [4]. Previous LCA studies have suggested that HP development is linked with negligible GHG emissions compared to fossil fuels, but more recent studies have suggested that LHP can emit GHG levels comparable to, or even greater than, fossil fuels [19]. However, there is no clear consensus in the literature regarding the comparative environmental performance of SHP and LHP [5,19,21,23,25,27]. This uncertainty, combined with increasing energy demand and the need for renewable energy systems, highlights the importance of further research on the environmental performance of HP technologies.

The aim of this study is to address the identified gaps in the current literature, namely the limited number of peer-reviewed LCAs of SHP, the lack of studies applying consistent SHP definitions, and the lack of case studies from Iceland and other cold-climate regions. It does so by conducting an LCA of a 9.9 MW RoR SHP in Iceland, assessing and quantifying the environmental impacts of the life cycle associated with electricity generation from the SHP and comparing the results with LHP LCAs in Iceland. In addition, the study includes a hot spot analysis, sensitivity analysis of three different scenarios (plant lifetime, dam construction material, and capacity factor), and an indicative estimation of reservoir-related emissions. The results are interpreted in the context of both LCA methodology and EIA, with particular emphasis on the Icelandic energy system.

2. Materials and Methods

2.1. Case Project Description

The base case assessed in this study is a 9.9 MW RoR SHP plant in the south of Iceland. All structural and technical descriptions of the plant are based on the project's bill of quantities, technical design documents, and personal communication with the plant's operating company. The SHP consists of a main dam and three smaller weirs, which all use only earth-fill excavated from the construction site as filling. Water is channelled from the intake to the powerhouse through a 1700 m underground headrace tunnel in a pressure shaft made of both glass fibre reinforced plastic (GRP) pipe and stainless steel parts. The powerhouse is a concrete structure, clad with weathering steel and softwood. The SHP utilizes a small intake reservoir, with a surface area of 8 hectares (ha). About 40% of the reservoir is in the current course of the river, whereas the other 60% is outside the riverbed and therefore artificially made (operating company, Iceland, personal communication, 7 November 2023) [48].

While a 100-year lifetime is commonly assumed in hydropower LCA studies [27], the base case adopts a 60-year lifetime based on operator information, reflecting the expected service life of the turbine system under site-specific operational conditions (operating company, Iceland, personal communication, 21 February 2024) [49]. No turbine replacement is planned within the assumed lifetime [49]. The plant is remotely operated, meaning no personnel operate on site. The annual electricity generation is based on the average generation of the plant from the years 2021 and 2022, or 88,265 GWh (operating company, Iceland, personal communication, 7 November 2023) [48].

2.1.1. Comparison Systems Description

The results from existing LCAs, conducted by the consulting engineering firm EFLA, of four LHPs in Iceland are used for comparison in this study. Their installed capacity ranges from 95 to 690 MW, and all utilize a storage reservoir. The functional unit used in all comparison studies is 1 kWh of electricity generated in the respective system, and all have a lifetime of 100 years [44–47].

Table 1 presents an overview of the compared LHPs, including installed and generation capacity, and the reported global warming potential (GWP) from the LCA results. The GWP refers to the potential global warming over a 100-year period due to anthropogenic emissions that can increase the radiative forcing of the atmosphere [50].

Table 1. Overview of the Icelandic large hydropower plants used for comparison, including installed capacity, annual electricity generation, and reported global warming potential (GWP).

Hydropower Plant	Installed Capacity (MW)	Generation Capacity (GW/yr)	GWP (g CO ₂ eq/kWh)
Búðarhálsstöð	95	585	1.5
Fljótsdalsstöð	690	5000	1.2
Blöndustöð	150	990	20.4
Búrfellsstöð II	100	700	0.5

Adapted from Landsvirkjun [44–47].

2.1.2. Reservoir Emissions Estimations

Reservoir emissions are recognized as a potential hot spot in HP LCAs, particularly for LHPs due to the accumulation of decayed biomass [1,13,19]. However, as the SHP is a RoR plant, utilizing only a small intake reservoir, reservoir emissions were not included in the system boundaries. A commonly used Iceland-specific estimation method exists [13,51] and is applied here only for indicative purposes due to the lack of site-specific data. The method is presented in Appendix B.

2.2. Life Cycle Assessment Methodology

2.2.1. Goal and Scope

This study assesses the life cycle environmental impacts of a 9.9 MW RoR SHP in Iceland in accordance with the ISO 14040 and 14044 standards [52,53].

2.2.2. Functional Unit

The functional unit is 1 kWh of electricity generated by the studied SHP over a 60-year lifetime. It is assumed that the annual electricity generation from the system will remain the same over the lifetime, with a total electricity generation of 5295.9 GWh or about 5.3 TWh over 60 years.

2.2.3. System Boundaries

This study uses the cradle-to-gate approach, including the manufacturing and construction and operation phases. However, the system is remotely operated, so waste, fuel and energy use are negligible as no personnel operate on site. Almost all electricity generated in the plant is transmitted to the national grid. According to the operator of the system, no major maintenance or replacement of equipment is expected within the 60-year lifetime [49]. Accordingly, no additional operational inputs were included in the base case model, and all modelled inputs relate to the construction phase. The SHP includes a small intake reservoir; however, no primary data were available for this component. Given the high site-specific variability of reservoir emissions and the lack of reliable input data, reservoir emissions were excluded from the system boundaries. Indicative estimates of potential reservoir emissions are provided separately (Sections 2.1.2 and 3.5, and Appendix B). Figure 1 presents a simplified diagram of the system boundaries.

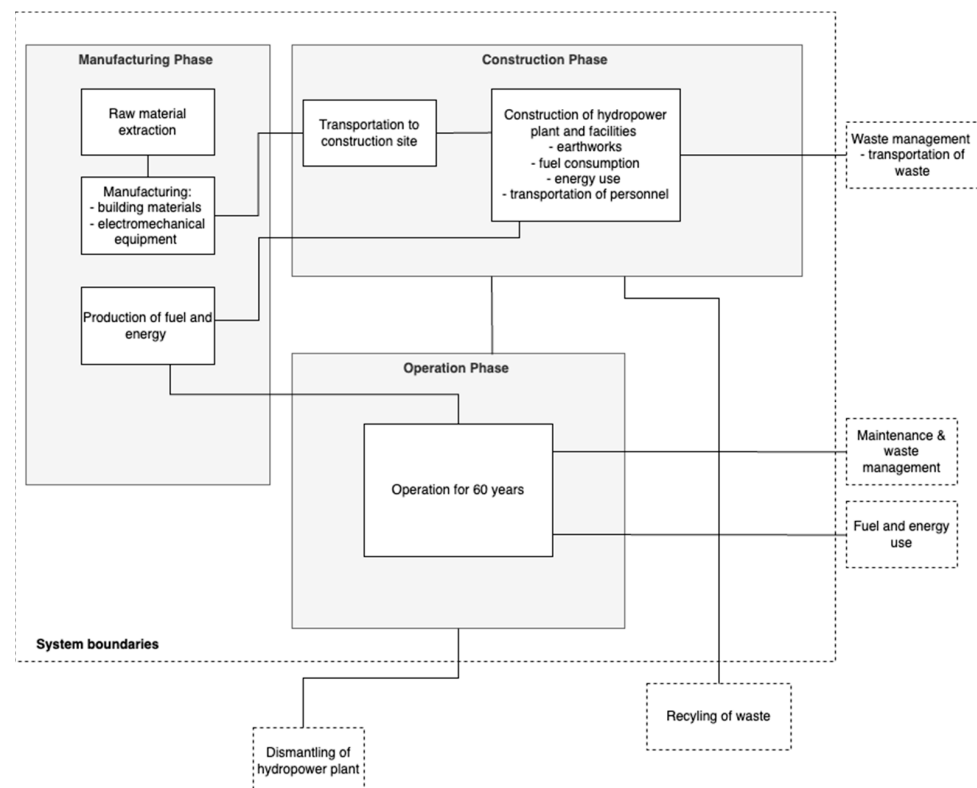


Figure 1. The system boundaries are enclosed within the large dotted frame, and include the manufacturing, construction, and operation phases presented in the shaded areas. The lines indicate how the processes connect to each other and the different life stages. The processes shown in the smaller dotted boxes outside the system boundary are excluded from the life cycle assessment.

2.2.4. Life Cycle Inventory

All numerical information was obtained from the operating company or borrowed from previously conducted LCAs of LHP in Iceland [44–47]. The bill of quantities and other project-specific documentation from the SHP could not be shared publicly. Nevertheless, the life cycle inventory is reported in as much detail as possible in the manuscript and Appendix A to facilitate transparency and reproducibility.

Foreground data was gathered from the operating company, head of construction, and manufacturers, in the form of a bill of quantities, explosives report, product information documents, and personal communication. These included all inputs for the building materials, fuel, explosives, and turbines. Background data was gathered from the ecoinvent 3.91 database. Additionally, where no primary data was available, assumptions regarding the material inputs of equipment and maintenance processes of the SHP were made. These assumptions were made based on numerical information from existing LCAs of Icelandic LHPs [44,47]. Each input was manually mapped and scaled to the functional unit and then matched to the most appropriate available process in the ecoinvent database, based on material type, production technology and geographical representativeness.

Because of the specific features of the SHP described in Section 2.2.3, the base case results of this study focus on the construction phase of the SHP. As recommended in the literature, building structures, equipment, and fuel and energy usage during construction were used for modelling [27,30]. These include, e.g., steel structures, concrete, cement, steel and rock bolts for rock reinforcement, exterior steel and wood claddings, geotextiles, plastic pipes for drainage, and glass-fibre-reinforced plastic and steel in the pressure shaft. Other materials and processes, such as doors, windows, insulation, lighting systems, air ventilation and electric systems (not relating to the machinery), were excluded. Inputs for the operation phase were used for assessing the scenario of extended lifetime and included maintenance of materials and replacement of equipment. Table 2 presents the main materials and processes of the life cycle inventory, as well as the class and origin of the data, and Table 3 highlights key materials and processes of the inventory. More detailed information on life cycle inventory can be found in Appendix A, Tables A1–A7.

Table 2. Main system components, life cycle inventory processes, and data sources used in the assessment.

System Component	Life Cycle Phase	Material, Processes	Class	Origin
Canals, dam, and weirs	Construction	Excavation and blasting, rock bolts, reinforcing steel, concrete, plastics.	Foreground data	Bill of quantities, operating company, explosives report, product information documents, personal communication.
Building structures	Construction	Excavation and blasting, rock bolts, reinforcing steel, steel structures, glass fibre reinforced plastic, plastics, concrete.	Foreground data	Bill of quantities, operating company, explosives report, product information documents, personal communication.
Turbines	Construction	Steel.	Foreground data	Product information documents, operating company
Other equipment	Construction	Steel, copper.	Foreground, background data	Previously conducted LCAs [44,47]
Fuel and energy	Construction	Diesel oil, gasoline.	Foreground, background data	Personal communication, head of construction, ecoinvent database

Table 2. *Cont.*

System Component	Life Cycle Phase	Material, Processes	Class	Origin
Transportation of material	Construction, operation (sensitivity analysis)	Diesel, unspecified fuel.	Foreground, background data	Operating company, head of construction, transportation company, previously conducted LCAs [44,47]
Maintenance of building materials	Construction, operation (sensitivity analysis)	Steel, concrete, plastics.	Foreground, background data	Previously conducted LCA [47]
Reservoir emissions	Construction, operation (sensitivity analysis)	GHG emissions.	Background data	Previously conducted research [13,51]

Table 3. Main materials and process inputs used for modelling the case project.

Material/Process	Unit	Total Quantity
Explosives	kg	28,188
Earth fillings	m ³	25,424
Rock bolts	kg	9270.85
Concrete	m ³	7367.4
Reinforcing steel	kg	490,104.5
Cement for grout	kg	153,626.5
Other steel (structures, cladding, pressure shaft)	kg	43,409.6
Glass-fibre-reinforced plastic	t	1779.2
Geotextile fabric	m ²	63,995
PE and PVC pipes	m	428
Turbine, steel	kg	26,468
Other equipment, steel	t	96.39
Copper	t	6.85
Fuel, diesel oil	l	576,814

No major maintenance is assumed over the estimated 60-year lifetime, and no processes were accounted for in the operation phase (e.g., waste management, replacement of equipment, etc.). For a sensitivity analysis, a 100-year lifetime of the plant was explored. For the operation phase, fuel and energy use and waste are assumed to be none, as the SHP is remotely operated. Maintenance of building materials was considered and assumed to be the same proportion as for Búrfellsstöð II [47]. It is assumed that the equipment is replaced once over the lifetime, and transportation of building materials and equipment is accounted for. The estimated need for maintenance of materials for this scenario can be found in Appendix A, Table A8.

2.2.5. Life Cycle Impact Assessment Method

The life cycle impact assessment (LCIA) was performed using SimaPro Flow 2.47, online software, using the ecoinvent 3.91 database. The midpoint CML-IA baseline impact assessment method was selected because it is frequently used in HP LCAs [19,27,30,31], including the Icelandic LHP LCAs used for comparison [43–47]. Using the same method ensures consistency and comparability. Seven environmental impact categories were assessed: global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), ozone depletion potential (ODP), abiotic depletion of non-fossil resources (ADPE), abiotic depletion of fossil-based resources (ADPM), and photochemical ozone creation potential (POCP) [50]. Environmental impact category descriptions are provided in Appendix A, Table A9.

Additionally, potential reservoir emissions were estimated, and the results presented separately for indicative purposes. The method is presented in Appendix B.

2.3. Scenarios

The following three scenarios were evaluated using sensitivity analysis.

2.3.1. Extended Lifetime

The most commonly assumed lifetime for HP in LCA is 100 years [27]. As the assumed lifetime of the SHP is 60 years, the environmental impacts associated with the lifetime will be assessed using the 100-year lifetime recommended by the literature. To assess the sensitivity of the results to an extended lifetime, the electricity generation was increased to represent the functional unit of generating 1 kWh of electricity from the SHP over a 100-year lifetime. The operational phase was included, with maintenance of building structures and replacement of equipment used as operational inputs. To ensure consistency and comparability, this scenario was used in the comparison with the LHPs, which have a lifetime of 100 years [43–47].

2.3.2. Concrete Main Dam

Concrete in dam construction is associated with higher impacts to global warming potential, compared to earth-filled dams [54,55]. As the SHP includes earth-filled dams and weirs, using excavated material from the construction site, the potential change in environmental impacts by substituting earth fill with concrete instead of earth fill in the construction of the main dam was assessed with sensitivity analysis. It is assumed that the amount of concrete is the same as the amount of earth fill used in the construction, as recommended by the concrete manufacturer (Kai Westphal, Steypustöðin, personal communication, 29 February 2024) [56].

2.3.3. Reduced Capacity Factor

The capacity factor (CF) is a measure of how efficiently a system is being operated over a certain period [57]. The CF of HP can vary greatly, depending on various factors, e.g., site-specific conditions, seasonal fluctuations in hydrological conditions, and the efficiency of the turbines [57,58]. In general, CF values for HP span a wide range, and no consistent difference between SHP and LHP can be assumed, as this depends strongly on the type of plant in question and site-specific conditions. RoR HPs are particularly sensitive to hydrological conditions due to limited storage capacity compared to reservoir-based systems [59]. In this study, a CF range of 50–70% is used as a reference for SHP [57]. The studied plant operates at a higher level based on average annual generation. The method for calculating CF is exhibited in Equation (1):

$$CF (\%) = \frac{\text{Annual energy generation (kWh)}}{\text{Installed capacity (kW)} * 8760 \text{ (h/year)}} \quad (1)$$

The average electricity generation for the past two years was used for this scenario, or 88.265 MWh. For the sensitivity analysis, the CF was reduced to 50% and 70%, respectively.

3. Results

The results presented in this section are based on the life cycle inventory and modelling approach described in Sections 2.2.4 and 2.2.5. Key figures of inventory data are presented in Table 3 and a detailed list of inventory data in Appendix A.

3.1. Base Case Results

The results for GWP per functional unit is 4 g of CO₂ eq per kWh. The cradle-to-gate results for each of the assessed impact categories are presented in Table 4, along with the total lifetime impacts from the generation of 5295.9 GWh of electricity. Because of the

features of the SHP, no inputs were used for the operation phase, so these results are based on the construction inputs (see Section 2.2.3).

Table 4. Total life cycle environmental impacts of the studied SHP per impact category, expressed per functional unit (1 kWh) and aggregated over the plant lifetime.

Impact Category	Reference Unit	Impacts per kWh	Lifetime Impacts
Global warming potential (GWP)	kg CO ₂ eq	4×10^{-3}	2.3×10^7
Acidification potential (AP)	kg SO ₂ eq	2×10^{-5}	9.8×10^4
Eutrophication potential (EP)	kg PO ₄ eq	5×10^{-6}	2.5×10^4
Ozone depletion potential (ODP)	kg CFC-11 eq	3×10^{-11}	1.6×10^{-1}
Abiotic depletion potential, non-fossil resources (ADPE)	kg Sb eq	2×10^{-8}	8.6×10^1
Abiotic depletion potential, fossil-based resources (ADPM)	MJ	5.2×10^{-2}	2.7×10^8
Photochemical ozone creation potential (POCP)	kg C ₂ H ₄ eq	9×10^{-7}	4.5×10^3

How each component of the construction contributes to the different environmental impact categories varies slightly. Table 5 lists the project components and their relative contribution to each impact category, based on the inventory described in Section 2.2.4 and Appendix A. Fuel and energy and building structures are based on primary data from the operating company, equipment on primary data from the turbine manufacturer and assumptions based on previously conducted LHP LCAs [44,47], and transport are based on primary data from the operating company and assumptions based on previously conducted LHP LCAs [44,47].

Table 5. Percentage contribution of construction-related components to total life cycle environmental impacts across selected impact categories for the studied SHP system.

Impact Category	Fuel and Energy	Building Structures	Equipment	Transport
GWP	8.8%	85.5%	4.6%	1.1%
AP	13.8%	77.6%	6.4%	2.3%
EP	12.8%	77.5%	8.4%	1.3%
ODP	16.7%	70.8%	9.8%	2.7%
ADPE	0.7%	34.9%	63.5%	0.7%
ADPM	9.8%	86.1%	2.9%	1.3%
POCP	8.1%	81.9%	8.3%	1.6%

The construction of buildings, dams, and canals contributes the most to all impact categories, except for ADPE, where the manufacturing of equipment bears most of the impact associated with the category. The impact of building structures per category ranges from 34.9 to 86.1% due mainly to the use of GRP for the pressure shaft, as well as cement and reinforcing steel. Fuel and energy usage are the second highest contributors to AP, EP, and ADPM. The transportation of materials to the construction site contributes the least, of the included life cycle stages, to all impact categories (see Table 5).

3.2. Hot Spot Analysis

The hot spot analysis applied is twofold: first, assessing each component of the SHP, and secondly, individual materials used for construction. As information on how fuel and energy use was divided between components of the SHP was not available in the primary data, these processes are excluded from the analysis of HP components but included when assessing the material processes (Figure 2). The hotspot analysis is based on the construction phase as no inputs were used for the operation phase in modelling the SHP (see Section 2.2.3). Figure 1 presents the results of the contribution of each component of the SHP based on the inventory data obtained from the operating company and previously

conducted LCAs [44,47]. Further description of the data can be found in Section 2.2.4 and Appendix A.

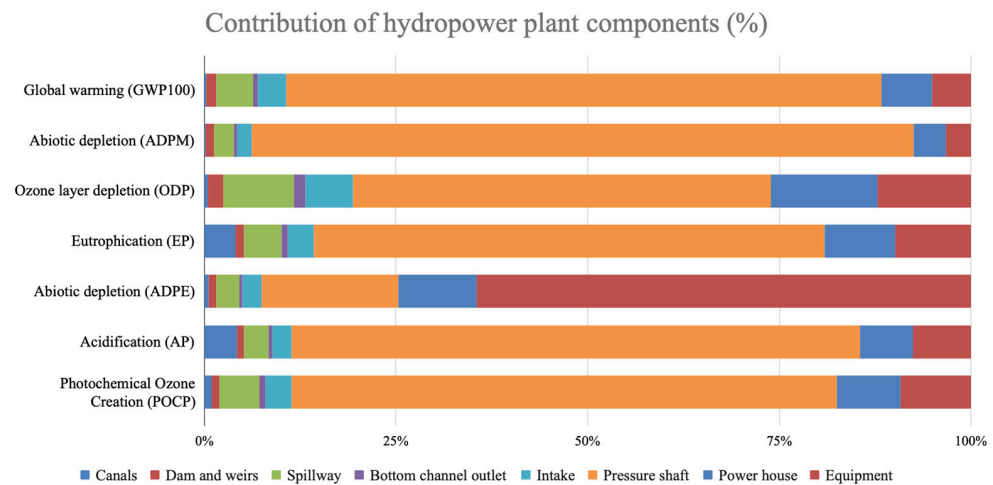


Figure 2. Percentage contribution of individual hydropower components (e.g., dam and weirs, pressure shaft, powerhouse, and equipment) to each life cycle impact category for the studied SHP. Values represent the relative contribution of each component to the total impact in each impact category per functional unit (1 kWh).

The results indicate that of the individual components of the SHP, the pressure shaft is responsible for the highest relative contribution to all impact categories, except ADPE. The pressure shaft, e.g., contributes 77.6% to GWP and 86.4% to ADPM. The equipment is responsible for the highest impacts to ADPE, or 64.5%.

As seen in Figure 2, the GRP, used in the pressure shaft, is responsible for the highest contribution to all impact categories, except for ADPE. For example, the GRP contributes 67.56% of the impacts to GWP and 61.1% to the POCP. Other identified hot spots are cement, which, e.g., accounted for the second highest impacts (11.72%) to the GWP, used in concrete for building structures, as well as in grout for rock reinforcement; copper, which is used in the equipment (generators, transformers, cables, etc.), contributing 59.2% to the category of ADPE; reinforcing steel; and diesel oil, used for the machinery during construction.

3.3. Sensitivity Analysis

The scenarios presented in Section 2.3 were assessed with a sensitivity analysis. The results are based on primary data from the operating company and manufacturers and assumptions made from Icelandic LHP LCAs [44,47]. Description of the life cycle inventory used for modelling the SHP can be found in Sections 2.2.4 and 2.3 and Appendix A.

3.3.1. Extended Lifetime

The results indicate that an extended lifetime is associated with a reduction in impacts to all categories, except for ADPE, which remains the same. The GWP of a 100-year lifetime is 3 g CO₂ eq/kWh, compared to 4 g CO₂ eq/kWh for a 60-year lifetime. The relative decrease in impacts ranges from 0% (ADPE) to 50% (AP). Table 6 presents the total impacts per category of 60 years compared to 100 years.

The results suggest that the construction phase is responsible for over 84% of the impacts to all categories, except for ADPE. This is due to the considerable amounts of fuel and materials used for the construction of the SHP. For ADPE, the construction phase is responsible for 56.8% of the impact compared to a 43.2% impact from the operation phase, which can potentially be explained by the benefits of recycling copper, used in the equipment, being excluded from the study. Figure 3 presents the relative contribution of

the construction phase, compared to the operation phase, as the lifetime is extended to 100 years. The results are based on the inventory described in Section 2.2.4 and Appendix A.

Table 6. Total environmental impacts per impact category for the studied SHP over a 60-year lifetime compared to a 100-year lifetime scenario.

Impact Category	Reference Unit	60 Years	100 Years	Decrease (%)
GWP	kg CO ₂ eq	4×10^{-3}	3×10^{-3}	25%
AP	kg SO ₂ eq	2×10^{-5}	1×10^{-5}	50%
EP	kg PO ₄ eq	5×10^{-6}	4×10^{-6}	20%
ODP	kg CFC-11eq	3×10^{-11}	2×10^{-11}	33%
ADPE	kg Sb eq	2×10^{-8}	2×10^{-8}	0%
ADPM	MJ	5.2×10^{-2}	3.4×10^{-2}	35%
POCP	kg C ₂ H ₄ eq	9×10^{-7}	6×10^{-7}	33%

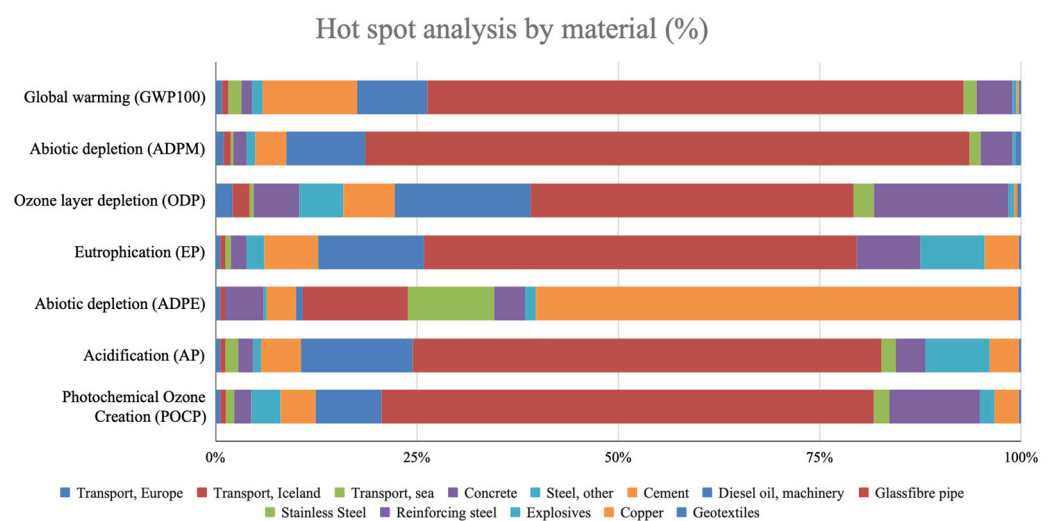


Figure 3. Hot spot analysis showing the percentage contribution of materials and material transport to each life cycle impact category for the studied SHP system.

3.3.2. Concrete Main Dam

The results of the sensitivity analysis for this scenario, with the main dam made of concrete instead of earth materials, show an increase in all impact categories, where the main dam is then responsible for most of the impacts. As an example, for the GWP category, the main dam contributes 0.011 kg/CO₂ eq of total impact, or about 92%. Table 7 presents the results, compared to results of an earth fill dam, based on the inventory described in Sections 2.2.4 and 2.3 and Appendix A.

Table 7. Total environmental impacts per impact category for the studied SHP, comparing earth fill dam (base case) and the concrete dam scenario.

Impact Category	Reference Unit	Base Case Scenario	Concrete Dam Scenario	Increase (%)
GWP	kg CO ₂ eq	4×10^{-3}	1.2×10^{-2}	200%
AP	kg SO ₂ eq	2×10^{-5}	4×10^{-5}	100%
EP	kg PO ₄ eq	5×10^{-6}	1×10^{-5}	100%
ODP	kg CFC-11eq	3×10^{-11}	2×10^{-10}	567%
ADPE	kg Sb eq	2×10^{-8}	4×10^{-8}	100%
ADPM	MJ	5.2×10^{-2}	8.9×10^{-2}	71.2%
POCP	kg C ₂ H ₄ eq	9×10^{-7}	3×10^{-6}	233%

Note that in the base case results, the potential emissions of different earth fill materials were not accounted for as no data was available. Only the excavation processes (i.e., fuel use and explosives) and building materials (e.g., steel, concrete) were accounted for. This could potentially explain the increase in impacts for some impact categories.

3.3.3. Reduced Capacity Factor

The CF of the case project was calculated using Equation (1), presented in Section 2.3. According to the calculations, the CF is considerably higher than what is most often expressed in the literature. The calculations can be found in Appendix B.

The results suggest that with reduced CF, the environmental impacts increase for most assessed impact categories. Table 8 presents the results of reducing the CF of the system, based on inventory data described in Section 2.2.4.

Table 8. Total environmental impacts per impact category, comparing the base case capacity factor (CF) with the scenarios of 70% and 50% capacity factors.

Impact Category	Reference Unit	Base Case CF	70% CF	50% CF
GWP	kg CO ₂ eq	4×10^{-3}	6×10^{-3}	9×10^{-3}
AP	kg SO ₂ eq	2×10^{-5}	3×10^{-5}	4×10^{-4}
EP	kg PO ₄ eq	5×10^{-6}	7×10^{-6}	1×10^{-5}
ODP	kg CFC-11eq	3×10^{-11}	4×10^{-11}	6×10^{-11}
ADPE	kg Sb eq	2×10^{-8}	2×10^{-8}	3×10^{-8}
ADPM	MJ	5.2×10^{-2}	6.4×10^{-2}	10.4×10^{-1}
POCP	kg C ₂ H ₄ eq	9×10^{-7}	1×10^{-6}	2×10^{-6}

When the CF is reduced to 70%, the results show increased impacts to all categories, except for ADPE, which remains the same as for the base case. The total impacts of GWP increase by 50%, AP by 54%, EP by 42%, ODP by 46%, and ADPM and POCP by 44%. For a CF of 50%, the results indicate an increase in impacts for all selected impact categories. The total impacts to GWP increased by 102%, AP and EP by 101%, ODP by 104%, ADPE by 101%, ADPM by 102%, and POCP by 101%.

3.4. Comparison to Larger Hydropower Plants in Iceland

The results from the sensitivity analysis for an extended lifetime to 100 years were used to compare the SHP with four LHPs with storage in Iceland. The functional unit for these four LCAs is defined as 1 kWh of electricity generated from the power plants over a lifetime of 100 years. The impact categories used in these assessments are the same as for this study, and the LCIA method used is CML. Table 9 presents the comparison of GWP of all HP plants [44–47].

Table 9. Comparison of global warming potential (GWP) of the case project and the larger Icelandic hydropower plants, with and without reservoir emissions.

Hydropower Plant	Installed Capacity (MW)	Lifetime	GWP (g CO ₂ eq/kWh)	GWP w/o Reservoir Emissions (g CO ₂ eq/kWh)
Blöndustöð [46]	150	100	20.4	0.85
Búðarhalsstöð [44]	95	100	1.5	1
Búrfellsstöð II [47]	100	100	0.5	0.498
Fljótsdalsstöð [45]	690	100	1.2	0.9
The studied system	9.9	100	3	3

The LHPs in the comparison includes estimated reservoir emissions. As reservoir emissions can contribute considerably to the GWP (e.g., 96% of the GWP of Blöndustöð is associated with reservoir emissions), an attempt was made to compare the power plants excluding reservoir emissions [46]. When excluding reservoir emissions, the case project had the highest GWP. Figure 4 presents these findings. The case project did not include reservoir emission estimations in the base case results; thus, the GWP is presented as the same number in the column excluding reservoir emissions.

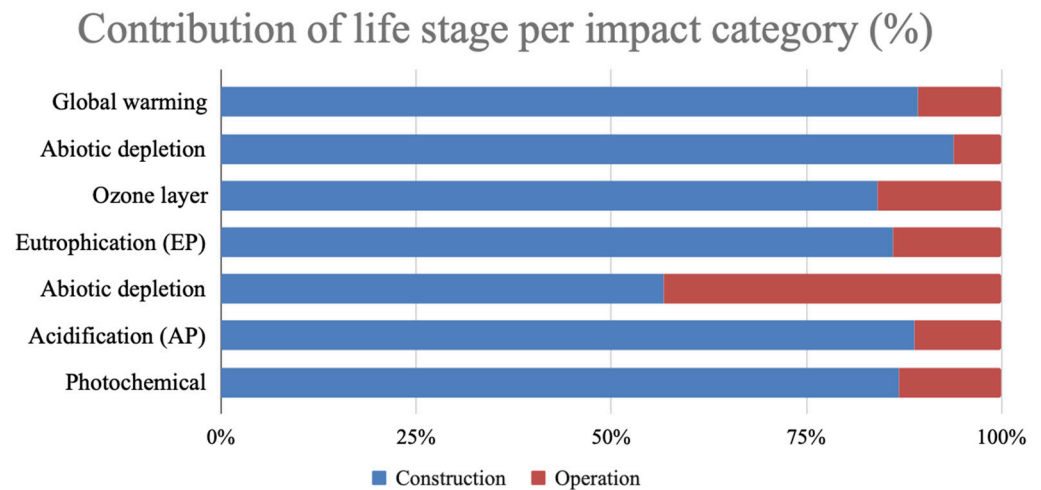


Figure 4. Relative contribution of construction and operation phases to total life cycle environmental impacts over a 100-year lifetime (%).

The comparison results are obtained from the life cycle inventory described in Section 2.2.4 and Appendix A and from the LCA reports of the LHPs [44–47]. When comparing the HPs across all assessed environmental impact categories, the results indicate that the case project is responsible for the highest or second-highest contribution to all impact categories. The SHP is responsible for the highest impacts to ADPM, ODP, and ADPE. Blöndustöð contributes the highest impacts to GWP, AP, EP, and POCP [46]. Búðarhálsstöð is responsible for the second highest impacts to ADPE and the second lowest impacts to EP and ADPM [44]. The SHP is responsible for the second highest impacts to EP. The comparison, by all assessed impact categories, can be found in Appendix B, Table A10.

3.5. Reservoir Emissions

Reservoir emissions are excluded from the system boundaries of the present study but were estimated separately to provide an indication of their potential magnitude. Reservoir-related emissions are highly site-specific and can vary substantially depending on factors such as vegetation, soil, temperature and depth of the reservoir, amount of oxygen in the water, and how much carbon was stored in the land pre-flooding [13]. The estimated reservoir emissions suggest that the GWP of the reservoir is about 1.53 g CO₂ eq per kWh generated. This means that, if included in the results of the SHP, the GWP of generating 1 kWh of electricity over 60 years would be 5.53 g CO₂ eq (see Appendix B, Table A10) instead of 4 g CO₂ eq. Using the same calculations for the results of the sensitivity analysis for 100 years, the total GWP of 100 years would be 3.91 g CO₂ eq. The method and calculations are provided in Appendix B.

4. Discussion

4.1. Base Case Results and Hot Spot Analysis

The GWP is often the impact category of focus in energy LCAs [19]. The GWP deals with emissions from human activity that contribute to climate change, threatening both the health of humans and the health of the planet's ecosystems [50]. Generally, renewable energy sources, such as HP, are considered to emit considerably lower amounts of GHG into the atmosphere compared to fossil fuels and are thus believed to be a preferable alternative to the traditional fossil-based energy sources.

The results of this study show that the GWP of generating 1 kWh of electricity from the 9.9 MW SHP over its 60-year lifetime is 4 g CO₂ eq. Most of these emissions are associated with the manufacturing of materials for the building structures or 85.5% of the total impact. These results are in line with the findings of Turconi et al. [25], where most of the impacts from HP are associated with the infrastructure. The hot spot analysis showed that the pressure shaft contributed most to this impact category, or 77.6%. The pressure pipe is mainly made of GRP, which contributed 67.56% to the GWP. The pressure pipe is about 1693 m long, and the GRP part alone weighs about 1779 tonnes, explaining the high contribution to the overall impact. Fuel and energy use are the second highest contributors to the GWP, or 8.73%. This is mainly because of the use of diesel oil for machinery during construction. No data was available on how the fuel use was distributed between the different life cycle stages, so this accounts for total fuel use during the construction phase, including excavation (not blasting) and transportation of personnel to and from the construction site (although this process is considerably small, accounting for less than 0.5% of the total impact). The equipment, then, accounts for 5.1% of the total GWP, and transportation of building materials accounts for 0.78% to 1.59%.

The hot spot analysis suggests that cement, GRP, copper, reinforcing steel and diesel oil are the main hot spots. The high amounts of cement used in concrete have been linked to concrete being a hot spot in HP LCAs [25,30,54,55]. Cement contributed the second-highest impacts to GWP after GRP, or 11.72%. Cement was used for concrete and grout in building structures and for rock reinforcements. The impact of the GRP is significantly higher than all other materials, except for copper (used in the equipment), which is responsible for 59.92% of ADPE impacts. Ribeiro and da Silva [27] define copper as one of the main materials to consider in HP LCAs, and Geller et al. [30] list copper as one of the hot spots of their study. The impact category of ADPE describes the relationship between the ultimate reserves and rates of extraction. Copper is a limited resource, increasingly used in various sectors, explaining the high influence of copper on ADPE [60]. Reinforcing steel was used for reinforcement for most components of the SHP, as well as the rock bolts. The contribution of reinforced steel to POCP was the second highest after the GRP pipe, accounting for 11.24%. For the impact category of ADPM, reinforcing steel is responsible for the third highest impact (after GRP and diesel oil), accounting for 16.68% of the total impact of the category. Diesel oil, used for machinery, ranked second or third for all impact categories measured. The highest contribution of diesel oil was to the impact category of ozone layer depletion (ODP), or 16.87%.

As cement and reinforcing steel are identified as major contributors to several impact categories, the selection of lower-carbon alternatives might offer opportunities for further reducing the environmental impacts of SHP construction. This has been demonstrated, for example, by Liu et al. and Zhang et al., where substituting concrete with earth-rock fill in dams significantly lowered GHG emissions [54,55]. Other alternatives could include, e.g., recycled steel where technically feasible. However, the environmental substitutions were not assessed in the study and therefore cannot be quantified. Evaluating the influence of

alternative material choices on the life cycle impacts of SHPs could represent an important area for future research.

4.2. Sensitivity Analysis

Three different scenarios were explored by performing a sensitivity analysis: extended lifetime to 100 years, concrete dam, and reduced capacity factor.

The results show that extended lifetime reduces impacts of all assessed impact categories, except for ADPE. The GWP was reduced by a total of 1 g CO₂ eq per kWh. This might be linked to the increasing energy production, as with more energy generated, less material is needed per kWh. Most studies agree that the manufacturing and construction phase is mainly responsible for the lifetime environmental impacts of HP, which is associated with the considerable amounts of fuel and material used for the construction [5,27,30,31]. The results of the sensitivity analysis support these statements, indicating that the construction phase is responsible for over 84% of the impacts to all selected categories, except for the ADPE.

Concrete has been identified as a potential hot spot due to its ample use of cement. Therefore, a sensitivity analysis was used to explore the potential changes in impacts if concrete is used instead of earth fill [54,55]. The results indicate a considerable increase for all assessed impact categories. The baseline results show a GWP of 4 g CO₂ for each kWh of electricity produced, while the sensitivity results indicate a GWP of 12 g CO₂ eq per kWh, or a 200% increase. The results also suggest a significant increase in impacts for all other impact categories, ranging from 71.2% for ADPM to 567% for ODP. These results highlight the importance of material selection for dams. Earth filling, especially when it is excavated material from the construction of canals or from the riverbed, such as was done for the SHP, can potentially reduce the overall impacts of the HP development. Similar findings have been found in the literature. Zhang et al. [54] compared the carbon footprint of earth rock-fill dams to concrete gravity dams using hybrid LCA. Their results indicate a 24.7% reduction in CO₂ emissions when earth rock-fillings are used instead of conventional concrete [54]. Liu et al. [55] compared rock-filled concrete and conventional concrete using LCA and found that rock-filled concrete reduced CO₂ emissions by 64% and the total energy use by 55%. Their results additionally indicate a reduction for all life cycle stages of the dam when rock-filled concrete was used [55]. The use of excavated material from the construction site could be expected to reduce costs associated with material production, transportation and construction. The focus of this study was to assess the environmental performance of the SHP using LCA. However, Life Cycle Costing (LCC) would be a logical next step for further research, especially from a practical operation perspective, providing further insight into the trade-offs and potential co-benefits associated with alternative dam construction approaches.

RoR HPs are sometimes regarded as the most viable utilization of HP [61]. CFs vary widely across hydropower systems and depend primarily on plant type, hydrological conditions, and operational strategy. RoR systems are particularly sensitive to seasonal flow variability due to limited storage capacity [59]. In this study, a capacity factor range of 50–70% is used as a reference for small hydropower systems [57]. The CF is a measure of how efficiently a system is being operated over a certain period, expressed as the difference between the actual energy generation and the potential total output of the power plant at full capacity [57]. Thus, it can be expected that a reduction in the CF would increase the impact per kWh as less energy is being generated over the period. The results of the sensitivity analysis suggest that with lower CF, the total environmental impacts to all categories increase relative to the reduction. For a CF of 70%, the results indicated an increase in total impacts from 42% to 54% for all categories except ADPE. For a CF of

50%, the increase in total environmental impacts to all categories was over 100%, with the highest increase of 104% to the ODP. The sensitivity analysis for the reduction in CF was based on the average annual electricity generation for the past two years, or 88,265 MWh. However, a 9.9 MW SHP operating with a CF of 100% would generate 86,720 MWh annually. This discrepancy in generated electricity arises because the case project's physical installed capacity, approximately 10.4 MW under favourable conditions, is greater than its registered and operative capacity of 9.9 MW [48]. Consequently, annual generation can exceed the theoretical output derived from the registered capacity, which was used as the basis of this study. Additionally, according to the plant operator, the SHP has been operating at near full capacity for the past few years, due to high flow rates and negligible downtime [48]. In general, several factors can affect the CF of HP systems, such as flow rate and hydraulic conditions, the power and efficiency of the turbines, and downtime due to, e.g., maintenance [57,58]. The sensitivity analysis demonstrates that the SHP is particularly sensitive to a reduction in CF, highlighting the importance of water availability, selection of turbines, and proper maintenance. From an operational perspective, these findings suggest that maintenance scheduling during periods of lower water availability may help maintain a high CF while avoiding additional environmental impacts.

4.3. Comparing Small and Large Hydropower in Iceland

There is no general agreement in the literature on whether the environmental impacts from SHP or LHP are greater [1,19,21,23,25,27]. When assessing and comparing the environmental impacts of using LCA, the results also vary. Some studies have suggested that SHPs have a lower GWP than LHPs that utilize a reservoir [23,25]. Other studies suggest that SHPs generally will have worse environmental performance, due to economies of scale—i.e., per unit of energy produced, SHPs will have greater environmental impacts [5,27].

The results of this study indicate that compared to the LHP assessed, the overall environmental performance of the SHP is worse per functional unit—the case project had the highest or second-highest environmental impacts of all impact categories.

The 9.9 MW hydropower plant had the second-highest GWP. The GWP of Blöndustöð was higher, but about 96% of it is associated with GHG emissions from the reservoir [46]. Impacts to the GWP of the other reservoirs were less, contributing 1% (Búrfellsstöð), 12% (Búðarhálstöð), and 27% (Fljótsdalsstöð), respectively [44,45,47]. Reservoir emissions depend largely upon the site-specific qualities of the land pre-impoundment (i.e., vegetative cover and carbon content of the land flooded), explaining the variations in the relative contribution to GWP. When reservoir emissions were excluded, the SHP had the highest GWP of all systems. These findings indicate the importance of including reservoir emissions in HP LCA, as their exclusion could risk underestimating the environmental impacts associated with the development, as well as overstating its positive climate impacts. The higher impacts of the SHP can be explained by economies of scale. The SHP generates less energy over the lifetime of 100 years, compared to the LHP, and thus per unit of generated energy (kWh), the material consumption is higher for the SHP.

The comparison with Icelandic LHP LCAs highlights that the environmental performance of SHP is not inherently lower than that of LHP but is strongly influenced by system design, material selection, and operational assumptions. In particular, construction materials (notably GRP, concrete, and steel) dominate environmental impacts, while results are highly sensitive to capacity factor and lifetime assumptions. The inclusion of indicative reservoir emission estimates further shows that even small RoR systems may contribute additional impacts if such emissions are considered, which is often not the case in SHP LCAs.

4.4. Limitations to the Study

4.4.1. Functional Unit and System Boundary Limitations

The functional unit of 1 kWh was based on the annual average electricity production of the SHP, consistent with conventional attributional LCA practice in which electricity is treated as a homogeneous product. This is a common practice in HP LCAs, such as the comparison LCAs used in this study [44–47]. Consequently, the study does not account for, e.g., temporal variations in generation. Addressing these effects would require a consequential or time-dependent LCA framework, which was beyond the scope of this study.

This study focuses mainly on the manufacturing and construction phase of the SHP. The operation phase was included in the system boundaries, but due to the specific features of the SHP, no inputs were used for modelling this phase (see Section 2.3 System Boundaries). For the modelling of the scenario of the extended lifetime, assessed with the sensitivity analysis and used for comparison with the LHPs, inputs for maintenance of building structures and replacement of equipment were used for modelling the operation phase. Thus, the operation phase was included in the system boundaries. Reservoir emissions were not included in the modelling, but estimations based on an Icelandic-specific method [13] were addressed separately for indicative purposes (see Section 3.5). This introduces some uncertainty into the overall results, particularly regarding upstream and site-specific emissions.

4.4.2. Data and Modelling Limitations

Although primary data was in general comprehensive, some components and processes were not included. Additionally, for some processes, the primary data lacked consistency in presentation, e.g., for values and units of certain materials. This led to the exclusion of some preconstruction processes (e.g., road work, facility creation), as well as building materials (e.g., painting, insulation, formwork) and electric systems (e.g., lighting, security systems, air ventilation). Additionally, the bill of quantities and explosives reports for the construction included the fuel and the explosives used for excavation, while the excavated rock was reused as filling material for the dam and weirs. Data on any additional on-site processing of the excavated material (e.g., crushing or screening) were not available and were therefore not included in the study. If such processes occurred, their exclusion may have resulted in an underestimation of the environmental impacts. Assessing and quantifying the material relating to these processes would have been impossible within the time frame of the study. Moreover, these processes do not directly relate to energy generation and are usually excluded from HP LCAs [26,30,31]. The exclusion of these inputs to the modelling of the case project could result in an underestimation of the total environmental impacts of the SHP. Generally, a materiality threshold of 1%, applied to the GWP indicator, has been recommended for HP LCAs [62]. Gallagher et al. [62] note that the materiality threshold of 1% applied to the GWP indicator alone might not capture the total environmental impact of the system. Rather, they recommend a materiality threshold of 0.2–0.5% to ensure the representation of at least 95% of the environmental burdens associated with HP development [62]. However, this could not be determined within the time frame of the study.

Where data were lacking related to equipment necessary for generating electricity and directly related to the functional unit, inventory from the comparison LCA reports was downscaled to represent the SHP. The inventory was scaled per MW of installed capacity, but as HP equipment varies greatly and depends on site- and technical-specific conditions, this will not accurately represent the SHP. It could, however, provide some insight into the potential material consumption and related environmental impacts.

Similarly, the maintenance processes used in the 100-year lifetime scenario were assumed to be the same as those for Búrfellsstöð II, as no primary maintenance data were available for the SHP and published maintenance inventories for hydropower plants are limited and inconsistent [26,30,31]. Consequently, the use of maintenance inputs derived from Búrfellsstöð II was considered a reasonable approximation for the present assessment [47]. However, this assumption introduces uncertainty, as RoR systems may experience different maintenance requirements and wear mechanisms than large reservoir-based hydropower plants. Future studies could improve available inventories by incorporating site-specific maintenance records and replacement schedules where available.

Limitations relating to the modelling software and database are several. Data from the ecoinvent database are not always representable for the system assessed. In some cases, the inputs are based on averages from several countries, and location-specific data is sometimes not available. Furthermore, sometimes data is simply not available in the database. To best represent the studied system, some inputs used from the ecoinvent database were modified to reflect the inventory.

4.4.3. Comparison Limitations

Due to a lack of primary data, reservoir emissions were not included in the SHP assessment, and therefore not in the comparison with LHP studies. In addition, several background processes included in the LHP LCAs were not available for the SHP, e.g., reservoir emissions and recycling processes [13,44–47]. These differences introduce uncertainty into the comparison and may lead to an underestimation of the environmental impacts of the SHP. At the time of data collection for this study, the available information on the LHPs was limited to non-peer-reviewed reports. These have since been consolidated into a single peer-reviewed publication [43]. Similarly, direct comparison with comparable European SHPs was not possible due to the study timeframe and the limited availability of comparable peer-reviewed LCAs. Such comparisons would provide valuable context and represent an important direction for future research. Furthermore, as the study is based on a single SHP, it does not allow for general conclusions regarding whether the environmental impacts of LHP or SHP are higher. The results should therefore be interpreted as site-specific.

4.4.4. Generalisability Limitations

The results of this study are based on a single SHP case and therefore reflect site-specific design, operational, and hydrological conditions. Furthermore, the SHP is an RoR system, and the results are not directly representative of reservoir-based LHPs. While the quantitative results are not directly transferable to other HPs, the methodological approach and the observed sensitivity of the system to variations in CF are expected to be applicable to SHPs with similar characteristics. In particular, the findings highlight the importance of water availability, turbine selection, and operational strategy in determining system performance.

4.5. Environmental Impact Assessments in Iceland

Under current Icelandic laws, all major energy development is subject to the Master Plan of Nature Protection and Energy Utilization, which is regulated by Act no. 48/2011, and also requires an EIA [40,41]. For HP, this means that all HP developments of 10 MW are subject to the Master Plan. The Master Plan is a strategic, legally established framework that evaluates and ranks all major energy options before they proceed through the EIA and permitting process. Iceland is perhaps the only country that has established such an extensive framework as the Master Plan on a national level [39]. In contrast, SHP

development is not regulated by Icelandic law, apart from having a notification obligation to the National Planning Agency.

While the National Planning Agency is responsible for overseeing EIAs, the project owners are responsible for their execution in accordance with relevant procedures [63,64]. The National Planning Agency can, if necessary, impose conditions and countermeasures to which the project owners should submit [64]. Although laws on EIA have been established and are mandatory for LHP, the evaluation of the National Planning Agency is more advisory than obligatory. Even if the results of an EIA are significantly negative, the project owners can still apply for necessary permits and continue with the development. A notable example of this is the approval of the Kárahnjúkar HP plant, which, despite being rejected by the National Planning Agency because of its significant and irreversible environmental impacts, was granted operational permission [65]. As Cook et al. [65] note, this might suggest weaknesses in the regulatory and decision-making processes regarding EIA and energy utilization.

The procedures relating to EIA and the Master Plan can be lengthy. The Master Plan should be re-evaluated at least every 4 years [40], but this has often been delayed due to parliamentary processes, which results in postponement of developments included in the framework. This poses significant uncertainty for project owners in terms of time and economic costs, as often during this early stage, capital has already been invested [65]. The increasing development of SHP in Iceland could imply that project owners are deliberately scaling their projects just below the 10 MW limit, so as to forgo the Master Plan. As development of SHP is not subject to the parliamentary decision process, the regulatory processes of SHP development are often less time-consuming, even if the National Planning Agency requires an EIA (The National Planning Agency, personal communication, 4 April 2024) [66].

SHPs are generally only required to notify the National Planning Agency and apply for relevant permits, such as power plant permits from the Icelandic Environment and Energy Agency, and construction permits from the municipalities. Permitted electricity generation is typically limited to the installed capacity approved in the planning assessment, meaning that a 9.9 MW plant cannot exceed its designated installed capacity [66]. Although EIAs are not legally required for SHP, they are increasingly requested for projects close to the 10 MW threshold [66].

4.6. LCA as an Environmental Impact Assessment Tool

In recent years, LCA has gained increasing popularity as a decision-making tool in product development, policy making, and energy utilization [21]. In the energy sector, LCA has been used to assess environmental impacts of various projects, compare technologies and options, and evaluate the effects of different construction materials [5,23–26,54,55].

The EIA of hydropower development varies considerably, depending on regional policies, albeit a general requirement is that they should be based on environmental research [67]. LCA offers several advantages that could complement and potentially improve the traditional EIA process of energy development. One of these advantages of LCA is the inclusion of the whole life cycle, accounting for environmental impacts from cradle to grave, identifying the life stage contributing most of the impacts, considering both regional and global impacts [68,69]. HP LCAs, however, are usually cradle-to-gate, where the end-of-life phase is left out as the dismantling of HPs is not a common practice, and rather, it is assumed that because of proper maintenance, the HP will be fully operational at the end of its life [5,27]. Additionally, LCAs provide the ability to compare systems and alternative options, in a quantitative manner, using environmental indicators (e.g., the global warming potential, ozone depletion potential) [69]. Additionally, because of

the comprehensive data inclusion, LCA can identify potential hot spots, which can be of significance for decision-making purposes.

LCAs cannot, however, be used as a stand-alone procedure for EIA because of the limitations imposed by the method. Several major aspects of hydropower development, such as impacts on ecosystems, biodiversity, and wildlife, are generally excluded from the LCIA as they are not readily assessed or are even impossible to assess using LCA [27,69–71]. To assess these factors, environmental impact assessments are important, even crucial, for all hydropower development.

5. Conclusions

The aim of this study was to address gaps in the current literature on SHP, particularly the limited number of peer-reviewed LCAs, inconsistencies in SHP definitions, and the scarcity of case studies from Iceland. To this end, a life cycle assessment of a 9.9 MW RoR SHP plant in Iceland was conducted using the commonly applied European definition of SHP (<10 MW), thereby contributing a peer-reviewed Icelandic case study and improving the empirical basis for evaluating SHP. The results represent model-based indicators rather than absolute environmental impacts and were compared with existing LCA results for LHP in Iceland.

The results show that the studied SHP exhibited higher life cycle environmental impacts than the compared LHP systems across most assessed impact categories. The estimated GWP of producing 1 kWh of electricity over a 60-year lifetime is 4 g CO₂ eq per kWh, decreasing to 3 g CO₂ eq per kWh in the 100-year sensitivity scenario, although the base case results may underestimate impacts due to lack of data availability. The hot spot analysis identified construction materials (i.e., GRP, concrete and steel) and fuel as the dominant contributors to most impact categories, while the sensitivity analysis demonstrated that plant lifetime, capacity factor and dam construction material can significantly influence the results. Indicative estimates further showed that inclusion of reservoir emissions could increase the GWP of the studied SHP, highlighting the importance of considering reservoir-related emissions where reliable site-specific data are available. Overall, comparison with Icelandic LHP LCAs suggests that the studied SHP generally exhibited higher life cycle environmental impacts per functional unit than the compared LHP systems. While SHP contributes to renewable electricity generation and may avoid some of the environmental burdens associated with large reservoir-based systems, its increasing relevance in energy planning is partly linked to the limited availability of remaining feasible large hydropower sites [12,14]. However, the results of this case study indicate that SHP can still be associated with considerable life cycle environmental impacts depending on design, material use, and site-specific conditions.

The findings support the use of LCA as a complement to EIA by providing information on life cycle environmental burdens that are not typically captured in conventional EIAs, including life cycle GWP and potential reservoir emissions [19,69]. The results also suggest that the environmental performance of SHP should not be assumed solely on the basis of installed capacity and that capacity-related regulatory thresholds may influence project design. However, any adjustment of EIA thresholds should carefully consider potential unintended incentives, such as optimizing projects to remain below regulatory limits. By providing a peer-reviewed Icelandic case study using a clearly defined SHP threshold and transparent LCA methodology, this study contributes to improving the evidence base for SHP assessment. Nevertheless, additional case-specific LCAs are needed to strengthen the robustness and comparability of future studies. Extensive research efforts into SHP would strengthen both LCA and EIA applications, providing more robust, location-specific environmental data.

The transition to renewable energy sources is essential to reach global climate goals, where, to date, HP development plays a significant role and will likely continue to do so in the coming years [1–4]. The development of SHP could prove essential to meet future energy demand, especially as most of the feasible sites for LHP have been utilized. However, further research and comparison of the environmental impacts and risks associated with HP development is crucial to ensure its sustainable development, especially when considering future water availability, as this is one of the major risks and limitations associated with HP development as temperatures continue to rise [4,19].

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Assessment
SHP	Small Hydropower
LHP	Large Hydropower
HP	Hydropower
RoR	Run-of-river
EIA	Environmental Impact Assessment
LCIA	Life Cycle Impact Assessment
GWP	Global Warming Potential
AP	Acidification Potential
EP	Eutrophication Potential
ODP	Ozone Depletion Potential
ADPE	Abiotic Depletion Potential (non-fossil resources)
ADPM	Abiotic Depletion Potential (fossil-based resources)
POCP	Photochemical Ozone Creation Potential
eq	Equivalent

Appendix A

Appendix A lists the life cycle inventory and environmental impact categories.

Appendix A.1. Construction Phase

Data on earth works and building materials were gathered from the bill of quantities. The bill of quantities is segmented into several project components, wherein the constituents of each component and material quantities are listed. Table A1 lists the project components, as they appear in the bill of quantities.

Table A1. Project components, as listed in the bill of quantities.

Project Component	Constituent
Canals	Irrigation canal, headrace canal, bottom channel canal, tailrace canal.
Dams and weirs	Main dam, weir I, weir II, weir III.
Spillway and retaining wall	
Bottom channel outlet	
Intake	
Pressure shaft	
Powerhouse	

For each of these components, the key figures for construction and building materials were gathered. Table A2 presents the key figures for material and processes of the construction of canals, dams, and weirs.

Table A2. Key material and processes of the construction of canals, dams, and weirs as presented in the bill of quantities.

Building Material	Unit	Total Quantity	Quantity per kWh	Manufacturing Country
Excavated and blasted material	m ³	97,326.5	1.84×10^{-5} m ³ /kWh	Iceland
Earth fillings	m ³	123,243.5	2.33×10^{-5} m ³ /kWh	Iceland
Rock bolts	kg	22	4.15×10^{-9} kg/kWh	Norway
Concrete	m ³	445.8	8.42×10^{-8} m ³ /kWh	Iceland
Reinforcing steel (rebars)	kg	13,964	2.64×10^{-6} kg/kWh	Belarus
Cement for grout	kg	74,317	1.40×10^{-5} kg/kWh	Denmark
Admixture for grout	kg	2284	4.31×10^{-7} kg/kWh	Denmark
Stainless steel	kg	229	4.32×10^{-8} kg/kWh	Russia
Geotextile fabric	m ²	37,615	7.10×10^{-6} m ² /kWh	Netherlands
PE and PVC pipes	m	180	3.40×10^{-8} m/kWh	Italy

The building structures include the spillway and retaining wall, bottom channel outlet, intake, pressure shaft, and powerhouse. The list of key figures for the building structures and the country of manufacturing are presented in Table A3.

Table A3. Key material and processes for building structures, as presented in the bill of quantities.

Equipment	Unit	Total Quantity	Quantity p/kWh	Manufacturing Country
Excavated and blasted material	m ³	164,763.8	3.11×10^{-5} m ³ /kWh	Iceland
Earth fillings	m ³	130,180.5	2.45×10^{-5} m ³ /kWh	Iceland
Concrete	m ³	6921.6	1.31×10^{-6} m ³ /kWh	Iceland
Reinforcing steel	kg	476,140.5	8.99×10^{-5} kg/kWh	Belarus
Rock bolts	kg	9248.85	1.75×10^{-6} kg/kWh	Norway
Cement for grout	kg	79,309.5	1.50×10^{-5} kg/kWh	Denmark
Stainless steel	kg	3638.4	6.87×10^{-7} kg/kWh	Russia
Galvanized steel	kg	16,753.1	3.16×10^{-6} kg/kWh	Russia
Pressure pipe, stainless steel	kg	20,828	3.93×10^{-6} kg/kWh	Italy
Glass fibre pipe	t	1779.2		Spain
Geotextile fabric	m ²	26,380	3.36×10^{-7} kg/kWh	-
PE and PVC pipes	m	319	6.02×10^{-8} m/kWh	Italy
Corten steel	kg	1961.1	3.70×10^{-7} kg/kWh	Finland
Softwood	m ²	205	3.87×10^{-8} m ² /kWh	-

Appendix A.2. Blasting and the Use of Explosives

The figures for the use of explosives were gathered from a report on explosives from the operating company. The total excavated and blasted materials during the construction phase amounted to 262,090.3 m³; thereof, blasted rock was 40,579 m³. Blasting was used in the construction of all canals, as well as the spillway, bottom channel outlet, intake, pressure shaft, and powerhouse. The total amount of explosives used in the construction of the hydropower plant was 28,188 kg. Table A4 presents the amount of rock blasted and explosives used per project component, obtained from the explosives report.

Table A4. Amount of blasted rock and explosives used during the construction of the case project.

Project Component	Unit	Amount of Rock per Component	% of the Total	Explosives in kg per Component
Irrigation canal	m ³	4248	10.47%	2951.3 kg
Headrace canal	m ³	3119	7.69%	2167.7 kg
Bottom channel canal	m ³	1322	3.26%	918.9 kg
Tailrace canal	m ³	9481	23.36%	6584.7 kg
Spillway	m ³	428	1.05%	296.0 kg
Bottom channel outlet	m ³	555	1.37%	386.2 kg
Intake	m ³	707.2	1.74%	490.5 kg
Pressure shaft	m ³	12,379	30.51%	8600.2 kg
Powerhouse	m ³	8341	20.55%	5792.6 kg

Appendix A.3. Equipment

Primary data in the form of a technical guide provided the weight and material inputs for the turbines. No data was obtained for the manufacturing process of the turbines or other equipment, so only the material inputs are accounted for.

Two Francis turbines are operated in the power station, each weighing approximately 32.5 tonnes. Table A5 lists the components of the turbines and the total weights and materials.

Table A5. Turbine components, type and amount of material in kilograms, scaled to the functional unit of 1 kWh. Primary data from technical documents, obtained from the operating company.

Component	Unit	Quantity	Quantity p/kWh	Material
Runner	kg	4900	9.25×10^{-7}	Stainless steel
Spiral case	kg	30,000	5.66×10^{-6}	Unalloyed steel, hot rolled
Wicked gate mechanism	kg	13,330	2.52×10^{-6}	Stainless steel, unalloyed steel
Shaft sealing	kg	86	1.62×10^{-8}	unalloyed steel
Draft tube	kg	16,620	3.14×10^{-6}	unalloyed steel, hot rolled

No primary data was obtained for other equipment. Assumptions regarding the material inputs of the equipment were made based on existing LCAs of two larger Icelandic hydropower plants. The estimations are based on average material consumption per MW for each type of equipment [44,47].

Table A6 presents the average material consumption for the equipment of the two hydropower plants, scaled to 1 MW of installed capacity, and Table A7 presents the estimated material for the equipment for the 9.9 MW hydropower plant.

Table A6. Average material consumption of equipment per 1 MW of installed capacity.

Material	Unit	Generators	Governor	Electric System	Control System	Transformers	Cables	Turbine Inlet Valve
Steel	t	4.13	1.01	0.16	0.116	1.41	-	2.91
Copper	t	0.21	-	0.20	0.021	0.21	0.05	-
Aluminum	t	-	-	0.11	-	-	0.11	0.001
Bronze	t	-	-	-	-	-	-	0.005
Plastic	t	-	0.02	-	0.084	0.10	0.28	0.003
Lubricate oil	t	-	-	-	-	0.29	-	-
Epoxy/painting	t	0.05	-	-	-	0.002	-	0.009
Concrete	t	-	-	-	-	-	-	0.210
Other	t	0.04	-	0.17	0.002	0.23	-	-
Total	t	4.43	1.03	0.64	0.223	2.243	0.443	3.14

Adapted from Landsvirkjun [44,47].

Table A7. Estimated material consumption of equipment, scaled to 9.9 MW installed capacity.

Material	Unit	Generators	Governor	Electric System	Control System	Transformers	Cables	Turbine Inlet Valve
Steel	t	40.89	10	1.58	1.148	13.96	-	28.81
Copper	t	2.08	-	1.98	0.208	2.08	0.50	-
Aluminum	t	-	-	1.09	-	-	1.09	0.01
Bronze	t	-	-	-	-	-	-	0.0495
Plastic	t	-	0.20	-	0.832	0.99	2.77	0.03
Lubricate oil	t	-	-	-	-	2.87	-	-
Epoxy/painting	t	0.495	-	-	-	0.0198	-	0.0891
Concrete	t	-	-	-	-	-	-	2.079
Other	t	0.40	-	1.68	0.02	2.28	-	-
Total	t	43.86	10.2	6.33	2.208	22.2	4.36	31.07

Adapted from Landsvirkjun [44,47].

Appendix A.4. Fuel and Energy Use

The total fuel used for machinery during the construction was 576,814 L of diesel oil, but no information on how it was distributed between machinery or project components was available (head of construction, personal communication, 2 February 2024). Fuel use because of transportation of personnel was based on the bill of quantities. The travelling of personnel is estimated in kilometres (km) per vehicle. The estimated distance travelled for a passenger vehicle with less than five passenger capacity is 5000 km, and 1000 km for a passenger vehicle with more than five passenger capacity, or 6000 km in total. The electricity use during construction was approximately 100 kWh per month, in total 1800 kWh over the 18-month construction period [49].

Appendix A.5. Operation Phase

Estimates for the maintenance of materials during the operation phase are assumed to be the same proportion as for Búrfellsstöð II. According to this, the need for maintenance of steel is 6% of the total steel used for construction, 48% of concrete, and 14% of plastics [47]. Table A8 presents the estimated maintenance of building materials for the case project.

Table A8. Estimated amount of building materials used for maintenance.

Maintenance of Building Materials	Unit	Quantity	Quantity p/kWh
Steel	t	31.26	5.90×10^{-9}
Concrete	m ³	3536.35	6.68×10^{-7}
Plastics	t	3.46	6.53×10^{-10}

Adapted from Landsvirkjun [44,47].

Table A9. Title and description of environmental impact categories addressed in the study.

Impact Category Title and Abbreviation	Description	Expression of Results	Reference Unit
Global warming potential (GWP)	Potential global warming over a 100-year period. Deals with human-caused emissions that can increase radioactive forcing of the atmosphere.	Kilograms of greenhouse gas emissions to air.	kg CO ₂ eq
Acidification potential (AP)	Impacts of acidifying pollutants on, e.g., groundwater, soil, surface water and ecosystems.	Kilograms of acidifying substances to air.	kg SO ₂ eq
Eutrophication potential (EP)	Impacts of excess micronutrient concentration in terrestrial and aquatic ecosystems. Major consideration here is the build-up of nitrogen (N) and phosphorus (P).	Kilograms of eutrophication emissions to air, soil or water.	kg PO ₄ eq
Ozone depletion potential (ODP)	Impacts to the thinning of the stratospheric ozone layer due to human emissions.	Kilograms of ozone-depleting gases to air.	kg CFC-11 eq
Abiotic depletion potential, non-fossil resources (ADPE)	Impacts to depletion of natural, non-fossil based resources.	Kilograms of extracted antimony from reserves.	kg Sb eq
Abiotic depletion potential, fossil-based resources (ADPM)	Impacts to depletion of natural, fossil-based resources.	Megajoules, referring to depletion of total energy reserves	MJ
Photochemical ozone creation potential (POCP)	Creation of reactive chemical compounds (i.e., summer smog). These compounds are formed by the action of ultraviolet light on certain air pollutants, e.g., organic compounds (VOCs) and carbon monoxide (CO), in the presence of nitrogen oxides (NO _x).	Kilograms of emissions of ethylene	kg C ₂ H ₄ eq

Adapted from Guinée, J.B. (2002) [50].

Appendix B

Appendix B includes further details of the results.

Appendix B.1. Comparison of Large and Small Hydropower Plants in Iceland

Table A10 presents the results of comparing the four larger hydropower plants to the case project by all assessed impact categories.

Table A10. Comparison of Icelandic hydropower plants across impact categories.

Impact Category	Reference Unit	The Studied System	Blöndustöð	Búðarhálsstöð	Búrfellsstöð II	Fljótsdalsstöð
Global warming potential	kg CO ₂ eq	3.00×10^{-3}	2.0×10^{-2}	1.5×10^{-3}	5.1×10^{-4}	1×10^{-3}
Acidification potential	kg SO ₂ eq	1.00×10^{-5}	3.2×10^{-4}	9.10×10^{-7}	2.7×10^{-6}	4.40×10^{-6}
Eutrophication potential	kg PO ₄ eq	4.00×10^{-6}	1.5×10^{-4}	1.40×10^{-6}	4.5×10^{-7}	3.10×10^{-6}
Ozone depletion potential	kg CFC-11 eq	2.00×10^{-11}	2.1×10^{-15}	7.10×10^{-15}	6.0×10^{-14}	3.00×10^{-15}
Abiotic depletion, non-fossil resources	kg Sb eq	2.00×10^{-8}	2.8×10^{-9}	9.50×10^{-9}	8.5×10^{-9}	3.10×10^{-9}
Abiotic depletion, fossil-based resources	MJ	3.40×10^{-2}	8.1×10^{-3}	2.4×10^{-3}	4.7×10^{-3}	9.00×10^{-3}
Photochemical ozone creation potential	kg C ₂ H ₄ eq	6.00×10^{-7}	2.5×10^{-6}	1.10×10^{-7}	2.3×10^{-7}	3.20×10^{-7}

Appendix B.2. Reduced Capacity Factor

According to Equation (1), the annual generation of a 9.9 MW hydropower plant with a capacity factor of 100% would be 86,724 MWh or 86,724,000 kWh.

$$CF (\%) = \frac{86,724,000 \text{ (kWh)}}{9900 \text{ kW} * 8760 \text{ (h/year)}}$$

However, the average annual electricity generation from the past two years was used to find the capacity factor of the case project, or 88,265 MWh. This means that the capacity factor of the case project is higher than 100%. The reason for the CF exceeding 100% is that the physical installed capacity of the SHP is greater than its registered installed capacity. The plant operates two turbines, each with an output of 5.222 MW. Thus, the SHP can achieve the output of approximately 10.4 MW under favourable conditions. The plant is, however, licensed, registered and operated as a 9.9 MW SHP. The 10 MW threshold is of particular regulatory significance in Iceland, as hydropower developments with an installed capacity of 10 MW or greater are subject to additional requirements under the Master Plan for Nature Protection and Energy Utilization. Consequently, the registered capacity of 9.9 MW was used in the present analysis, although actual generation may occasionally reflect the higher technical capability of the installed equipment.

Appendix B.3. Reservoir Emissions

EFLA's study of Búðarhálsvirkjun was used as the basis for estimating potential reservoir emissions. The flooded land for the Búðarhálsvirkjun reservoir consisted of both unvegetated and vegetated land. In the present case, the flooded land is predominantly vegetated. It is assumed that the carbon content in the top 30 cm of the soil is equivalent to that reported for vegetated land in Búðarhálsstöð, i.e., 4.24 kg C/m² [51]. It is acknowledged that this may not accurately represent the actual carbon stock of the area flooded by the studied system.

The surface area of the reservoir of the SHP is 8 ha. Approximately 40% of this area corresponds to the pre-existing river channel and is assumed to contribute no emissions due to the absence of land-use change [51]. The remaining 60% (approximately 4.8 ha) is assumed to be highly vegetated, according to the system's operator. Based on the methodology of The Agricultural University of Iceland [13], it is assumed that 10% of the organic matter is released during the lifetime, including 90% as CO₂ and 10% as CH₄. To estimate the emission of CO₂ and CH₄, the amount of carbon was converted using molar mass ratio calculations (44/12 for CO₂ and 16/12 for CH₄) [51]. Table A11 presents the calculations for estimating reservoir emissions.

Table A11. Calculation of potential reservoir emissions of the 9.9 MW hydropower plant.

Factor	Calculations	Amount
Total carbon stored in the flooded area	$4.24 \times 10^{00} \text{ kg C/m}^2 \times 4.8 \times 10^{04} \text{ m}^2$	$2.035 \times 10^{05} \text{ kg C}$
Total amount of carbon released during the lifetime (10%)	$1.0 \times 10^{-1} \times 2.035 \times 10^{05} \text{ kg C}$	$2.035 \times 10^{04} \text{ kg C}$
Total amount released as CO ₂	$9.0 \times 10^{-1} \times 2.035 \times 10^{04} \text{ kg C} \times 4.4 \times 10^1 / 1.2 \times 10^{01}$	$4.03 \times 10^{06} \text{ kg CO}_2$
Total amount released as CH ₄	$1.0 \times 10^{-1} \times 2.035 \times 10^{04} \text{ kg C} \times 1.6 \times 10^1 / 1.2 \times 10^1$	$1.628 \times 10^{05} \text{ kg CH}_4$
Total amount of GHG released for 60 years	$[4.03 \times 10^6 \text{ kg CO}_2 + 1.628 \times 10^{05} \text{ kg CH}_4 \times 2.5 \times 10^{01}] \times 60$	$8.1 \times 10^{06} \text{ kgCO}_2 \text{ eq}$
Translated for the functional unit	$8.1 \times 10^{06} / 5.3 \times 10^{09}$	$1.53 \times 10^{03} \text{ kgCO}_2 \text{ per kWh (1.53 g/CO}_2 \text{ p/kWh)}$

Calculation method and amount of carbon stored in the flooded area adapted from EFLA's report on reservoir emissions [51].

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