Life Cycle Environmental Impact of Pumped Hydro Energy Storage

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Abstract. Pumped hydro energy storage (PHES) is one of the energy storage systems to solve intermittent renewable energy and support stable power generation of the grid. About 95% of installed capacity of the global energy storage system is contributed by PHES. Life cycle assessment (LCA) is used to analyse the environmental impact of PHES construction and operation phase in this study, and 1 MWh of electricity delivered from PHES to the power grid is set as the functional unit. The results show that the electricity power structure and electricity loss caused by the charging-discharging of PHES are the main environmental burden contributors, contributing 80 to 99% of the total environmental emissions. And environmental impacts during the construction phase is mainly due to the use of concrete, steel, and cement. In the future, as the proportion of renewable energy in the grid structure increases, the environmental impacts caused by PHES will decrease accordingly.

1. Introduction

Nowadays, with the limitation of fossil energy resources and the deterioration of the global climate, renewable energy is widely used [1-2]. However, there are intermittency problems with using renewable energy (such as wind energy, solar energy)[3], which might cause erratic output of the electricity grid [4]. Setting up energy storage systems can effectively solve this intermittency problem[5] and ensure the stability of grid power supply [6]. Energy storage systems can be divided into mechanical storage system, electrochemical systems, chemical storage and thermal storage systems[7]. Pumped hydro energy storage (PHES) is the dominating energy storage technique worldwide[8], which is belonged to the mechanical storage systems[9]. As of 2021, the installed capacity of PHES is about 181273 MW, accounting for 95% of the installed capacity of the global energy storage system [10]. PHES pumps water from a lower basin to a higher-level basin to store gravitational potential energy of water transfered from the low-cost electric power (electricity in off-peak time), and the stored water is released through hydro turbines to produce electric power during the periods of high energy demand [11].

Life cycle assessment (LCA) is a extensively employed methodology for evaluating the comprehensive environmental impact of product systems throughout their entire life cycle.[12] Within the field of energy storage, numerous studies have been conducted utilizing the LCA approach. Manal AlShafi et al[13] undertook a thorough analysis employing life cycle assessment to evaluate three energy storage technologies, namely compressed air energy storage, vanadium redox flow battery, and molten salt thermal storage, with the aim of addressing environmental sustainability concerns. Laurent Vandepaer et al[14]conducted a life cycle assessment specifically focused on lithium-ion battery energy storage to ascertain the environmental impact associated with different specifications and types of lithium-ion batteries. Lydia Stougie et al[15] conducted a multidimensional environmental impact assessment on five energy storage systems, including PHES, which was found to cause the least damage to human health, ecosystem diversity, and resource availability. However, many current studies are based on inventories established by predecessors, which may result in certain discrepancies from the actual circumstances.

In this study, we quantify the potential environmental impacts of PHES based on life cycle assessment model and original data to determine the main environmental burden contributors in construction and operation phases, which might further support the construction and operation of the PHES systems.

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2. Methods and Modelling

2.1. Scope and overview

This study analyses the environmental impacts of the construction and operation of Huizhou pumped hydro energy storage in Guangdong Province, China under a life cycle perspective. The goal is to (1) determine the environmental impacts of PHES, (2) analyse the main factors that caused environmental impacts in the construction and operation phases.

2.2. System boundary & functional unit

Figure 1 shows the system boundary selected in this study, and the analysis includes the construction phase and operation phase of PHES. The construction phase includes the construction of lower basin, upper basin, water conveyance system, underground plant, electricity and diesel input. Electricity loss is considered due to charging and discharging efficiency during operation phase. Due to the lack of data in PHES' end of life (EOL) phase, and there are other functional values such as irrigation and tourism after EOL period for PHES[16]. Thus, the EOL phase is not considered. In this study, 1 MWh electricity delivery during the 60-year lifetime of the PHES was used as the functional unit.

2.3. Life cycle inventory and assumptions

Data on raw material input, energy consumption, and charge-discharge efficiency during construction and operation were provided by Guangdong Hydropower Planning & Design Institute Co. Ltd. In addition, according to relevant literature, this study assumes that the PHES has a lifetime of 60 years [17].

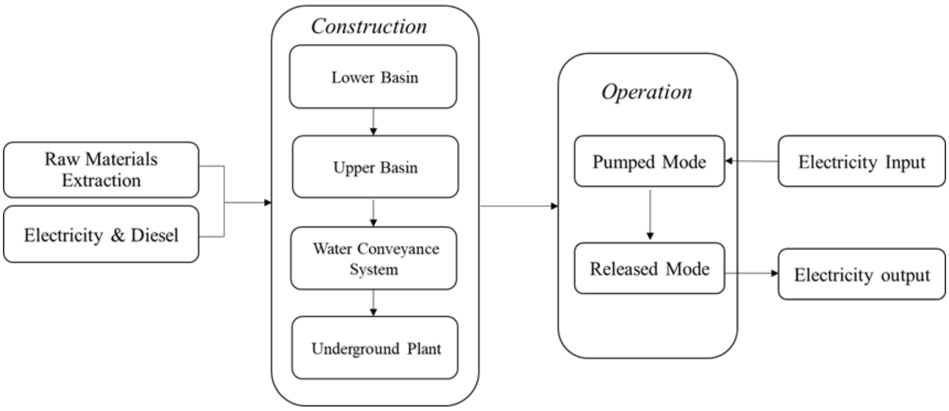

Figure 1. The system boundary of PHES for life cycle assessment

2.4. Life cycle assessment

SimaPro software was used to model the life cycle impacts assessment, and the most widely used ReCiPe 2016 method in the LCA model is applied for the midpoint environmental impacts assessment of the PHES construction and operation periods[18]. The midpoint assessment includes 18 environmental impact categories, global warming (GW), Stratospheric ozone depletion (SOD), ionizing radiation (IR), Ozone formation, human health (OFHH), fine particulate matter formation (FPMP), ozone formation, terrestrial ecosystems (OFTE), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU), mineral resource scarcity (MRS), fossil resource scarcity (FRS), water consumption (WC).

3. Results and discussion

3.1. Environmental impacts analysis

The LCA results reflect the environmental impacts of PHES (Table 1). In order to better understand the environmental impacts of different phases, Figure 2 shows the proportions of PHES environmental impacts contribution. Due to the characteristics of the raw materials used in the construction phase, the proportion of mineral resource scarcity in the construction phase is higher than other indicators, but it is the lowest contribution in operation phase of all indicators. However, the influence of the operation phase accounted for more than 90% in the remaining 17 indicators. For example, the 1MWh energy delivery causes about 350 kgCO_2eq emissions, while the operation phase accounts for more than 99% of this value. The environmental impacts of the operation phase are mainly related to the charge-discharge efficiency and electricity sources. Compared to other electricity sources, Chinese electricity may cause higher carbon emissions [19].

Table 1. Environmental impacts of delivery 1MWh electricity by PHES

Impact category	Unit	Total	Construction ratio (%)	Operation ratio (%)
GW	kg CO2 eq	349.88	0.64	99.36
SOD	kg CFC11 eq	0.00	0.75	99.25
IR	kBq Co-60 eq	5.46	1.04	98.96
OFHH	kg NOx eq	0.97	0.60	99.40
FPMP	kg PM2.5 eq	0.53	0.56	99.44
OFTE	kg NOx eq	0.97	0.62	99.38
TA	kg SO2 eq	1.19	0.53	99.47
FE	kg P eq	0.06	0.94	99.06
ME	kg N eq	0.00	0.91	99.09
TET	kg 1,4-DCB	178.64	4.11	95.89
FET	kg 1,4-DCB	3.23	2.07	97.93
MET	kg 1,4-DCB	4.51	2.12	97.88
HCT	kg 1,4-DCB	9.74	2.54	97.46
HNCT	kg 1,4-DCB	75.64	2.74	97.26
LU	m2a crop eq	4.15	1.04	98.96
MRS	kg Cu eq	0.12	19.19	80.81
FRS	kg oil eq	68.30	0.71	99.29
WC	m3	0.91	6.16	93.84

3.2. Environmental impacts of the construction

Figure 2 shows the environmental impact contributions of construction phase. The construction phase contains four processes, the constructions of water delivery system and the lower basin contribute relatively high environmental impacts during the whole construction phase. The use of concrete and steel is the two most influential factors during the construction of the water delivery system, the lower basin and the underground plant. And a large amount of sand, copper, and concrete are used in the construction of the upper basin. In general, the extensive use of concrete is the main cause of environmental impacts of the construction phase, and the impacts of steel and cement consumption should not be ignored.

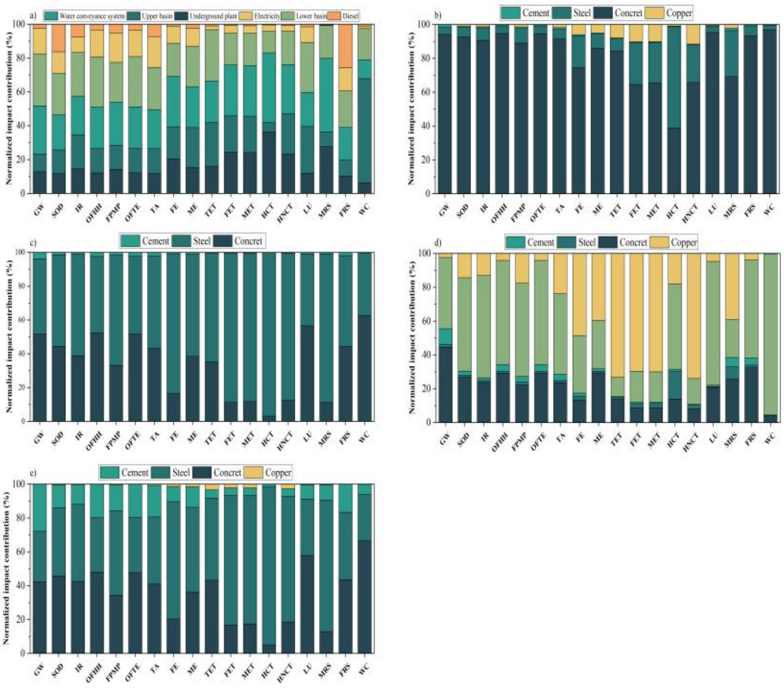

Figure 2. Environmental impact contributions of PHES construction, lower basin, underground plant, upper basin and water conveyance system (a-e).

3.3. Discussion

The results show that electricity loss during operation phase is the main factor of environmental impacts for PHES. In 2020, China's electricity power structure is 67.9% thermal power, 17.0% hydropower, 6.0% wind power, 3.5% photovoltaic power, and 5.6% other power generation. It can be seen from the current power structure that China's power grid structure largely relies on thermal power generation which may creates more serious environmental impacts than renewable energy power generation. The research results conducted by Oliveira et al.[20] on the environmental impact of energy storage systems applied in the power grid under different power combinations prove that the use of renewable energy for power generation significantly reduces environmental impact. In the future, thermal power proportion will decrease to 32.0% and 15.0% in 2040 and 2050, respectively, and the proportion of renewable energy used in the grid will increase [21]. So the environmental impacts caused by electricity loss during the operation of PHES in the future will also be reduced accordingly. Besides, the concrete and steel used in a large number of construction phase can be considered to use alternative materials to reduce environmental impacts. For example, Ueda et al [22] consider replacing the concrete factory building structure with a timber structure with the same architectural requirements as the concrete block building in micro-hydropower construction. This material substitution can significantly reduce the potential environmental burdens. In this study, the lifetime of PHES is conservatively assumed to be 60 years, which may underestimate the actual lifetime of PHES and may lead to an overestimation of its environmental impact. For examples, Flury et al. conducted a study on the environmental impact of PHES over a period of 150 years lifetime[23], Immendoerfer et al [24] analysed the environmental impacts of different years lifetime of PHES, 80 and 150 years respectively, and found that the environmental impacts caused by PHES are lower as the lifetime increases.

4. Conclusion

Based on the original data, this paper assesses environmental impacts of the construction and operation for PHES. The results show that concrete, steel, sand and other raw materials cause main environmental impacts during the construction of PHES. The electricity loss caused by the charge-discharge efficiency is directly related to the environmental impacts of the operation phase. For the construction, one of the ways to reduce environmental impacts is to consider the use of alternative materials; this paper uses the Chinese power grid that is highly dependent on thermal power generation to simulate the operation of PHES. In the future, as the proportion of renewable energy in the power grid increases, the resulting environmental impacts will also be reduced. This study quantifies the environmental impact of PHES, identifies the main environmental hotspots, and provides some future improvement recommendations, serving as a reference for the life-cycle management of PHES.

Acknowledgments

This study was supported by the Research on carbon balance and sustainability evaluation method system of pumped hydro energy storage (Contract No. CE682022000386).

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