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Life cycle assessment of the Kamchay hydropower plant in Cambodia

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Abstract: As a developing country, Cambodia is promoting hydropower as a renewable energy source to increase electricity production, minimize the cost of electricity and enhance energy security. However, potential adverse impacts from hydropower still remain to be assessed. The objectives of this study consisted in evaluating the environmental impacts of the Kamchay hydropower plant, the first large scale dam in Cambodia, using life cycle assessment and identifying mitigation options for the sustainable development of hydropower in the country. The greenhouse gas emissions from the Kamchay hydropower plant amount to 141 kg CO_2-eq./MWh and are the major contributor to the impacts on human health and ecosystem damage. These emissions were identified to be mainly from the construction and operation & maintenance phases. The rest of the emissions and resources consumption had a marginal significance compared to greenhouse gas emissions. These findings point out to the necessity of focusing on the construction and operation phases to mitigate greenhouse gas emissions and in doing so improve the environmental performance of large-scale dams with reservoir.

Keywords: Cambodia, hydropower, life cycle assessment (LCA), reservoir, renewable energy.

1. Introduction

As for other developing countries in the Association of South East Asia Nations (ASEAN), Cambodia needs to increase its electricity production using indigenous resources in order to meet the increasing demand due to population, economic growth and industrial development, and address the issue of increasing cost caused by energy importation from neighboring countries [1]. Renewable energy has been promoted in Cambodia to fulfill the increasing demand for electricity and contribute to climate change mitigation. Cambodia is a country located in the middle of the Greater Mekong Sub-region (GMS) possessing major rivers and waterways which naturally provide a high potential for hydropower production [2]. The potential generation capacity of this type of renewable energy exceeds 10,000 Megawatts (MW), with 60 possible sites identified for future hydropower plant development [3]. In 2005, the Royal Government of Cambodia (RGC) approved the construction of the Kamchay hydropower plant, the first large scale dam built in the country. In an attempt to supply electricity for 100% of the rural areas in the country by 2030 as per the rural electrification target stated under the 2006 renewable energy policy plan, hydropower is expected to play a crucial role with 70% of the total power generation being contributed by hydropower dams [4]. In 2007, the country implemented 5 additional hydropower dams and twelve more are known to be under study in collaboration with Chinese, Korean, and Vietnamese dam-builders [5]. In 2017, the electricity supplied to households, industries, commercial organizations and every other sector in Cambodia, was generated from five main sources including, coal (53.80%), hydropower (40.87%), diesel/heavy fuel oil (HFO) (4.37%), biomass (0.89%), and solar energy (0.07%) [6]. Hydropower is the second largest energy source in Cambodia and plays a major role in meeting the electricity demand of such a rapidly growing economy and in minimizing the electricity tariff, which is higher than in any other ASEAN countries [7]. In 2018, 60% of the electricity generated in Cambodia was from renewable energy, with largest contributions from hydropower plants followed by biomass and solar power plants [8]. In February 2019, the RGC investigated a potential new hydropower dam in the Pusat province at an estimated cost of 160 million US dollars and which is expected to produce 80 MW power [9]. Hydropower is one of the renewable energy sources that is considered as clean power [10]. However, all kind of energy systems, including hydropower, emit greenhouse gases (GHGs) and other emissions to air, water and soil in addition to resource use via material, energy, as well as transportation in both the construction and operation stages [11]. Hydropower plants with reservoir type have been reported as potential emitters of GHGs, especially, carbon dioxide (CO_2) and methane (CH_4) due notably to the controversial decomposition of biomass in the flooded land [12-13]. The environmental burdens from hydropower can be investigated using Life Cycle Assessment (LCA) which is widely recognized as a systematic approach that considers both resource usage and environmental discharges associated with products or services throughout their entire lifespan (e.g. from raw material extraction, processing, manufacturing, and use until demolition) [10-12, 14]. According to the literature, the majority of LCA studies on hydropower have focused on run-of-river type projects [14-15], and only a few studies have been conducted on reservoir type, and mostly in non-ASEAN countries [10, 12]. Therefore, the main objective of this research is to evaluate the environmental impacts of the Kamchay hydropower plant, the first large-scale dam with reservoir type in Cambodia, based on an LCA approach. Environmental hotspots are also identified and some mitigation options discussed.

2. Materials and Methods

2.1 The Kamchay hydropower dam

The Kamchay hydropower plant is located in the Elephant Mountain range in the southwestern part of Cambodia on the Kamchay river which is situated in Mak Prang commune, Teuk Chhou district, Kampot province. The river basin is located between latitudes 10°40' and 11°05' and longitudes 103°50' and 104°10'. About 15 km downstream of the river from the hydropower dam is the nearest city, the provincial town of Kampot, which is situated 150 km away from Phnom Penh, the capital city of Cambodia.

The Kamchay hydropower plant is a BOT (build, operate, and transfer) project between the RGC and a Chinese dam builder, with a generation capacity of 194.10 MW. The purpose of this project is to generate electricity to meet the increasing demand of the country in energy and reduce the importation of electricity from neighboring countries including, Thailand, Lao PDR and Vietnam. The importation of electricity represents an energy security challenge and leads to a higher cost of electricity compared to other ASEAN countries. The construction of the Kamchay hydropower plant started in September 2007 and was completed in November 2011. The plant is composed of two dams and three powerhouses (PH), PH1 with a generating capacity of 180 MW, PH2 and PH3 with generating capacities of 10.1 MW and 4 MW, respectively. The dimension of the first dam is 112 m high, 6 m wide, and 568 m long while the second dam is 20 m high, 2 m wide, and 195 m long. The main dam blocks the water from the upstream and forms a reservoir with a volume of 7.18 billion m^3. The flooded land for reservoir 1 and reservoir 2 is 1990 ha and 25.7 ha, respectively. The average annual net electricity output of the plant to the grid is 508.2 GWh which is equivalent to about 68% of the total electricity used in Cambodia in 2004 [16]. The detailed technical information of the Kamchay hydropower plant is shown in Table 1.

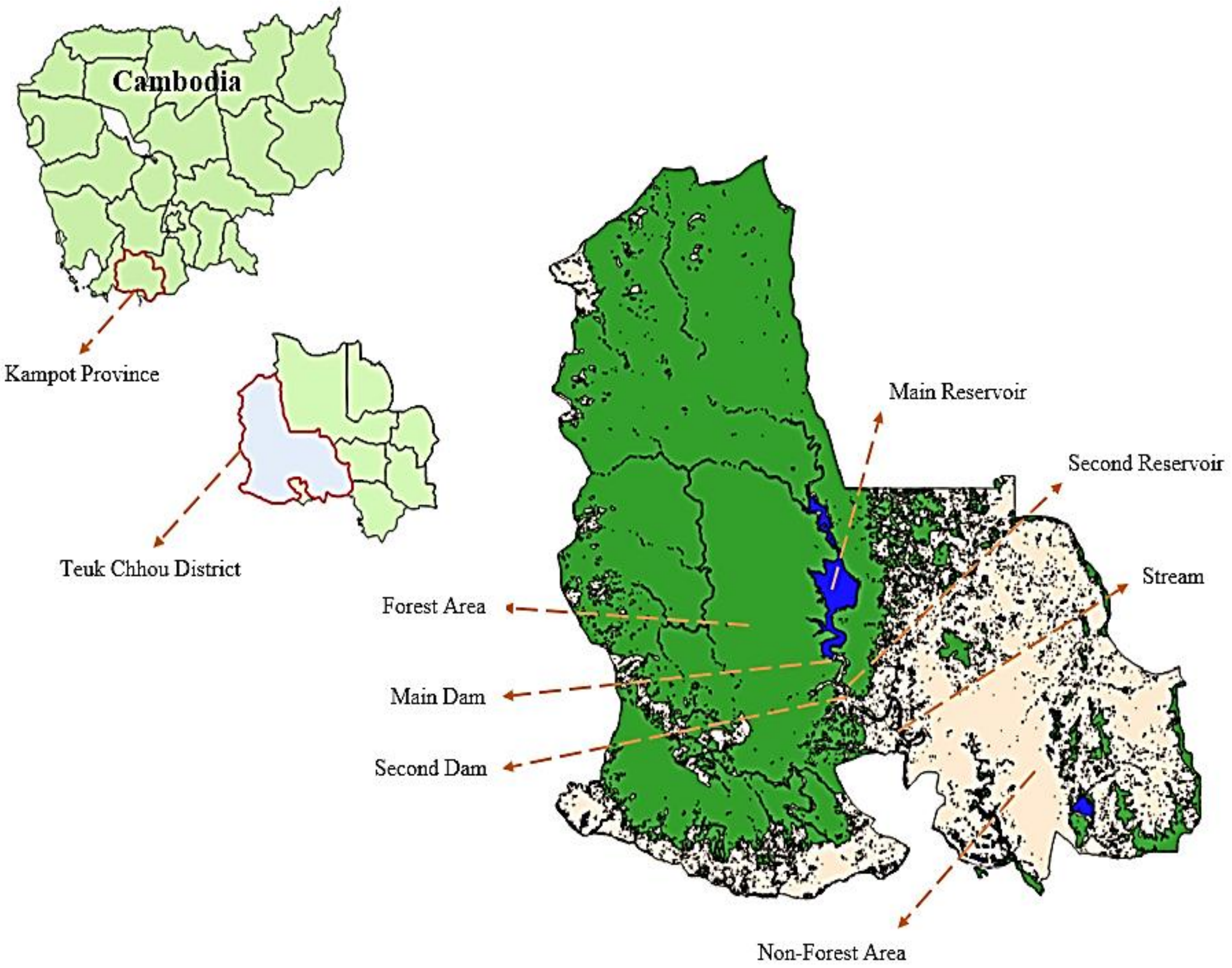

Figure 1. Kamchay Hydropower Plant in Cambodia.

Table 1. Technical details of the Kamchay hydropower plant.

	PH1	PH2	PH3
Installed capacity	180 MW	10.1 MW	4.0 MW
Quantity of units	3	4	1
Turbine type	3×Vertical- Francis	3×Bulb extension tubular 1×Propeller	1×Horizontal Francis
Generator type	3×SF60-78/5500	3× SFW3100-36/3260 1× SFW1800-20/2150	1× SFW4000-8/1730
Water head	122 m	6.8 m 9.0 m	93 m
Design flow rate	163.5 m^3/s	52.47 m^3/s 10.00 m^3/s	5.124 m^3/s
Rated voltage	13.8 kV	10.5 kV	6.3 kV

2.2 Goal and scope of the research study

The goal of this research is to evaluate the environmental impacts of the first large scale hydropower plant in Cambodia from cradle-to-grave using process-based LCA following the International Organization for Standardization (ISO) 14040 and 14044 guidelines. The study also aims at identifying potential environmental hotspots and mitigation options in support of the sustainable development of hydropower in the country. The materials, equipment, transportation types, and energy used over the whole life cycle of the Kamchay hydropower plant were considered in this research. The emissions caused by the decomposition of biomass in the flooded land of the reservoir were also investigated. However, the resources used for habitation of workers during the construction period as well as the transmission and distribution for electrical network were considered as beyond the scope of this study. The decommissioning of the dam after full operation and disposal of the waste to landfill were included in the assessment of environmental impacts. The energy, resources and materials used in this research were calculated based on 1 MWh of electricity generation from the Kamchay hydropower plant which is the functional unit (FU).

2.3 System boundaries

The system boundary of this study includes four phases, representing the whole life cycle of the plant. These are the (1) construction phase, (2) operation & maintenance phase, (3) demolition & disposal phase, and (4) transportation phase. Deforestation for infrastructure development is in the pre-construction phase, which in turn is part of the construction phase including the resources, materials, and energy used from land preparation to completion of the hydropower plant construction. The operation & maintenance phase covers the energy and materials used in that stage, including the replacement of equipment throughout the lifespan of the Kamchay hydropower plant. The lifespan of this plant is 100 years according to the design document. The energy and materials used in the decommissioning stage of the dam are part of the demolition phase, including final disposal to a nearby landfill (i.e. demolition & disposal phase). The transportation of materials, equipment and waste (both local and overseas) throughout the whole system are part of the transportation phase. The overall system boundary of this research is illustrated in Fig. 2.

2.4 Life cycle inventory

In order to produce the life cycle inventory (LCI) of the Kamchay hydropower plant, two methods of data collection were implemented. A major part of the data was collected from the design report of the Kamchay hydropower plant and through a face-to-face interview with the head of the site engineers. Secondary data was obtained from technical reports, the literature and interviews with technical staff from the Ministry of Environment (MoE) and the Ministry of Mine and Energy (MME) of Cambodia. The materials, energy, equipment, and transportation used within the system boundary of the Kamchay hydropower plant were investigated from the construction phase to the demolition & disposal phase.

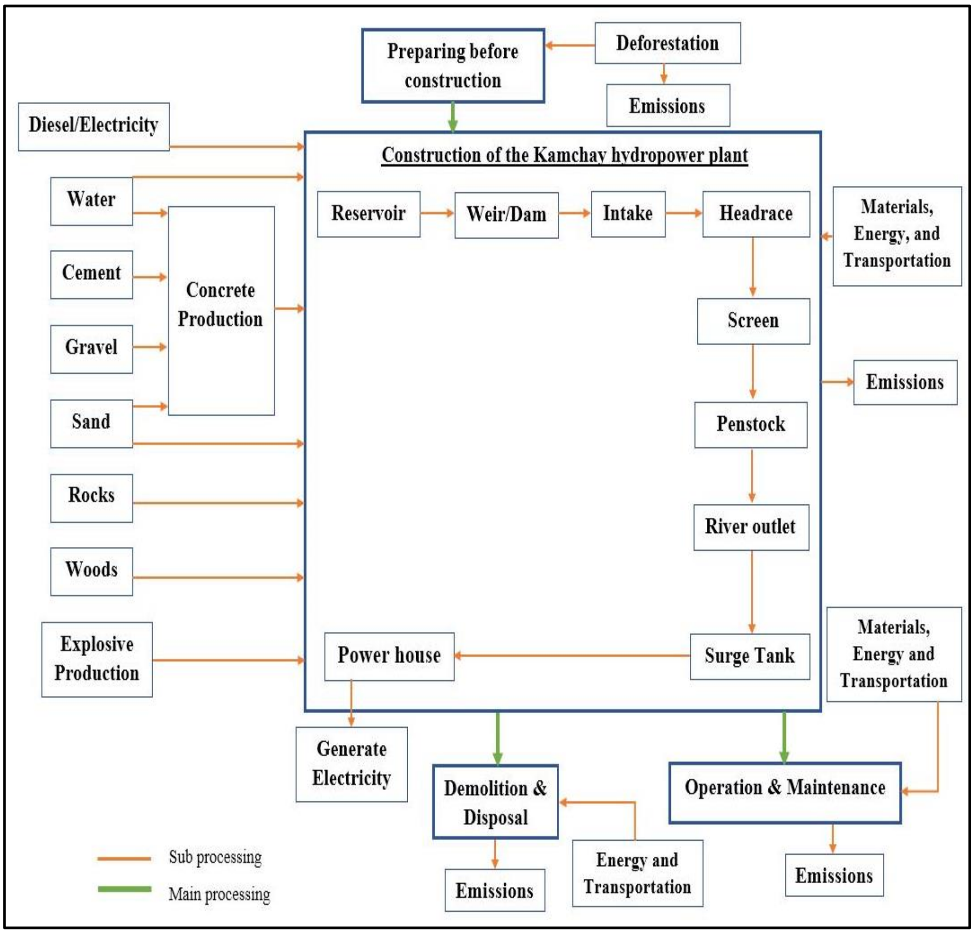

Figure 2. System boundary of the Kamchay hydropower plant.

Table 2. List of pollutants and the sources of their respective emission values.

Pollutants	Sources
• Deforestation	• IPCC [17]
• Production of construction materials (i.e. cement, steel, gravel, etc.)	• Song et al. [18]
• Energy	• IPCC [19], European Environmental Agency [20]
• Transportation	• IPCC [21], European Environmental Agency [22]
• Demolition	• Suwanit & Gheewala [14]

Table 3. Selected impact categories at midpoint and endpoint levels based on ReCiPe 2016.

Midpoint impact categories	Unit
Climate Change	kg CO_2-eq.
Stratospheric Ozone Depletion	kg CFC-11-eq.
Photochemical Ozone Formation	kg NO_x-eq.
Particulate Matter Formation	kg PM2.5-eq.
Terrestrial Acidification	kg SO_2-eq.
Freshwater Ecotoxicity	kg 1,4-DCB-eq.
Mineral Resource Scarcity	kg Cu-eq.
Fossil Resource Scarcity	kg Crude oil-eq.
Land use	m^2

Endpoint impact categories	Unit
Human Health	DALY
Terrestrial Ecosystems	species.yr
Freshwater Ecosystems	species.yr
Resource Scarcity	USD2013

2.5 Calculation of GHG emissions from the flooded land of the Kamchay reservoir

The biogenic GHG emissions related to the decomposition of biomass in the flooded land of the Kamchay reservoir were estimated based on an emission rate for tropical climate from Song et al. [18]. To perform the assessment, Equation (1) was used as follows:

$$E = (ER \times Age \times Land\ use)/EP \quad (1)$$

Where *E* represents the final estimated amount of GHG emissions (g CO_2-eq. per MWh), *Age* is the lifespan of the reservoir following its construction (year), *Land use* refers to the total flooded area of the reservoir (m^2), and *EP* is the net electricity output of the plant over the lifespan of the plant (MWh). *ER* is the reservoir GHG emission rate for the tropical climate zone (i.e. 2,733 g CO_2-eq./m^2/year based on Song et al. [18]).

2.6 Life cycle impact assessment

The purpose of life cycle impact assessment (LCIA) is to quantify the potential environmental impacts of every single inventory parameter, including, energy, materials, equipment, and transportation by converting LCI data into potential impacts.

The ReCiPe 2016 LCIA method provides assessment results at both the midpoint and endpoint levels. The characterization factors at the midpoint level are located somewhere along the impact pathway, typically at the point after which the environmental mechanism is identical for all environmental flows assigned to that impact category [23]. Those at the endpoint level correspond to the three areas of protection which are human health, ecosystem quality and resource scarcity. The LCIA, based on the midpoint results, helps the interpretation of LCA studies by translating those emissions and resource extractions into a limited number of environmental impact scores. The endpoint characterization factors provide information on the environmental relevance of the environmental flows [23]. Thus, in this study, both midpoint and endpoint impact categories from the ReCiPe 2016 method were considered as shown in Table 3. The assessment was based on ReCiPe 2016 with hierarchist perspective calculated according to the functional unit of 1 MWh.

3. Results and Discussion

3.1 Life cycle inventory

The inventory data of the Kamchay hydropower plant was collected for each of the four phases of its life cycle. These include the construction phase, operation & maintenance phase, demolition & disposal phase, and transportation phase. The life cycle inventory data is presented in Table 4 and related major considerations for each of the four phases detailed in the sub-sections that follow.

3.1.1 Construction phase

The construction process involves many resources such as cement, gravel, sand, stone, wood and equipment (i.e. hydraulic machinery, heavy-duty truck, electric motor, etc.). The energy used in this process (diesel and electricity) also plays an important role in the development of infrastructure. Deforestation for the construction of the Kamchay hydropower plant is part of the land clearing stage under the construction phase. The carbon emissions, materials and energy used during the deforestation stage were calculated based on the Intergovernmental Panel on Climate Change guidelines 2006 [17] and the European Environmental Agency guidelines 2019 [20]. The construction of the plant is the most complex phase compared to other life cycle phases of the hydropower plant. It mainly consists of building works and equipment installations. Building works comprise land clearing, filling and cutting (including ground compaction, covering, drilling and use of explosives), and construction from the laying of foundations to the final buildup of all components of the hydropower plant (i.e. dam, penstock, powerhouse, tailrace, road, reservoir and substation). The greenhouse gas emissions for different materials used in the construction phase (i.e. cement, steel, gravel, sand) were calculated using emission factors from Song et al. [18]. The energy and materials used for equipment were considered while the energy used for the manufacture of equipment was excluded from the scope of the study. The use of energy and materials was calculated based on information from the design report of the Kamchay hydropower plant, the literature and from interviews with technical staffs, site engineers and operators of the Kamchay hydropower plant during a field survey in 2019.

3.1.2 Operation and maintenance phase

The operation & maintenance phase requires less input of resources compared to the construction phase. Electricity, lubricant oil, and water flow are used for electricity generation using hydro-turbines. There are no emissions from the combustion of diesel fuel to generate electricity since the whole operation is mainly from the hydro-turbines. The electricity used in the operation phase was estimated based on energy use data collected from the provincial town of Kampot [6, 24-29]. Due to limitations in data availability, the lubricant oil used in the operation phase was calculated based on a previous hydropower related LCA study by Pang et al. [11]. Water flow was estimated based on records from the plant. In this study, the lifespan of equipment such as turbines, generator, etc., was assumed to be 25 years. In order to operate over 100 years, each piece of equipment is to be replaced 3 times. As part of the operation & maintenance phase, the decomposition of biomass in the flooded land of the reservoir was also considered as it is expected to be an important source of GHG emissions.

Table 4. Life cycle inventory of the Kamchay hydropower plant based on 1 MWh of electricity.

Materials	Plant Total (100 years)	Unit	Total per FU (1 MWh)	Unit
Construction Phase				
Materials				
Cement	1.10E+08	kg	2.16E+00	kg/FU
Sand	8.00E+06	m^3	1.57E–01	m^3/FU
Gravel	1.20E+06	m^3	2.36E–02	m^3/FU
Steel	1.60E+07	kg	3.15E–01	kg/FU
Steel formwork	6.00E+06	kg	1.18E–01	kg/FU
Wooden formwork	2.00E+03	m^3	3.94E–05	m^3/FU
Admixture	3.60E+06	kg	7.08E–02	kg/FU
Explosive	1.50E+06	kg	2.95E–02	kg/FU
Stone	2.00E+06	m^3	3.94E–02	m^3/FU
Diesel fuel	1.46E+07	kg	2.87E–01	kg/FU
Electricity	2.73E+07	kWh	5.37E–01	kWh/FU
Land use (Deforestation)	5.02 E+05	m^2	9.87 E–03	m^2/FU
Equipment				
Turbine				
Steel	1.99E+07	kg	3.91E–01	kg/FU
Stainless steel	6.32E+05	kg	1.24E–02	kg/FU
Iron	3.54E+05	kg	6.97E–03	kg/FU
Aluminum	2.62E+04	kg	5.16E–04	kg/FU
Generator				
Steel	1.46E+07	kg	2.86E–01	kg/FU
Copper	1.02E+07	kg	2.01E–01	kg/FU
Auxiliary (steel)				
Crane	1.58E+06	kg	3.10E–02	kg/FU
Water gate and screen	2.67E+06	kg	5.25E–02	kg/FU
Penstock	7.89E+06	kg	1.55E–01	kg/FU
King valve	1.21E+06	kg	2.39E–02	kg/FU
Exciter	2.33E+05	kg	4.58E–03	kg/FU
Speed governor	2.28E+06	kg	4.49E–02	kg/FU
Transformer	4.66E+06	kg	9.17E–02	kg/FU
Transportation Phase				
45t-Truck	6.45E+08	tkm	1.27E+01	tkm/FU
20t-Truck	4.73E+07	tkm	9.31E–01	tkm/FU
6t-Truck	5.24E+06	tkm	1.03E–01	tkm/FU
Ship	5.41E+08	tkm	1.06E+01	tkm/FU
Operation & maintenance Phase				
Electricity	1.31E+07	kWh	2.58E–01	kWh/FU
Lubricant oil	2.43E+06	kg	4.77E–02	kg/FU
Water flow	1.84E+11	m^3	3.62E+03	m^3/FU
Land use (Flooded Land)	2.02E+07	m^2	3.97E–01	m^2/FU
Disposal Phase (Landfill)				
Steel structure	1.76E+07	kg	3.46E–01	kg/FU
Equip. steel	2.34E+07	kg	4.60E–01	kg/FU
Stainless steel	1.11E+05	kg	2.18E–03	kg/FU
Iron	8.86E+04	kg	1.74E–03	kg/FU
Aluminum	6.55E+03	kg	1.29E–04	kg/FU
Copper	2.55E+06	kg	5.01E–02	kg/FU

3.1.3 Demolition and disposal phase

At the end of the lifespan of hydropower plants, dams are demolished, and valuable components and materials can be recycled. Most LCA studies tend to neglect the decommissioning phase, leaving the dam in place due to a lack of information on this last stage [10, 11, 15, 18, 30]. Some studies, however, argue that excluding the demolition phase does not provide a complete estimation of impacts. These studies therefore include the demolition and removal of major components. This includes the main dam and the powerhouse as well as the recycling of valuable materials such as steel, stainless steel and iron. They also assume that there are no emissions from accumulated sedimentation [11, 14, 31]. In this study, emissions from the decommissioning of the plant were considered, excluding recycling of valuable materials and emissions from sedimentation. The demolition waste from the dam was considered to be disposed in a nearby landfill site. However, the land used for waste disposal was excluded from the study scope. As part of the estimation of the amount of waste to be disposed, the weight of steel was assumed to be reduced by 20% of its original weight because of deterioration. For steel equipment in contact with water, a 2% reduction in weight was considered [14]. Emissions related to the energy used for demolition were also included in the assessment of environmental impacts.

3.1.4 Transportation phase

Emissions from the transportation phase relate to the transport of materials and products from one place to another via trucks, cars and ships. The total weight of transported materials and products, travel distances, and types & modes of transportation were considered to estimate emissions. According to the design report of the Kamchay hydropower plant and the Observatory of Economic Complexity (OEC), 98% of the cement, admixture and diesel were imported from Bangkok in Thailand via the Laem Chabang international port [32]. It is located about 706 km from the Kamchay hydropower site in Cambodia. Most of the materials and products used in the construction phase as well as the operation & maintenance phase (i.e. steel, stainless steel, turbines, generator, etc.) were imported from Beijing in China via the Shanghai international port. It is located about 5,010 km from the Kamchay hydropower site. To be cost-efficient, the sand, gravel, stone and other aggregates used in the construction phase of the plant were collected from quarries located in the Kampot province (within a 30 km radius from the construction site). At the end of the lifespan of the hydropower plant, it was assumed that demolition waste is transported to a landfill site located 50 km away from the plant using a 45t-truck with empty return trip. The distance was assumed based on the master plan of the provincial town of Kampot in 2010 [33]. The distances for transportation in this research were estimated from the google map calculator for route distance (https://www.google.co.th/) and the sea-routes calculator for maritime transportation (overseas-shipping) (https://searoutes.com/). A return-trip with no load was estimated only for local transportation.

3.2 Midpoint level impact assessment

As indicated earlier, the ReCiPe 2016 midpoint method with world-hierarchist observation was used for the life cycle impact assessment of the Kamchay hydropower plant based on a functional unit of 1 MWh of electricity. The results for each impact category based on the four phases of the life cycle of the Kamchay hydropower plant, are shown in Table 5.

According to Table 5, the emissions contributing to each impact category are mainly from the construction and transportation phases of the hydropower plant. This is except for climate change and mineral resource scarcity, where the impacts are mostly contributed by emissions from the construction, and the operation & maintenance phases. Looking further into the results, climate change, stratospheric ozone depletion, freshwater ecotoxicity, fossil resource scarcity and land use are primarily caused by the construction phase while the transportation phase mainly contributes to photochemical ozone formation, particulate matter formation and terrestrial acidification. The demolition & disposal phase contributes the least impact to each impact category. Details for each impact category are provided below.

3.2.1 Climate change

As shown in Table 5, the total life cycle GHG emissions of the Kamchay hydropower plant are 141 kg CO_2-eq./MWh. The major contributors to these emissions are the operation & maintenance phase with 77% followed by the construction phase with 22%. These are followed by the transportation, and demolition & disposal phases with 0.7% and 0.3%, respectively. The GHG emissions from the construction phase are due to the deforestation before the construction process and the large amount of construction materials (especially concrete and steel), energy and land use consumed during that stage to build the hydropower system, i.e. dams, powerhouses, penstocks, roads, etc. The GHG emissions associated with deforestation during the construction phase were estimated to be 26 kg CO_2-eq./MWh, i.e. 18% of the total GHG emissions from the Kamchay hydropower plant. The plant is located in a mountainous and remote area [34]. Therefore, the electricity used for its construction was mainly produced by

Table 5. Life cycle impacts of the Kamchay hydropower plant based on 1 MWh of electricity.

Impact category	Construction	Operation & Maintenance	Demolition & Disposal	Transportation	Total
Climate Change (kg CO_2-eq.)	30.71	109	0.30	0.89	141
Stratospheric Ozone Depletion (mg CFC-11-eq.)	3.89	0.02	0.88	0.41	5.20
Photochemical Ozone Formation (g NO_x-eq.)	10.60	0.13	2.16	14.43	27.32
Particulate Matter Formation (g PM2.5-eq.)	1.83	0.17	0.38	2.38	4.76
Terrestrial Acidification (g SO_2-eq.)	3.84	0.51	0.94	7.38	12.67
Freshwater Ecotoxicity (g 1,4-DCB-eq.)	0.31	0.03	0.03	0.05	0.42
Mineral Resource Scarcity (mg Cu-eq.)	0.65	0.73	0.04	0.63	2.05
Fossil Resource Scarcity (kg Crude oil-eq.)	1.05	0.05	0.03	0.93	2.06
Land Use (m^2)	0.03	0.001	-	-	0.03

on-site diesel-powered generators that contributed to enhance the emissions of GHGs during that step. For operation & maintenance, it is the decay of biomass in the flooded land of the reservoir that contributes mostly to the GHGs released during that phase. Biogenic emissions from the reservoir contribute almost 77% of the total life cycle GHG emissions; approximately 0.2% is contributed by the energy and materials used during the operation phase. When the reservoir was initially created, the land was inundated with water resulting in the submersion of plants and soil. Under these conditions, CO_2 is gradually released from the oxidation of organic carbon in the submerged biomass and soil. Reservoirs also often develop anoxic conditions, leading to the anaerobic digestion of organic carbon and therefore to CH_4 emissions. These biogenic emissions play a major role in the contribution of the operation & maintenance phase to climate change as the global warming potential of methane is 34 times higher than that of carbon dioxide [23]. Overall, it was found that CO_2 emissions are mostly contributed by the construction, demolition & disposal, and transportation phases (in the range 91 to 99%) while CH_4 emissions are mainly contributed by the operation & maintenance step (96%). Minimal contributions from nitrous oxide (N_2O) emissions were observed over the life cycle of the Kamchay hydropower plant.

3.2.2 Stratospheric ozone depletion

Major contributors to stratospheric ozone depletion include the construction, and demolition & disposal phases with about 75% and 17%, respectively. These are followed by the transportation phase with almost 8%, and a minor contribution from the operation & maintenance phase. The emissions were found to be mostly contributed by nitrous oxide (N_2O). Emissions leading to stratospheric ozone depletion are related to material and energy used during the construction phase as well as the demolition & disposal phase. Energy was also found to be a major contributor to emissions from the transportation, and operation & maintenance steps but the impact of these emissions on stratospheric ozone depletion were found to be minor compared to those from the construction, and demolition & disposal steps.

3.2.3 Photochemical ozone formation

Significant contributors to photochemical ozone formation include emissions from the transportation and construction phases with 53% and 39%, respectively. Emissions from the demolition & disposal phase contribute about 8% with negligible contribution from the operation & maintenance phase (see Table 5). Transportation is a major contributor to this impact category as a result of the importation of materials and equipment from overseas. Contributions from the construction phase relate mostly to materials and energy use (diesel fuel oil) for infrastructure development. Demolition & disposal as well as operation & maintenance phases have a much less significant impact on tropospheric ozone formation due to the lower amount of resources used in those two stages compared to the transportation and construction phases. NOx emissions were found to contribute the largest share to this impact category with values in the range 80-90% depending on the life cycle stages of the hydropower plant. This is followed by NMVOC emissions with values in the range 10-20%.

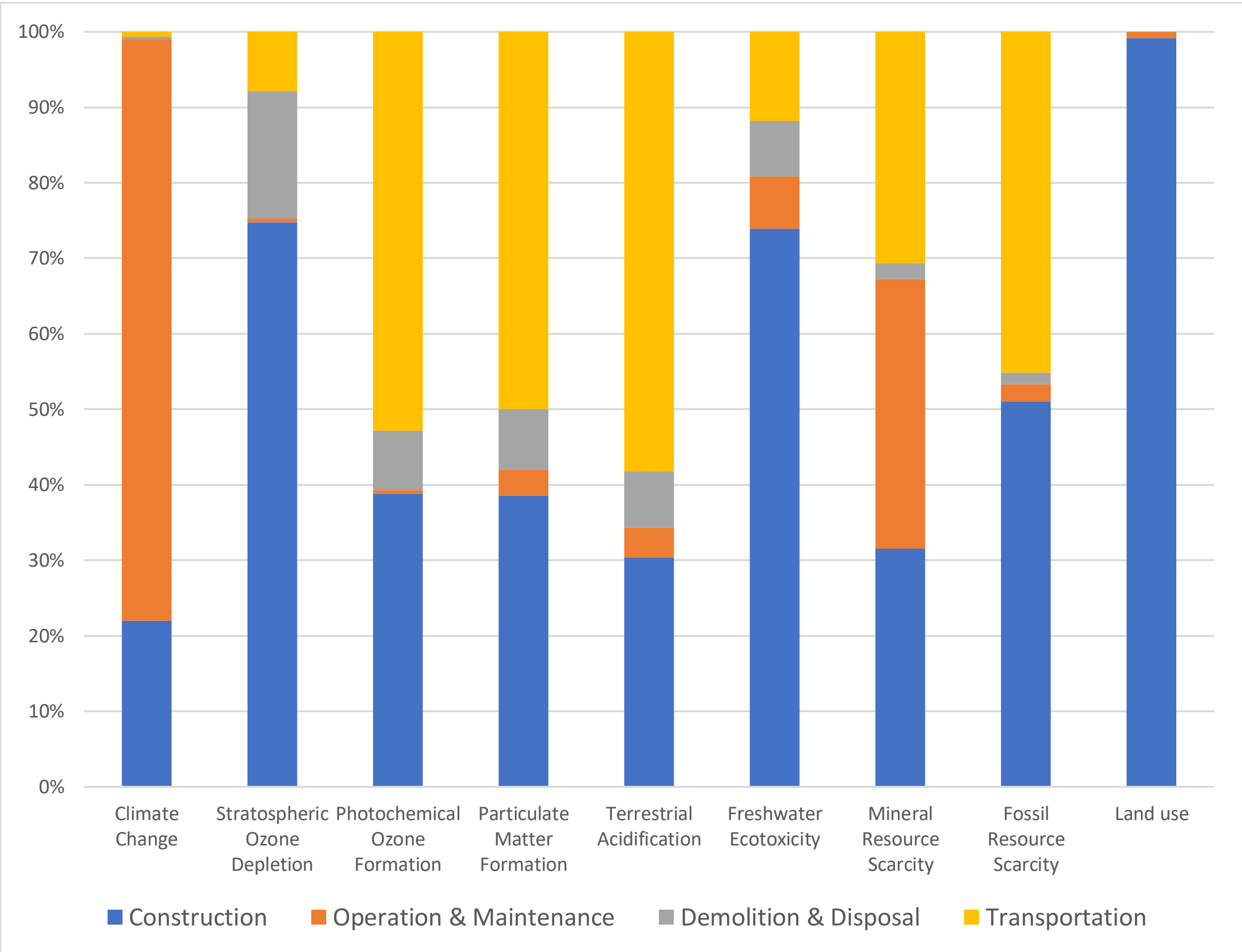

Figure 3. Life cycle environmental impact of the Kamchay hydropower plant.

3.2.4 Particulate matter formation

The results indicate that the majority of the impact on particulate matter formation is from transportation. Almost 50% of the emissions from the transportation stage were found to relate to the importation of materials and products. The second largest contributor is construction with almost 40%, followed by demolition & disposal with 8%, and operation & maintenance with 3.5%. The lower contribution from these two steps (demolition & disposal and operation & maintenance) is due to the lower amount of energy consumed in those two phases. The main contributing emissions to this impact category are from the construction, transportation, and demolition & disposal phases. These include NO_x (60-65%), SO_x (10-30%), $PM_{2.5}$ (5-40%), and NH_3 (>1%). Main contributing emissions from the operation & maintenance step include SO_x (80%), NO_x (10%) and $PM_{2.5}$ (10%).

3.2.5 Terrestrial acidification

The results in Table 5 show that the major contributing phases to terrestrial acidification are transportation and construction with about 58% and 30%, respectively. Lower contributions are from the demolition & disposal phase with 7.5% and the operation & maintenance phase with 4%. Main contributing emissions from the construction, demolition & disposal, and transportation phases include NO_x (80-90%), SO_x (>30%) and NH_3 (>2%). For operation & maintenance, main contributing emissions are SO_x (80%) and NO_x (20%). The lower contribution from the operation & maintenance phase was found to be related to the lower amount of resources consumed during that stage compared to the other phases.

3.2.6 Freshwater ecotoxicity

The largest contributor to this impact is the construction step with 74%. This is followed by transportation with 12%, the demolition & disposal phase with 7%, and the operation & maintenance phase with 7% (see Table 5). The emissions leading to freshwater ecotoxicity were found to be higher during the construction phase due to the larger number of materials and energy used during that step for infrastructure development. In relation to the construction phase and the demolition phase, zinc (23 and 77%), copper (25 and 7%) and fluoranthene (25 and 6%) were identified as the major contributors to this impact category. For emissions from the operation & maintenance phase and the demolition & disposal phase, zinc (59 and 36%), nickel (37 and 10%) and copper (2 and 31%) were identified as the largest contributing emissions to freshwater ecotoxicity.

3.2.7 Mineral resource scarcity

The largest contributors to mineral resource scarcity include the construction, operation & maintenance, and transportation phases with about 36%, 31% and 31%, respectively. A lower contribution is from the demolition phase with 2%. As the construction phase requires many types of mineral resources such as zinc, copper, nickel and cadmium to produce materials and equipment for infrastructure development, it was found to be the major contributing step to this impact category. Operation & maintenance, and transportation, in almost equal proportion, are the second-largest contributing phases. This is due to the resources used for equipment replacement, and the energy required for both operation and transportation. The demolition & disposal phase was found to require less material and energy for the decommissioning of the dam, leading to lower emissions compared to the first three phases.

3.2.8 Fossil resource scarcity

The major contributor to fossil resource scarcity was found to be diesel, which is used for infrastructure development, transportation and decommissioning of the dam after full operation. During the operation & maintenance phase, lubricant oil is the most significant contributor to fossil resource scarcity. There is no combustion of diesel fuel during that phase and so no contribution to this impact category in that stage. Overall, the construction and transportation phases were found to be the greatest contributors to fossil resource scarcity with 51% and 45%, respectively. This is followed by the operation & maintenance phase with 2.5% and the demolition & disposal phase with 1.5%.

3.2.9 Land use

Table 5 shows that the total impact on land use amounts to 0.03 m^2/MWh and that most of the impact is from the construction phase (99%). The remaining fraction is contributed by the operation & maintenance phase. This impact category is mainly contributed by land use transformation for infrastructure development during the construction stage and a minor contribution from the operation & maintenance stage.

3.3 Endpoint level impact assessment

According to Table 6, the results indicate that the impacts on human health, resource scarcity, terrestrial ecosystems and freshwater ecosystems amount to 1.34E-04 DALY, 9.48E-01 USD (2013), 4.01E-07 species.yr and 1.11E-11 species.yr, respectively. The results show that the four midpoint level impact categories that contribute to human health impact are climate change, stratospheric ozone depletion, photochemical ozone formation and particulate matter formation. The four midpoint level impact categories that contribute to terrestrial ecosystem impact are climate change, photochemical ozone formation, terrestrial acidification and land use. The results also show that climate change and freshwater ecotoxicity are the two midpoint impact level categories that contribute to freshwater ecosystem impact. With regard to the endpoint impact on resources, it is mostly contributed by fossil resource scarcity; mineral resource

Table 6. Endpoint results of the Kamchay hydropower plant based on 1 MWh of electricity.

Midpoint	Endpoint			
	Human Health (DALY)	Terrestrial Ecosystems (species.yr)	Freshwater Ecosystems (species.yr)	Resources (USD2013)
Climate Change	1.31E-04	3.95E-07	1.08E-11	-
Stratospheric Ozone Depletion	2.76E-09	-	-	-
Photochemical Ozone Formation	2.49E-08	3.52E-09	-	-
Particulate Matter Formation	2.99E-06	-	-	-
Terrestrial Acidification	-	2.69E-09	-	-
Freshwater Ecotoxicity	-	-	2.95E-13	-
Mineral Resource Scarcity	-	-	-	4.75E-07
Fossil Resource Scarcity	-	-	-	9.48E-01
Land use	-	3.07E-10	-	-
Total	1.34E-04	4.01E-07	1.11E-11	9.48E-01

Table 7. Comparing the life cycle GHGs of the Kamchay hydropower plant with fossil fuel power plants [10, 34, 39].

Type of power plant	Total GHG emissions kg CO_2-eq./MWh	Comments
This study	141	The construction phase and decomposition of biomass are the major contributor.
Hydropower	4.2-273	
Coal	800-1000	The GHG emissions of fossil fuel mainly come from the process of combustion of each source.
Oil	700-800	
Natural gas	360-608	

scarcity contributes a negligible share to this impact. These findings indicate that climate change is the most significant midpoint level impact category as it plays a major role in human health and ecosystem impacts. For both these endpoint level impact categories, photochemical ozone formation is also involved but with a marginal contribution. Land use and freshwater ecotoxicity contribute minor shares to the impacts on ecosystem. Concerning the major contribution of climate change to endpoint level impact categories, based on the analysis of the data in Table 5, these are mostly related to emissions from the construction and operation & maintenance steps.

3.4 Comparison of results with literature

The results of this study show that GHG emissions are major contributors to the life cycle environmental impacts of the Kamchay hydropower plant. Construction, and operation & maintenance phases were identified as the main contributing steps to GHG emissions, i.e. 22% and 77% of the total GHG emissions, respectively. These results follow those of Amponsah et al. [35] who also indicated that construction and operation are the main contributing steps to GHG emissions from hydropower plants. As part of the operation & maintenance phase, the decomposition of biomass in the flooded land of the Kamchay power plant reservoir was found to contribute the largest share of the GHG emissions from the plant. This major contribution from the reservoir is in line with findings from Amponsah et al. [35]. The total GHG emissions from the Kamchay hydropower plant were estimated to be 141 kg CO_2-eq./MWh. This value is within the range of values provided by the literature for similar types of plants, i.e. 4.2-273 kg CO_2-eq./MWh [35-37]. Differences in geographic location, age, climate condition, reservoir characteristic and installed capacity are among the main factors influencing the GHG emissions from hydropower plants with reservoir type [38].

When comparing the greenhouse gases performance of hydropower to fossil fuels, Table 7 shows that the Kamchay hydropower plant is much more competitive than coal, oil and natural gas. The life cycle GHG emissions from the plant are about 5 to 7 times lower than coal, 5 to 6 times lower than oil and 3 to 5 times lower than natural gas. Carbon dioxide plays a crucial role in the GHG emissions from coal, oil and natural gas power plants, with significant contributions from the fuel combustion during electricity production (i.e. 91, 95 and 75% respectively).

3.5 Environment hotspots and mitigation options

The construction and operation & maintenance steps were found to contribute most of the GHG emissions from the Kamchay hydropower plant. Construction is the step that was also found not only to dominate the impacts on climate change but also most of the other midpoint level impact categories. Hence, mitigation strategies should focus on this initial life cycle step of the Kamchay hydropower plant to reduce emissions of GHGs as well as other pollutants. The construction phase requires construction materials, land use, and energy for the development of the plant's infrastructures. As this hydropower plant is located in a mountainous area (tropical region), the GHG emissions related to land use change and land flooding to establish a reservoir should be further investigated to provide adequate mitigation options for the sustainable development of the hydropower sector in Cambodia.

One mitigation option that can be considered relates to the large amount of construction materials required to build the dam. This is particularly the case for cement and steel which are responsible for high emissions of GHGs during that phase. According to a sensitivity analysis by Pang et al. [11], if the cement consumption could be decreased by 10%, the impact of GHG emissions on the global warming potential could be reduced by 7%. In the process of cement production, the ratio of clinker to cement could also be reduced to around 0.6 using pozzolan. This would contribute to further reduce GHG emissions from cement production by 25% [40]. Construction materials, such as steel pipes, could also be replaced by reinforced plastic whenever possible as they are more environmentally friendly than steel pipes [11, 41]. The effective environmental mitigation options of all kinds of the hydropower projects should be adopted as the "Hydropower Good Practice". This should also include practices where environmental and social problems were resolved successfully as a result of mitigation measures and the practices that provided environmental and/or social benefits through hydropower development [42].

With regard to land use change, the impact from infrastructure development during the construction phase should be minimized, notably by selecting sites where the loss of ecosystem is reduced [42]. Afforestation on an area equivalent to the land use impacted by hydropower is also highly recommended by planting trees nearby the construction area [43-44]. Measures consisting of selecting adequate construction sites and promoting afforestation would contribute to improve environmental performance, in particular with regard to GHG emissions and biodiversity preservation.

As stated earlier, negative impacts from hydropower plants with reservoir type (or dam-toed) relate to the biogenic emissions of CO_2 and CH_4 from the decomposition of biomass in the flooded land during its operation [12-13]. These emissions influence the impact of the operation & maintenance phase on climate change. The rate of release of these emissions depends on several conditions including, volume, age and geographic location [10, 36, 39]. For the future development of such type of hydropower plants, limitations should therefore be introduced regarding the size of the reservoir based on technical, economic and environmental considerations. Also, an important priority area to reduce environmental impacts from hydropower plants concerns the construction sites which should be selected taking into consideration the minimization of ecosystem losses [42, 44]. It is highly recommended that the GHG emissions from the decay of biomass in the flooded land of reservoirs throughout the lifespan be included as part of the environmental impact assessment (EIA) reports of future hydropower plants to be developed in Cambodia.

4. Conclusion

The LCA study of the Kamchay hydropower plant in Cambodia demonstrates that the major impact is from the GHGs released during the construction phase and the decomposition of biomass in the flooded land of the reservoir during its operation.

The rest of the emissions throughout the life cycle of the plant have a marginal contribution. Climate change is the main impact category, contributing the largest damage to human health and ecosystem. Resource scarcity is mainly contributed by the resources used during the construction and transportation phases for infrastructure development as well as the resources used in the operation & maintenance and the demolition & disposal phases. Total greenhouse gas emissions from this plant are 141 kg CO_2-eq. per MWh. This value lies within the range of emission values reported in the literature and is lower than the GHG emissions from fossil fuel power plants. The Kamchay hydropower plant is therefore a better option to enhance the production of electricity in the country.

Based on the environmental hotspots identified in this study, some mitigation options for the environmental performance improvement of hydropower in Cambodia were suggested. The construction site should be selected taking into account the minimization of ecosystem loss along with the implementation of afforestation measures to compensate for the loss of vegetation due to infrastructure development. Also, reinforced plastics could be used to substitute steel and the amount of cement reduced including the reduction of the clinker to cement ratio by using pozzolan. The findings of this study provide useful information to policy makers, stakeholders, owners and developers to select and implement adequate measures for the sustainable development of hydropower in Cambodia and also other parts of the world with similar characteristics.

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