Are large-scale dams environmentally detrimental? Life-cycle Environmental Consequences of Mega-Hydropower plants in Myanmar

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Graphical Abstract

A close up of a map

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Abstract

*Purpose:* Rivers control biophysical processes that underpin essential ecosystem services. Myanmar’s rivers provide great opportunities for increasing energy supply at low costs from hydropower plants and make important contributions to the national economy. However, associated environmental impacts, as well as input and output flows of hydropower developments remain less well understood. In this paper, we report on an investigation of the overall environmental effects of five hydropower plants in Myanmar, using a life-cycle impact assessment (LCIA) approach. The primary objective of this paper is to generate detailed life-cycle inventory data and quantify the environmental impacts of the existing five hydropower plants in Myanmar.

*Material and Method*: This paper reports on a “cradle to grave” LCIA of five hydropower plants in which environmental impacts associated with the construction, operation and maintenance, transportation, and decommissioning of large-scale hydropower plants in Myanmar were systematically assessed.

*Results:* The study shows that the construction, transportation, operation and maintenance phases are most sensitive to global warming, mineral resource depletion, acidification, freshwater aquatic ecotoxicity, human toxicity and photochemical ozone creation. There is heterogeneity in hydropower plants’ effects on the environment, based on the size of the powerplant.

*Conclusion:* In this paper, the complexities of hydropower plants affecting multiple environmental impacts is illustrated. Furthermore, it is suggested that a strategic selection of hydropower projects may enhance environmental resilience in environmentally sensitive areas. It is concluded that more comprehensive and rigorous environmental and social impact assessment (ESIA) is needed, not only for mega dams, but also for the smaller scale hydropower plants.

Keywords: Renewable energy, Hydropower, Myanmar, LCIA, Environment, Mega-dams.

Introduction

Myanmar currently has one of the lowest electrification rates in Asia, with less than one-third of the population having access to the electricity grid. There is also a marked rural-urban divide in access to electricity, with 75% of the urban population, but only 16% of the rural population enjoying electrification (Tsai, 2015). Electricity demand is growing at a rate of 15% per year, and an estimated amount of 500 MW additional generation capacity is needed annually to meet demand (Karen Human Rights Group, 2018). Myanmar aims to develop hydropower as a long-term energy solution. According to the 2015 National Electrification Plan, the country plans to triple hydropower capacity by 2030 (Asian Development Bank, 2015). Hydropower therefore has the potential to become a vital source of renewable energy.

However, the development of new hydropower plants in Myanmar is controversial and is often met with criticism due to a failure to consider effects on ecosystems. Although hydropower is considered to be environmentally benign compared with many other energy sources, negative environmental and social costs of hydropower plants are well-documented. If poorly planned, environmental, social, economic and human rights’ consequences of hydropower development projects can be significant and far-reaching (International Union for the Conservation of Nature, 2015). Hydropower plants require clearing of land, the use of large amounts of construction materials and electricity. Furthermore, water flows need to be diverted. During the construction of a dam, changes to water flows significantly affect surrounding ecosystems, flood regimes and sediment movements. For example, a 40% to 60% decline in migratory fish biomass was observed in the Mekong River basin due to the development of mainstem hydropower dams (Opperman et al., 2017). There can also be social conflict, in particular in connection with ownership and access to both, land and water. Hydropower projects are frequently extensive and involve complex construction and operation stages that are site-specific. Therefore, impacts can be very diverse.

Myanmar’s current approach to hydropower development fails to deliver sustainable hydropower and does not support management of associated environmental and social issues (Han, 2018). Projects are developed solely based on the economic return and engineering feasibility and little to no consideration is given to ecological and social impacts. As a consequence, the magnitude of environmental effects of hydropower projects is mostly unknown. Environmental impacts of hydropower projects can be estimated through life-cycle impact assessment (LCIA). The life-cycle based environmental assessment of hydropower projects allows to investigate the intensity and magnitude of impacts.

Currently, except for the sector-wide Strategic Environmental Assessment (SEA) conducted by the Ministry of Electricity and Energy (MOEE) and Ministry of Natural Resources and Environmental Conservation (MONREC), there are no studies investigating the environmental impacts of hydropower plants in Myanmar. In order to address this shortcoming, this paper reports on a “cradle to grave” LCIA that systematically assessed environmental impacts associated with the construction, operation and maintenance, transportation, and decommissioning of large-scale hydropower plants in Myanmar. LCIA is a tool that considers all material and energy use from “cradle-to-grave” (Pascale, Urmee, & Moore, 2011). It allows quantifying cumulative impacts of the system at local and global scales. Although LCIA has been applied to explore impacts of electrification systems, there are few studies solely focusing on large-scale hydropower plants (see Pang et al., 2015; Suwanit & Gheewala, 2011). Given that the hydropower plants’ environmental impacts are largely site-specific, extrapolation of LCA results from other parts of the world only offer limited support (Botelho et al., 2017).

The results presented in this paper can help to determine what life-cycle phases potentially have the most significant environmental impacts. Furthermore, intensity of environmental impacts is compared, based on the size and capacity of the plants. We believe that findings are particularly useful for policy makers, project developers, local communities and researchers in the decision-making process at the national level in Myanmar.

Materials and Methods

We followed the LCA framework proposed by ISO 14040 and 14044 with a slight modification in order to make it more suitable for the Myanmar context. The following phases were included:

* Goal and scope definition (system boundaries and functional unit)
* Life cycle inventory (LCI) data collection on hydropower plants in Myanmar
* Data and process entry to open LCA software
* Life cycle impact analysis (LCIA) and comparison of results

*Myanmar Hydropower Sector Description*

Myanmar has an underdeveloped hydropower potential, estimated at 108 gigawatts (GW). Hydropower could solve the country’s serious energy poverty. The estimated potential capacity is more than ten times the current total electricity generating capacity from all sources combined, including fossil fuel and renewable energy (Dapice, 2015). Table 1 presents Myanmar’s energy balance projection. The hydropower sector in Myanmar is still at an early stage of development with only about 3298 MW installed capacity from 29 small-scale projects (10 MW), accounting for 58% of national energy supply as of 2018 (Porter, 2018). In recent years, the government has identified 92 potential projects to harness the full potential of the sector (Han, 2018). Six projects with a total installed capacity of 1564MW are under construction and a total of 43848 MW capacity is proposed for 69 small- and large-scale projects nationwide, including six mega-dams with over 2000 MW capacity each and seven dams above 1000 MW capacity each. Approximately 64% of all projects are located in the Ayeyarwady river basin and 25% in the Sittaung river basin (Kirchherr et al., 2017).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Categories | 2012 | 2015 | 2018 | 2012 | 2024 | 2027 | 2030 | Total Share (%) 2018 |
| Hydropower | 0.7 | 0.8 | 0.9 | 1.6 | 1.9 | 2.5 | 2.8 | 5.7 |
| Solar PV & Wind | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gas | 13 | 16.6 | 15.7 | 12.8 | 11.3 | 9.1 | 8.5 | 13.5 |
| Coal | 0.2 | 0.3 | 0.5 | 0.7 | 0.8 | 1.1 | 1.3 | 3.3 |
| Oil | 1 | 1 | 1.5 | 2.2 | 3.5 | 3.6 | 3.6 | 22.9 |
| Biomass Type II | 8.8 | 8.9 | 9 | 9 | 8.8 | 8.6 | 8.4 | 54.6 |
| Total Production | 23.7 | 27.5 | 27.7 | 26.3 | 26.4 | 24.9 | 25.1 |  |
| Total Supply | 13.5 | 16.2 | 16.5 | 17.6 | 20.2 | 22.4 | 25.6 |  |

Table 1: Myanmar Energy Balance Projection to 2030 (mtoe)

Myanmar has an opportunity to develop the sector sustainably by harmonizing the much needed electricity generation with sustainable environmental and social outcomes (The Nature Conservancy, 2016). However, in Myanmar, hydropower projects are currently granted without the consideration for individual and cumulative impacts on river basins, other ecosystems and livelihoods. Myanmar is blessed with abundant freshwater resources, and more than 70% of the livelihood of the population depends on riverine and freshwater ecosystem services. Aquatic resources are essential for the national economy and communities in Myanmar, as nearly 3.2 million people are currently employed in the freshwater and marine fisheries sector. Despite the potentially important role the hydropower sector might play for the socio-economic development of the country, the industry currently faces several challenges due to public opposition and public protest, especially by ethnic minority communities (Simpson, 2013). As a result, eleven hydropower projects are currently suspended, and one has been cancelled. The most contested dam projects in Myanmar are the Chinese-led Myitsone dam (suspended) in Kachin State, Mong Ton dam and Upper Panlaung dam in Shan state, and Tamanthi dam in the Sagaing division (Kirchherr et al., 2017). The opposition mostly stems from the opaque and unjust revenue sharing and the environmental and social risks associated with the projects. While Myanmar is in dire need of electricity generation and investment in the energy sector, the country currently does not reap the full benefits from those mega hydropower projects developed jointly with neighbouring countries, especially China and Thailand (Dapice, 2015). The contracts signed with China to develop several mega hydropower projects state that Myanmar will get only a 10% of the revenue (in the form of electricity) while China will get 90%.

*Study Areas Description*

The hydropower plants considered in this paper are the existing projects of at least 100 MW installed capacity, covering medium to large size projects in Myanmar. All plants have similar local and technological contexts. Hydropower plants of this size have a higher potential to create adverse environmental impacts as they are likely to be located on larger river basins and have higher dams and larger reservoirs. More extensive projects also have higher risks of creating more significant flow charges and cutting river connectivity. However, the cumulative environmental and social impacts of smaller projects can be more significant than those of larger dams (International Finance Corporation, 2018). The projects chosen for further examination are Yeywa, Shweli (1), Paung Laung (lower), Dapein (1) and Thauk Ye Khat (2). Fig 1 presents the location map of these plants that were built between 2005 and 2014 and represent standard construction, operation technology and geographic locations of the hydropower plants in Myanmar. The technical parameters and descriptions of each individual hydropower plant are summarized in Table 2.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Description | Yeywa | Shweli 1 | Paung Laung (lower) | Dapein 1 | Thauk Ye Khat 2 |
| Location | Mandalay, Pyinoolwin | Shan, Muse | Naypyidaw, Pyinmana | Kachin, Bhamo | Kayin, Tangoo |
| LAT N/ LON E | 21.675, 96.474 | 23.698, 97.506 | 19.785, 96.335 | 24.421, 97.525 | 18.914, 96.619 |
| Basin | Ayeyarwady | Ayeyarwady | Sittaung | Ayeyarwady | Sittaung |
| Sub-basin | Myitnge | Shweli | Paung Laung | Dapein | Thauk Ye Khat |
| Status | Built | Built | Built | Built | Built |
| Developer | Ministry of Electricity and Energy (MoEE) | China Datang | Ministry of Electricity and Energy (MoEE) | China Datang | Gold Energy |
| Country | Myanmar | People Republic of China | Myanmar | People Republic of China | Myanmar |
| Investment Type | Sole | Foreign Joint Venture | Sole | Foreign Joint Venture | Sole |
| Commission Year | 2010 | 2009 | 2005 | 2011 | 2014 |
| System Design | Run-of-River | Run-of-River | Run-of-River | Run-of-River | Run-of-River |
| Installed Capacity (MW) | 790 | 600 | 280 | 240 | 120 |
| Domestic Use (MW) | 790 | 400 | 280 | 19 | 120 |
| Export | 0 | 200 | 0 | 221 | 0 |
| Annual Generation (GWh) | 3550 | 4022 | 911 | 1065 | 604 |
| Firm Power (MW) | 175 | 175 | 104 | 30 | 101 |
| Dam Type | Roller-Compacted-Concrete (RCC) | Roller-Compacted-Concrete (RCC) | Roller-Compacted-Concrete (RCC) | Concrete | Earth |
| Dam Height (m) | 132 | 47 | 131 | 46 | 94 |
| Catchment Area (km2) | 28,206 | 12,597 | 4,381 | 6,002 | 2,175 |
| Catchment Annual Rainfall (mm) | 838 | 1,418 | 1,650 | 1,330 | 2,692 |
| Mean Annual Inflow into Reservoir (m3/s) | 483.0 | 400.0 | 128.0 | 319.0 | 50.5 |
| Reservoir Area (km2) | 59.0 | 1.1 | 17.0 | 0.4 | 13.8 |
| Power House Type | Above Ground | Above Ground | Above Ground | Above Ground | Above Ground |

Table 2: Project description of the five hydropower plants in Myanmar

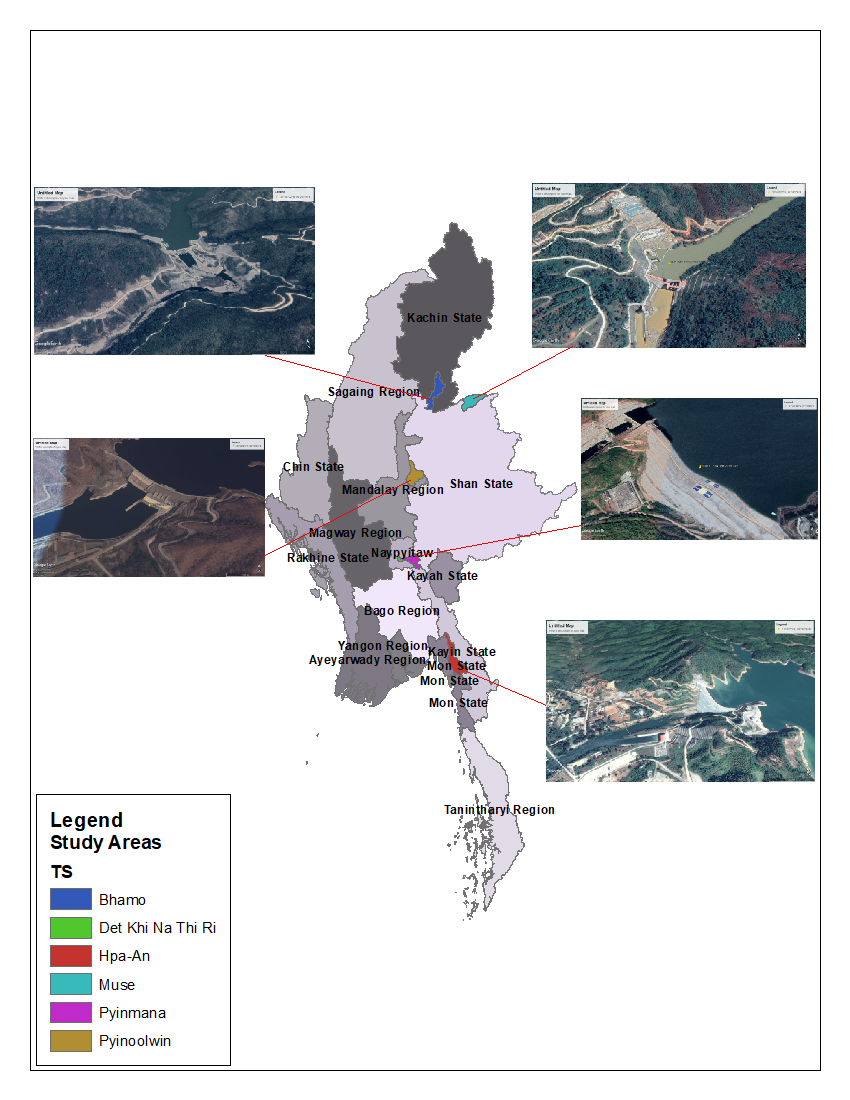


Figure 1: Location map of the five hydropower plants in Myanmar

*System Boundaries*

Following the recommendation of Ribeiro & da Silva (2010), the assumed life span of hydropower plants is 100 years. As illustrated in Fig. 2, the operational stages and the system boundaries of the life-cycle of the plants cover construction (e.g. main dam, powerhouse, spillway, equipment installation), operation and maintenance (electricity generation and overall maintenance activities through the power plants’ end-of-life), and decommissioning stages. Activities before the construction and transportation of material also need to be considered. Hydropower plants are designed to capture the energy of rivers to generate electricity. The dams are constructed to raise water levels of rivers and control the water flow, and the reservoir is formed to store energy. The water then flows into turbines installed in the powerhouse through a penstock. Turbines convert the kinetic energy of water into mechanical energy before the generator converts this into electrical energy. Finally, the transmission lines transport electricity from hydropower plants to local and foreign grids.

A screenshot of a cell phone

Description automatically generated

Figure 2: Simplified Product System Boundary for Hydropower plants in Myanmar

*Functional Unit*

The functional unit (FU) in the project underlying this paper is defined as 1 MWh of net electricity production from a hydropower plant in Myanmar in a 100 year life span. The life-cycle environmental impacts of plants are expressed quantitatively based on this unit.

*Goal and Scope Definition*

The goal of the project underlying this paper was to generate detailed life-cycle inventory data and quantify the environmental impacts of the existing five hydropower plants in Myanmar. The plants are evaluated based on the process-based LCA methodology, following ISO 14040 and ISO 14044. The approach of the project is cradle-to-grave assessment, including all aspects of the hydropower plant life-cycle from the raw material and energy resource consumption, transportation and deterioration of electric equipment to the handling of waste from the demolition of the plant.

*Life-cycle Inventory Analysis*

The lifecycle inventory (LCI) analysis consists of the collection of all relative inputs (raw material, fuel, water, energy) and outputs (product, emission, waste) throughout the lifecycle of the dams. LCI requires both, primary (local level) and secondary (global level) inventory data (Pang et al., 2015). Primary data for inputs and outputs were gathered from the engineering plants and design reports provided by the Myanmar Ministry of Electricity and Energy (MOEE). Interviews with the professionals involved in the construction from China and Myanmar and site visits were also conducted. This was supplemented by a comprehensive review of construction reports and project design documents of the power plants, detailed lists of the materials and equipment, and other reports. Secondary data for the inputs of the background process (life-cycle burden of equipment manufacturing, electricity consumption and transportation) were collected from the Ecoinvent 3.5 LCA database for hydropower projects. Data from the Ecoinvent have been adapted to reflect local conditions, such as the fuel composition and disposal methods in Myanmar.

There are no official data that would allow to estimate GHG and biomass-related emission factors from the decommissioning of dams. Previous hydropower plants’ LCAs that included GHG emissions relied primarily on the data directly obtained from hydropower companies (Verán-Leigh & Vázquez-Rowe, 2019). We were unable to obtain such data and relevant secondary databases are also not representative. In most hydropower LCA research, data quality for GHG emissions is often problematic due to uncertainties (Ribeiro & da Silva, 2010). Detailed lifecycle inventory data for the production of 1 MWh net electricity by hydropower plants in Myanmar are shown in Table 3. The hydropower construction phase includes inputs and outputs from land preparation, construction of the foundation formwork, reinforced concrete structure dam, penstock, powerhouse, tailrace and substation, and equipment installation. Energy consumption (electricity and diesel fuel) and materials flows (steel, stainless steel, iron and aluminium) are included at this stage. The energy used for the manufacturing of the equipment is beyond the scope of the study and is excluded from the LCIA. Extraction and smelting of metal materials account for the majority of the environmental impacts associated with equipment manufacturing (Pang et al., 2015).

Transportation of construction materials and equipment to the plant sites were also inventoried (in-country and overseas, i.e. China). Most of the explosive, wood and diesel fuel were purchased and transported locally by road, whereas cement, steel, transformers and cranes were transported from the manufacturers in China by road and ship. The inventory data for this stage consist of the transportation of materials for the construction to demolition stage of the plants. The distances for this stage, including transportation of materials for construction and maintenance stage, and recyclable materials transported to recycling facilities by truck, were estimated from Google Earth Pro (<https://www.google.com/earth/versions/#earth-pro>). Ship transportation calculator (<http://ports.com/sea-route/port-of-shanghai,china/port-of-yangon,myanmar/>) was used to estimate transoceanic shipments. The main resource inputs for the operation and maintenance phase of the hydropower plant is the natural water flows needed for electricity generation as well as electricity used over the operational life of the plant. At the maintenance stage, the upstream production of materials are the main reasons for environmental impacts. The replacement of turbines, spear tips, nozzles, seal plates and lubricant oil are also included.

Emissions from reservoir flooding are considered to be a significant source of GHG emissions generated from hydropower plants. Although the lack of readily available data for the system under study presents significant challenges for the life-cycle inventory, we used alternative well-established approaches to calculate the emissions from the reservoir. It is important to note that emissions from the decaying biomass from land flooded by the reservoir depends on the size of the reservoir. Despite the fact that Run-of-river (ROR) plants do not produce notable GHGs (Gagnon, 1997; Koch, 2002; Turconi, Boldrin, & Astrup, 2013) , Myanmar as a humid tropical country has the potential for higher GHG emissions than countries with a colder climate because hydroelectric dams in tropical areas generally emit more greenhouse gases than those in temperate or boreal areas due to increased emissions of N2O and CH4 (Fearnside, 2016b; Gagnon, 1997; Kare & Lomite, 2009; Koch, 2002; Tremblay, 2005; Turconi et al., 2014). This can be explained by water columns in reservoirs being stratified by temperature. Furthermore, oxygen at the bottom of the water is quickly exhausted in warmer climates. This leads to the decomposition of organic matter and formation of CH4 (Fearnside, 2016a). If water moves at sufficient speed stratification in the ROR dams is prevented. This is the case where reservoir volume is small and river stream flow is large.

Estimation of the biogenic emission inventory and the calculation of emissions generated by the biogenic decay in the reservoirs were conducted following the method of Verán-Leigh & Vázquez-Rowe, (2019) adapted from Hertwich (2013). Briones Hidrovo et al. (2017) also applied a similar method to assess GHG reservoir emissions in hydropower plants. This method allows to calculate biogenic emissions per unit of power generated by using energy production, land use, net primary production (NPP) and the age of the powerplant as variables. First, this study focuses on CO2 and CH4 emissions as greenhouse gases (GHGs). The emissions associated with the energy requirements are usually calculated from the process chain by multiplying the amount of energy inputs by its emission factor (Hondo, 2005). Some previous studies adopted an economic input-output approach to calculate GHG emissions associated with material manufacturing (Hondo, 2005; Varun et al., 2012; Verán-Leigh & Vázquez-Rowe, 2019; Q. Zhang et al., 2007). Due to the unavailability of economic data, it was not possible to conduct input-output analysis for the calculation of emissions from resource extraction and manufacturing. In this study, the quantification of the NPP for each powerplants was done based on the data from the Department of Meteorology and Hydrology (Myanmar), Koppen-Geiger climate zones classification of Myanmar (Myanmar Information Management Unit, 2010) and the NPP satellite data made available by Google Earth Engine data catalogue (NASA LP DAAC, 2000) (Haberl et al., 2007). NPP represents the amount of atmospheric carbon fixed by plants and accumulated as biomass (Peng et al., 2017). In other words, NPP is the rate at which an ecosystem accumulates energy minus the energy it uses for the process of respiration (Potter et al., 2013). We also cross-validated the NPP results with Myanmar countrywide NPP data (Wang et al., 2019). For more information about the use the Earth Engine public geospatial data catalogue, see (Gorelick et al., 2017). At the final step, we calculated the total biogenic emissions, using the following equation.

---------------(1)

Where E indicates the final estimated amount of emissions, land use refers to the total flooded area of the reservoir, age is the current lifetime of the plant since construction and NPP is the net primary production. The equation allows to predict CO2 and CH4 emission factors by considering the logarithms of land use, NPP and age of the powerplants. For more details about the regression coefficients and statistics parameters, refer to Hertwich (2013). CO2 equivalent was calculated on the basis of IPCC 2013 100-year method (Barros et al., 2011).

The next main focus is on the environmental impacts associated with the primary flows of material and energy during the life-cycle of plants. The decommission / demolition phases of hydropower plants consist of deconstruction, material disposal and material recycling at the end of life of a plant. Here, all chosen hydropower plants are in the operational phase of their lifecycles. Therefore, the primary information regarding this phase is minimal. In previous hydropower LCA research conducted in China and Thailand, it was assumed that 20% of the materials, such as steel, stainless steel, iron and copper, are recycled, and about 2% of the initial weight is reduced due to corrosion (Pang et al, 2015; Suwanit & Gheewala, 2011; Geller & Meneses, 2016). However, in our study, based on the conditions in Myanmar, we assumed that only about 15% of the materials can be recycled. Waste management and recycling in Myanmar currently suffers from weak technology, infrastructure, regulatory framework and human capacity (Premakumara et al., 2016). The inventory data for the environmental burdens of metal waste recycling were obtained from the Ecoinvent database.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Item | Unit | Yeywa | | Shweli 1 | | Paung Laung (lower) | | Dapein 1 | | Thuk Ye Khat 2 | |
|  |  | Unit\* Input | Total\*  Input | Unit Input | Total Input | Unit Input | Total Input | Unit Input | Total Input | Unit Input | Total Input |
| Construction Stage | |  |  |  |  |  |  |  |  |  |  |
| Material |  |  |  |  |  |  |  |  |  |  |  |
| Cement | kg/MWh | 2.88E-01 | 2.28E+04 | 2.94E-01 | 1.76E+04 | 3.30E-01 | 9.23E+03 | 2.72E-01 | 6.52E+03 | 1.94E-01 | 2.33E+03 |
| Construction minerals | kg/MWh | 9.80E-01 | 7.74E+04 | 9.80E-01 | 5.88E+04 | 9.89E-01 | 2.77E+04 | 9.23E-01 | 2.22E+04 | 6.60E-01 | 7.93E+03 |
| Steel | kg/MWh | 1.38E-02 | 1.09E+03 | 1.41E-02 | 8.46E+02 | 1.37E-02 | 3.85E+02 | 1.29E-02 | 3.10E+02 | 9.32E-03 | 1.12E+02 |
| Timber | m3/MWh | 8.07E-03 | 6.37E+02 | 8.23E-06 | 4.94E-01 | 8.24E-06 | 2.31E-01 | 7.60E-06 | 1.82E-01 | 5.44E-06 | 6.53E-02 |
| Explosive | kg/MWh | 8.65E-04 | 6.83E+01 | 8.23E-04 | 4.94E+01 | 8.79E-04 | 2.46E+01 | 9.32E-04 | 2.24E+01 | 5.83E-04 | 6.99E+00 |
| Diesel Fuel | kg/MWh | 3.63E-03 | 2.87E+02 | 3.68E-03 | 2.21E+02 | 4.34E-03 | 1.22E+02 | 3.42E-03 | 8.21E+01 | 2.45E-03 | 2.94E+01 |
| Electricity | kWh/MWh | 2.13E-02 | 1.68E+03 | 2.16E-02 | 1.29E+03 | 2.09E-02 | 5.85E+02 | 2.01E-02 | 4.82E+02 | 1.44E-02 | 1.72E+02 |
| Land use | m2/MWh | 2.51E+02 | 1.98E+07 | 1.70E-02 | 1.02E+03 | 1.52E-02 | 4.26E+02 | 2.23E-02 | 5.36E+02 | 6.14E-03 | 7.37E+01 |
| Equipment |  |  |  |  |  |  |  |  |  |  |  |
| Turbine |  |  |  |  |  |  |  |  |  |  |  |
| steel | kg/MWh | 2.36E-03 | 1.87E+02 | 2.41E-03 | 1.45E+02 | 2.42E-03 | 6.77E+01 | 2.23E-03 | 5.34E+01 | 1.59E-03 | 1.91E+01 |
| Stainless Steel | kg/MWh | 7.49E-04 | 5.92E+01 | 7.64E-05 | 4.58E+00 | 7.69E-05 | 2.15E+00 | 7.06E-05 | 1.69E+00 | 5.05E-05 | 6.06E-01 |
| Iron | kg/MWh | 4.21E-05 | 3.32E+00 | 4.29E-05 | 2.57E+00 | 4.07E-05 | 1.14E+00 | 3.96E-05 | 9.52E-01 | 2.84E-05 | 3.40E-01 |
| Aluminium | kg/MWh | 3.11E-06 | 2.46E-01 | 3.17E-06 | 1.90E-01 | 3.02E-06 | 8.46E-02 | 2.93E-06 | 7.04E-02 | 3.36E-06 | 4.03E-02 |
| Generator |  |  |  |  |  |  |  |  |  |  |  |
| Steel | kg/MWh | 1.73E-03 | 1.37E+02 | 1.76E-03 | 1.06E+02 | 1.70E-03 | 4.77E+01 | 1.63E-03 | 3.91E+01 | 1.17E-03 | 1.40E+01 |
| Cooper | kg/MWh | 1.21E-03 | 9.56E+01 | 1.23E-03 | 7.41E+01 | 1.15E-03 | 3.23E+01 | 1.09E-03 | 2.61E+01 | 8.16E-04 | 9.79E+00 |
| Speed governor | kg/MWh | 2.71E-04 | 2.14E+01 | 2.76E-04 | 1.66E+01 | 2.58E-04 | 7.23E+00 | 2.55E-04 | 6.13E+00 | 1.83E-04 | 2.19E+00 |
| Exciter (Steel) | kg/MWh | 2.77E-05 | 2.19E+00 | 2.82E-05 | 1.69E+00 | 2.69E-05 | 7.54E-01 | 2.61E-05 | 6.26E-01 | 1.86E-05 | 2.24E-01 |
| King valve (steel) | kg/MWh | 5.76E-04 | 4.55E+01 | 5.88E-04 | 3.53E+01 | 6.04E-04 | 1.69E+01 | 5.43E-04 | 1.30E+01 | 3.89E-05 | 4.66E-01 |
| Crane (steel) | kg/MWh | 7.49E-04 | 5.92E+01 | 7.64E-04 | 4.58E+01 | 7.69E-04 | 2.15E+01 | 7.06E-04 | 1.69E+01 | 5.05E-04 | 6.06E+00 |
| Water gate and screen (steel) | kg/MWh | 1.27E-03 | 1.00E+02 | 1.29E-03 | 7.76E+01 | 1.26E-03 | 3.54E+01 | 1.19E-03 | 2.87E+01 | 8.55E-04 | 1.03E+01 |
| Penstock(steel) | kg/MWh | 3.75E-03 | 2.96E+02 | 3.82E-03 | 2.29E+02 | 3.63E-03 | 1.02E+02 | 3.53E-03 | 8.47E+01 | 2.53E-03 | 3.03E+01 |
| Transformer | kg/MWh | 5.53E-04 | 4.37E+01 | 5.64E-04 | 3.39E+01 | 5.33E-04 | 1.49E+01 | 5.21E-04 | 1.25E+01 | 3.73E-04 | 4.48E+00 |
| Transportation stage | |  |  |  |  |  |  |  |  |  |  |
| Truck transport (20-t)  Ship | tkm/MWh  tkm/MWh | 3.40E-02  4.00E+00 | 2.69E+03  1.42E+07 | 3.47E-02  3.38E+00 | 2.08E+03  1.36E+07 | 3.30E-02  1.71E+01 | 9.23E+02  1.56E+07 | 3.20E-02  1.08E+01 | 7.69E+02  1.15E+07 | 2.29E-02  1.67E+01 | 2.75E+02  1.01E+07 |
| Operation and Maintenances Stage | | |  |  |  |  |  |  |  |  |  |
| Electricity | KWh/MWh | 8.07E-03 | 6.37E+02 | 8.23E-03 | 4.94E+02 | 8.24E-03 | 2.31E+02 | 7.60E-03 | 1.82E+02 | 5.44E-03 | 6.53E+01 |
| Lubricant oil | kg/MWh | 3.46E-04 | 2.73E+01 | 3.76E-04 | 2.26E+01 | 3.35E-04 | 9.38E+00 | 3.26E-04 | 7.82E+00 | 2.33E-04 | 2.80E+00 |
| Water flow | m3/MWh | 3.92E-04 | 3.10E+01 | 4.00E+02 | 2.40E+07 | 3.79E+02 | 1.06E+07 | 2.31E+02 | 5.54E+06 | 2.64E+02 | 3.17E+06 |
| Demolition Stage | |  |  |  |  |  |  |  |  |  |  |
| Steel landfill | kg/MWh | 1.04E-02 | 8.20E+02 | 1.06E-02 | 6.35E+02 | 1.04E-02 | 2.92E+02 | 9.78E-03 | 2.35E+02 | 6.99E-04 | 8.39E+00 |
| Iron landfill | kg/MWh | 4.09E-05 | 3.23E+00 | 4.17E-05 | 2.50E+00 | 3.96E-05 | 1.11E+00 | 3.86E-05 | 9.25E-01 | 2.76E-05 | 3.31E-01 |
| Aluminium landfill | kg/MWh | 3.00E-05 | 2.37E+00 | 3.06E-06 | 1.83E-01 | 2.91E-06 | 8.15E-02 | 2.82E-06 | 6.78E-02 | 2.02E-06 | 2.42E-02 |
| Stainless Steel landfill | kg/MWh | 7.49E-05 | 5.92E+00 | 7.64E-05 | 4.58E+00 | 7.69E-05 | 2.15E+00 | 7.06E-05 | 1.69E+00 | 5.05E-05 | 6.06E-01 |
| Copper landfill | kg/MWh | 1.21E-03 | 9.56E+01 | 1.23E-03 | 7.41E+01 | 1.21E-03 | 3.38E+01 | 1.14E-03 | 2.74E+01 | 8.16E-04 | 9.79E+00 |

Table 3: The inventory data for the selected hydropower plants in Myanmar \*Unit input is the amount of material needed per functional unit (1MW of hydroelectricity produced) \*Total input is the total amount of material used in the plants during the lifespan of 100 years

The quality of the inventory data was validated, using the Pedigree matrix proposed by Weidema, and Wesnaes (1996). The Pedigree matrix is based on five indicators, including reliability, completeness, temporal correlation, geographical differences and further technological differences. Table 4 shows uncertainty factors within the pedigree matrix. The numerical values are the data quality indicator (DQI) scores (1 to 5). Scores do not necessarily indicate good or bad data. Rather, they indicate how well the data relate to the intended goal and scope of the study (Edelen & Ingwersen, 2016).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Indicator score | 1 | 2 | 3 | 4 | 5 |
| Reliability | 1 | 1.05 | 1.10 | 1.20 | 1.50 |
| Completeness | 1 | 1.02 | 1.05 | 1.10 | 1.20 |
| Temporal correlation | 1 | 1.03 | 1.10 | 1.20 | 1.50 |
| Geographical correlation | 1 | 1.01 | 1.02 | 1.05 | 1.10 |
| Further technological correlation | 1 | 1.05 | 1.20 | 1.50 | 2.00 |

Table 4: Uncertainty factors applied together with the Pedigree Matrix Score

*Impact Assessment*

At this phase, results from the inventory analysis are portrayed, based on characterization models (CF), evaluating potential environmental impacts and significant impact pathways. Impact pathways are treated as the resource. Energy and materials used throughout the life cycle of hydropower plants have the most substantial influence on overall environmental impacts. Among several characterization factors, this study applies the CML 2001 baseline impact category (midpoint) to calculate the life-cycle environmental impact. This method was previously used for assessing mini-hydropower plants in several countries such as Thailand, Brazil, Tanzania, Mexico and China (Geller & Meneses, 2016; Pang et al., 2015; Santoyo-Castelazo et al., 2011; Suwanit & Gheewala, 2011; Felix & Gheewala, 2012; Pascale et al., 2011). Table S2 in the supplementary material summarizes the selected LCA studies involving hydropower electricity generation. Here, large-scale hydropower plants were analysed using CML 2001 and generating site-specific life cycle inventories. The impact categories in this method include global warming potential, acidification potential, mineral resource depletion potential, freshwater aquatic ecotoxicity potential, human toxicity potential, photochemical ozone creation potential and fossil fuel resource depletion potential, expressed based on the functional unit (Table.5). The study used freely available Open LCA 1.8 software to calculate and compare LCIA results for the five hydropower plants.

|  |  |  |  |
| --- | --- | --- | --- |
| Impact Category | Symbol | Unit | Description |
| Global Warming Potential (100 years) | GWP | kgCO2-eq | The potential global warming caused by the emission of greenhouse gases (CO2, CO, N2O, CH4) |
| Mineral Resource Depletion Potential | MRDP | g Sb-eq | Non- living resource depletion |
| Acidification Potential | ACP | g SO2-eq | Atmospheric pollution arising from acidifying gases being emitted to the atmosphere (SOx, NOx, N2O) |
| Freshwater Aquatic Ecotoxicity Potential | FWAP | kg DCB-eq | The effects of toxic substances on the freshwater aquatic ecosystem (Heavy metal substances) |
| Human Toxicity Potential | HTP | kg DCB-eq | The effects of toxic substances on the human environment (Dust, SO2, NOx, As, Pb, Mn, Hg, Ni, Se) |
| Photochemical Ozone Creation Potential | POP | g C2H4-eq | Primary air emissions forming ozone due to increase of ultraviolet UV-B radiation |
| Fossil Fuel Resource Depletion | FRP | g Sb-eq | Non-renewable energy depletion |

Table 5: Environment Impact categories

Results and Discussion

*Life Cycle Impact Assessment*

The LCIA characterization results per MWh electricity generation from the five hydropower plants in Myanmar are presented in Table 6. Tables 3 provides the contribution of each impact category per MWh for the entire life-cycle of the power plants. All five hydropower plants follow a similar pattern in LCIA results in terms of the contribution of life-cycle phases. The construction phase is the dominant contributor in all hydropower plants and for every impact category except for the FRP where the primary source is associated with the transportation phase. The high environmental and health impacts of the construction phase of hydropower plants can be attributed to a large number of raw materials and energy resources, required for the manufacturing of cement, steel, electricity and equipment. Transportation is the second-largest source of environmental burden for GWP, ACP, MRDP, POP and FRP. Transportation, operation and maintenance phases contribute equally to the FWAP and HTP. As the majority of the construction materials and equipment are imported from overseas, the transportation phase contributes significantly. Operation and maintenance phases represent a large share of ACP, MRDP and FRP, but see smaller shares in all other impact categories. The demolition phase of the hydropower plants comprises a minor percentage of all impact category results for all selected hydropower plants in Myanmar. This result is connected with most of the materials remaining on-site. They can partly be used for recycling after the end of their lifetime. Although recycling capacity in Myanmar is lower than in many other countries, the total impacts of waste production at the demolition stage can be insignificant compared with the impacts from the manufacturing of the materials used in the construction phase of the power plants (see table 3). However, although outside the scope of this study, CO2 equivalent emissions from the accumulated sediments in the reservoir can be noticeably higher in the decommissioning phase of the dam and should be considered in the Global Warming Potential impact category in future studies (Felix & Gheewala, 2012; Pacca, 2007).

Given the similarities in dam type, local climate and material used in construction, no large variations were observed among the selected power plants for all environmental indicators, except for FRP (see Fig.3). A high variability in FRP can be due to the differences in fuel efficiency, depending on dam size and generation capacity of the powerplants. Based on the results, smaller plants, Dapein 1 and Thuk Ye Khat 2 have higher FRP potential than larger plants. Similar results were also found for MRDP, ACP and HTP, where larger dams overall appear to have lower impacts. For GWP, FWAP and POP, the environmental concerns, both large and small, are similar. These results support the observations in previous LCA studies of hydropower systems, namely that smaller hydropower plants can result in higher environmental impacts per MWh (Pascale et al., 2011). Larger dams are considered more environmentally sustainable than smaller dams in terms of impact per amount of electricity generated (Rao, 1989; Koch, 2002). Kibler & Tullos (2013) also found that biophysical impacts of small hydropower projects can be higher than for larger dams. Although all the dams considered in this study can be classified as large dams (>10MW)(J. Zhang et al., 2015), these findings indicate that this observation is true even among the dams generally categorized as large.

Fig.4 illustrates the contribution analysis of materials and energy inputs. Cement is the biggest source of environmental burden in terms of GWP, MRDP, ACP and POP of the two largest hydropower dams, Yeywa and Shweli 1. These two dams have an installed capacity of 790MW and 600MW, respectively, and are almost two to three times larger than the remaining three dams. The large amount of cement used in the construction phase of the plants can result in large emissions of GHGs and other atmospheric pollution, contributing greatly to GWP, ACP and POP. From a life-cycle perspective, this can be attributed to significant emissions per unit of cement processes (Mahasenan et.al,2002). The production of cement can lead to the release of significant amounts of GHGs and CO2 (Naik, 2007). The extensive mineral resource depletion (MRDP) occurrs due to using large amounts of raw materials, such as limestones, clay and water (Kare & Lomite, 2009). Furthermore, direct emissions from cement production, especially SOx, NH3, N2O, SO2 and NOx, result in acidification (ACP) (Chen et al., 2010). In this regard, the environmental burdens from cement use are similar in both, large and small dams, regardless of the construction complexity of larger dams. In Paung Laung (lower), Dapein 1 and Thuk Ye Khat 2, cement is mostly responsible for GWP, MRDP and ACP, but the contribution of diesel fuel is highest for POP. This variability can be due to the lower fuel efficiency associated with smaller dams (Rao, 1989). Inventory data show that diesel fuel consumption in smaller dams is similar or even higher than that of the larger dams (See table 3). POP is measured in LCIA to address the “photo-oxidant formation” impact category and provides factors for volatile organic compounds (VOC) ( Labouze et al., 2004). VOC are considered an environmental concern because of their important contribution in the formation of photochemical oxidants, particularly ozone (Andersson-sköld et al., 2012). The combustion of diesel fuel can be significant in VOC emissions from these plants.

Cement and diesel fuel are the main sources of ETP of the Yeywa hydropower plant, whereas the environmental burden from electricity dominates HTP in the other four plants. This is mainly due to the differences in the sources of electricity used during construction, operation and maintenance stages. On the other hand, diesel fuel and electricity represent the largest impacts for FRP in all powerplants. The consumption of diesel fuel and electricity have a direct impact on the FRP. This can be explained by the similar amount of fuel and electricity inputs in all powerplants, regardless of size. A similar pattern is observed for the emission factors. Contribution from steel is the highest for FWAP for all power plants. It might be reasonable to assume that these results are attributable to heavy metal discharges into water typically associated with steel manufacturing. The production process of steel releases several types of heavy metals, such as lead, chromium and copper into the water which can be toxic to aquatic ecosystems (Goleman et al., 2019; Zakrzewski, 2002). It is also important that about 80% of the steel is estimated to be dumped in landfill for all plants (see table 3). A possible explanation for the large share of waste generation is the lack of advance recycling technologies in Myanmar. Similar scenarios can be observed for stainless steel, aluminium and copper, although the environmental impacts from these materials are negligible in all cases.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Impact Category | Unit | Yeywa | Shweli 1 | Paung Laung (lower) | Dapein 1 | Thuk Ye Khat 2 |
| Global Warming Potential (GWP100) | kgCO2-eq | 22.81 | 22.80 | 23.09 | 27.48 | 28.91 |
| Mineral Resource Depletion Potential | g Sb-eq | 92.7 | 94.29 | 103.62 | 108.86 | 139.29 |
| Acidification Potential | g SO2-eq | 76.59 | 82.28 | 110.4 | 129.3 | 132.29 |
| Freshwater Aquatic Ecotoxicity Potential | kg DCB-eq | 4.2 | 6.87 | 6.47 | 7.52 | 9.06 |
| Human Toxicity Potential | kg DCB-eq | 22.4 | 33.18 | 38.35 | 38.85 | 50.13 |
| Photochemical Ozone Creation Potential | g C2H4-eq | 4.35 | 6.57 | 6.8 | 7.83 | 8.47 |
| Fossil Fuel Resource Depletion | g Sb-eq | 34.11 | 38.69 | 35.95 | 64.16 | 89.87 |

Table 6: Life-cycle Environment Impact Resulted from the 1 MWh electricity produced form the five hydropower plants in Myanmar \*The higher value represents the bigger environmental impact per 1MWh of electricity production.

A screenshot of a cell phone

Description automatically generated

Figure 3: Percent of life-cycle environmental impact potential of five hydropower plants

*Global warming potential（GWP）*

This impact category refers to global warming potential, based on emissions of greenhouse gases (CO2, CO, N2O, CH4) as a result of the hydropower plants. Most of the global warming potential in hydropower generation originates from the construction stage in all hydropower plants (Fig.3). This is explained by upstream manufacturing of materials and equipment that are used in construction and that are usually very energy-intensive and polluting. At this stage, hydropower plants consume a substantial amount of materials and equipment, and, therefore, contribute substantially to the GWP. Felix & Gheewala (2012) reported that GHG emissions from hydropower plants come from both, construction of infrastructures and reservoirs. Nevertheless, as mentioned in the life-cycle inventory section, many factors such as dam size and type, climate, area of reservoir per unit of electricity produced and the amount and type of biomass flooded can substantially affect the GHG emissions from reservoirs. The transportation stage contributes approximately 29% of the GHG emissions on average, followed by 10% from the operation and maintenance stage. A negligible share (3%) comes from demolition.

The life cycle GHG emissions for the Yeywa and Shweli 1 hydropower plants are 22.80 and 22.81 kgCO2-eq, respectively, Paung Laung (lower) is 23.09 kgCO2-eq, Dapein 1 is 27.5 kgCO2-eq, and Thuk Ye Khat 2 is 28.91 kgCO2-eq. This result is consistent with previous studies, where GWP of hydropower plants range from 15-40 kgCO2-eq/MWh (Pang et al., 2015; Suwanit & Gheewala, 2011; Geller & Meneses, 2016; Ding et al., 2017). In comparison, GWP of all the plants considered are lower than the range reported in smaller scale (3 MW to 3 KW) power plants of the same type in previous studies. However, all GWP results are higher when compared with larger plants (800-1500 MW) (Mallia & Lewis, 2013). Similar observations are made in our LCA, where smaller plants resulted in higher GWP. This results support the claim that smaller hydropower systems have greater environmental impacts per MW produced.

*Acidification potential*

Acidification potential is the likelihood of atmospheric pollution arising from acidifying gases being emitted to the atmosphere due to the hydropower projects and expressed in kilograms of sulphur dioxide equivalent; g SO2-eq/MWh. The impacts of acidification can be deteriorating to soils, plants and aquatic animals. In our LCA, as in GWP, most of the acidification potential (ACP) resulted from the construction phase and none from the demolition phase. The transportation stage also contributes significantly to this impact category, while the operation and maintenance stage is only a minor contributor. The majority of acidifying pollutants come from the combustion of fossil fuels for the production of construction equipment and transportation. In previous studies, acidifying gases were mostly associated with dam construction (Turconi et al., 2014). The significant contribution from transportation is probably due to the fossil fuel dominant electricity mix in both, China and Myanmar (Pang et al., 2015). The total ACP of power plants is 76.59 g SO2-eq for Yeywa, 82.28 g SO2-eq for Shweli 1, 110.4 g SO2-eq for Paung Laung (lower), 129.3 gSO2-eq for Dapein 1 and 132.29 g SO2-eq for Thuk Ye Khat 2. These values correspond to the results from the LCA studies of much smaller hydropower plants (1-5 MW) (Suwanit & Gheewala, 2011). Similar to other environmental indicators, the larger the plants are, the higher the ACP values. Given the similarities among the considered powerplants, the variability is relatively low compared with previous studies (Asdrubali et al., 2015).

*Mineral Resource Depletion Potential*

Environmental impacts correspond to the depletion of non-living mineral and energy resources, such as fossil-fuel, copper and iron, expressed in a gram of antimony equivalent, g Sb-eq. Resources are depleted when a significant volume of fuel and other resources are consumed. The mineral resource depletion for Yeywa hydropower plant is 92.7 g Sb-eq, Shweli 1 is 94.29 g Sb-eq, Paung Laung (lower) is 103.62 g Sb-eq, Dapein is 108.86 g Sb-eq, and Thuk Ye Khat 2 is 139.29 g Sb-eq. The values are within the range of the results from other studies using both, smaller and larger scale power plants. Resource depletion per MWh of electricity generation is higher in smaller hydropower plants. It is also important to note that MRDP value is not determined by the type of dams, whether they are reservoir or run-of-river based (Garcia et al., 2014). MRDP is the dominant impact, resulting from the construction phase of the hydropower plants. As mentioned before, most of the depleted resources originate from the construction phase because of the consumption of a large amount of energy, electricity and resources (steel, iron, stainless steel, gravel, cement and sand) for the production of construction materials. Transportation also causes significant resource depletion, followed by operation and maintenance and demolition. The substantial contribution of transportation is due to the remoteness of the hydropower plants in Myanmar.

*Freshwater aquatic ecotoxicity potential*

This is an indicator for effects of the emission of toxic substances on freshwater aquatic ecosystems. Characterisation factors are expressed as kg 1,4 dichlorobenzene (1,4-DB) eq and apply at global/continental/ regional and local scales (European Centre for Ecotoxicology and Toxicology of Chemicals, 2016). Toxicity potential per 1MWh of electricity has resulted in 24.2 kg DCB-eq for Yeywa, 6.87 kg DCB-eq for Shweli 1, 6.47 kg DCB-eq for Paung Laung (lower), 7.52 kg DCB-eq for Dapein 1 and 9.06 kg DCB-eq for Thuk Ye Khat 2. Except for POP, FWAP from hydropower plants is comparatively smaller than other impacts in Myanmar (Fig 3). It is mainly caused by construction of hydropower plants due to the emissions of heavy metals to air and water during the material production process. Impacts of the transportation phase come from fossil fuel combustion. FWAP might also be contributed by the electricity used during operation and maintenance. Although these factors directly affect FWAP, total contamination of water from construction and operation of the dam also influence FWAP (Suwanit & Gheewala, 2011). FWAP is therefore the result of both, direct and indirect factors. In the electricity generation sector, fossil fuel and coal power plants result in high levels of FWAP, compared with hydropower electricity generation (Santoyo-Castelazo & Azapagic, 2014).

*Human toxicity potential*

Human toxicity potential (HTP) concerns the effects of toxic substances on the human environment and characterisation factors are expressed by kg 1,4 dichlorobenzene (1,4-DB) eq. HTP is the fourth largest environmental burden by all considered plants. However, HTP exceeded FRP in the two biggest dams, Yeywa and Shweli 1. HTP values owe to the high NOx and SOx emissions during the manufacturing of construction materials. Therefore, the construction phase of the hydropower plants is again the main contributor to this impact category, accounting for 97% of total impact. Transportation and operation and maintenance phases make minor contributions. In summary, the potential of human toxicity from the Yeywa power plant is 22.4 kg DCB-eq, Shweli 1 is 33.18 kg DCB-eq, Paung Laung (lower) is 38.35 kg DCB-eq, Dapein 1 is 38.35 kg DCB-eq, and Thuk Ye Khat 2 is 50.13 kg DCB-eq. In most cases, HTP is contributed by fuel oil and coal power plants within the electricity sector (Brizmohun et al., 2015; Santoyo-Castelazo et al., 2014). In contrast, Günkaya et al. (2016) found that in Turkey high carbon ferrochromium production in the construction of hydropower plants and wind power are mainly responsible for HTP. The differences in HTP results can be due to the use of both, reservoir and run-of-river types with different sizes.

*Photochemical ozone creation potential*

This category refers to the forming of reactive substances (ozone) due to the increase of ultraviolet UV-B radiation, which can be harmful to human health and ecosystems. Photochemical Ozone Creation Potential (POP) for the emission of substances to air is expressed in kg ethylene equivalents/kg emission. The total POP from hydroelectricity generation in Myanmar are 4.35 g C2H4-eq for Yeywa, 6.57 g C2H4-eq for Shweli 1, 6.8 g C2H4-eq for Paung Laung (lower), 7.83 g C2H4-eq for Dapein 1 and 8.47 g C2H4-eq Thuk Ye Khat 2. Like FWAP, hydropower plants in Myanmar do not have a significant POP (Fig 3). This result is consistent with the results from previous research conducted on both, large and mini-hydropower plants around the world (Garcia et al., 2014; Pascale al., 2011). Based on previous studies, POP from electricity generation is mainly contributed by heavy fuel oil and coal power plants, mostly due to high SO2 and NOx emissions (Brizmohun et al., 2015; Santoyo-Castelazo & Azapagic, 2014). CO and SO2 emissions from burning of natural gas and lignite also contribute to POP (Günkaya et al., 2016). For the hydropower plants in this study, around 68% of impact is from the construction phase. Transportation, operation and maintenance stages contribute 25% and 4%, respectively. This can be explained by the current coal-dominated electricity mix in China where most of the construction materials and equipment are manufactured.

*Fossil fuel resource depletion potential*

This impact category is concerned with the extraction of fossil fuels due to inputs into hydro electricity generation systems and is determined for each extraction of fossil fuels (gram of antimony equivalent), based on concentration reserves and rate of de-accumulation. The results show that FRP is relatively high for hydropower plants. Transportation of hydropower plants is the biggest contribution in this category. This result can be attributed to the remoteness of the power plants, and the requirement of the delivery of a large quantity of materials and equipment. Operation and maintenance stages are the second largest contributor to FRP. Contrary to other impact categories, the construction phase does not have any impact on the FRP. The assumption is that smaller plants might be environmentally more detrimental than larger plants (see fig.3). The larger the power plants, the more materials and equipment are demanded, the more fuel is required for vehicles used to transport them. The high FRP value can be a result of the combustion of fossil-fuel during transportation.

*Biogenic GHG emission*

Table 7 summarizes the inventory data and results obtained in terms of biogenic GHG emissions of the five hydropower plants. The emissions per FU range from 8.12 KgCO2 eq/Mwh to 16.62 KgCO2 eq/Mwh. The substantial differences in GHG emissions can be attributable to the varying installed capacity, size and electricity generation capacity of the plants. The general pattern of the results shows that power plants with higher installed capacity produce higher GHG emissions per FU from reservoirs. The exception in this case is Thauk Ye Khat 2 which produces higher emissions than the two other plants with higher installed capacity, Paung Laung (lower) and Dapein 1. This can be due to relatively lower annual generation capacity of the plant. Compare to the results from previous literatures on the hydropower plants in tropical regions, reservoir GHG emissions from all the five powerplants are on the lower end of the range. In most cases, power plants located in tropical regions generate from 7 KgCO2 eq/MWh to up to 4326 KgCO2 eq/MWh (A.Tremblay, 2005; Gagnon, 1997; Mallia & Lewis, 2013; Song et al., 2018). However, literature indicates that reservoir biomass GHG emission is much lower in boreal and temperate climates. The primary reason for comparatively lower GHG emission from the five hydropower plants in this study is the type of the plants. Run of River hydropower plants do not need flooding of reservoirs and GHG emission associated with decay of biomass is usually low (Fearnside, 2016b; Gagnon, 1997; Kare & Lomite, 2009; Koch, 2002; Mallia & Lewis, 2013; Tremblay, 2005; Turconi et al., 2013). Given that all selected power plants are run-of-river types, GHG emission factors from reservoir is not significantly high.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| System name | Lat/Long | Age  (y) | Area of Reservoir (Km) | Generation capacity | NPP  (bc/m2/y) | CO2  mgCm-2d-1 | CH4  mgCm-2d-1 | Total Emission  (KgCO2 eq) | KgCO2 eq/MWh |
| Yeywa | 21.675, 96.474 | 10 | 59.0 | 3.55E+09 | 4.78E+03 | 6.28E+03 | 12.8E+00 | 5.90E+10 | 16.62 |
| Shweli 1 | 23.698, 97.506 | 11 | 1.1 | 4.02E+09 | 4.17E+03 | 2.88E+03 | 9.74E+00 | 5.41E+10 | 13.43 |
| Paung Laung (lower) | 19.785, 96.335 | 15 | 17.0 | 9.11E+08 | 5.99E+03 | 1.79E+03 | 2.58E+00 | 7.42E+09 | 8.14 |
| Dapein 1 | 24.421, 97.525 | 9 | 0.4 | 1.07E+09 | 5.64E+03 | 2.66E+03 | 2.41E+00 | 7.79E+09 | 7.31 |
| Thauk Ye Khat 2 | 18.914, 96.619 | 6 | 3.8 | 6.04E+08 | 5.22E+03 | 1.48E+03 | 1.49E+00 | 4.95E+09 | 8.19 |

Table 7: The inventory data and biogenic emissions generated from the 1 MWh electricity produced form the five hydropower plants in Myanmar

Sensitivity and uncertainty analysis

A sensitivity analysis was conducted in order to determine how changes in variability and uncertainty parameters in the inventory data can influence the environmental performance of the hydropower plants. Considering that cement, steel, electricity and diesel fuel contributed most to the increase of all the environmental impact categories, the analysis is based on two different scenarios where consumption of these three resource inputs change. For each parameter, the first scenario is a 10% decrease and the second scenario is a 10% increase in the total consumption of cement, steel, electricity and diesel fuel. The analysis identifies the variability and importance of these types of resource inputs throughout the sector. The result of the analysis is shown in table 7. The increase in consumption of cement substantially influences the GWP in all power plants followed by MRDP. For instance, the ±10 variation in cement input leads to ±5.9% variation in the GWP of the Yeywa hydropower plant. The same scenarios were considered for all remaining powerplants. The scenario analysis results show that considerable variations in FWAP occur with changes in the use of steel for all hydropower plants. In this sense, the environmental impact of the plants will increase by 7-8% if steel consumption increases by 10%. As expected, ±10 variation in both, electricity and diesel fuel will result in a significant change in FRP for all the plants with the variation ranging from 6.1 to 6.8%. Moreover, the individual Monte Carlo simulations for each plant were calculated with regards to the sensitivity of the results. The results are show in the supplementary materials (Table S1).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Hydropower Plant | Input | Variation (%) | GWP  (%) | MRDP  (%) | ACP  (%) | FWAP  (%) | HTP  (%) | POP  (%) | FRP  (%) |
| Yeywa |  |  |  |  |  |  |  |  |  |
|  | Cement | -10 | -5.9 | -3.8 | -2.4 | -0.2 | -2.7 | -2.4 | -0.9 |
|  |  | +10 | 5.9 | 3.8 | 2.4 | 0.2 | 2.7 | 2.4 | 0.9 |
|  | Steel | -10 | -1.9 | -2.6 | -1.4 | -7.5 | -5.3 | -2.9 | -1.1 |
|  |  | +10 | 1.9 | 2.6 | 1.4 | 7.5 | 5.3 | 2.9 | 1.1 |
|  | Electricity | -10 | -2.2 | -1.5 | -2.7 | -1.8 | -0.9 | -1.7 | -6.8 |
|  |  | +10 | 2.2 | 1.5 | 2.7 | 1.8 | 0.9 | 1.7 | 6.8 |
|  | Diesel Fuel | -10 | -3.2 | -1.4 | -1.1 | -2.0 | -0.7 | -0.9 | -6.3 |
|  |  | +10 | 3.2 | 1.4 | 1.1 | 2.0 | 0.7 | 0.9 | 6.3 |
| Shweli 1 |  |  |  |  |  |  |  |  |  |
|  | Cement | -10 | -6.7 | -4.2 | -3.3 | -0.1 | -1.5 | -3.2 | -0.7 |
|  |  | +10 | 6.7 | 4.2 | 3.3 | 0.1 | 1.5 | 3.2 | 0.7 |
|  | Steel | -10 | -1.7 | -2.4 | -1.6 | -6.9 | -5.2 | -2.9 | -1.2 |
|  |  | +10 | 1.7 | 2.4 | 1.6 | 6.9 | 5.2 | 2.9 | 1.2 |
|  | Electricity | -10 | -1.2 | -1.6 | -2.6 | -1.8 | -0.9 | -1.8 | -6.6 |
|  |  | +10 | 1.2 | 1.6 | 2.6 | 1.8 | 0.9 | 1.8 | 6.6 |
|  | Diesel Fuel | -10 | -3.3 | -1.4 | -1.1 | -2.1 | -0.7 | -0.8 | -6.4 |
|  |  | +10 | 3.3 | 1.4 | 1.1 | 2.1 | 0.7 | 0.8 | 6.4 |
| Paung Laung (lower) |  |  |  |  |  |  |  |  |  |
|  | Cement | -10 | -5.6 | -3.9 | -2.8 | -0.6 | -1.9 | -2.6 | -0.7 |
|  |  | +10 | 5.6 | 3.9 | 2.8 | 0.6 | 1.9 | 2.6 | 0.7 |
|  | Steel | -10 | -1.5 | -2.8 | -1.8 | -7.4 | -5.6 | -2.8 | -1.1 |
|  |  | +10 | 1.5 | 2.8 | 1.8 | 7.4 | 5.6 | 2.8 | 1.1 |
|  | Electricity | -10 | -1.8 | -1.5 | -2.4 | -1.9 | -0.9 | -1.9 | -6.7 |
|  |  | +10 | 1.8 | 1.5 | 2.4 | 1.9 | 0.9 | 1.9 | 6.7 |
|  | Diesel Fuel | -10 | -3.4 | -1.2 | -1.1 | -2.2 | -0.8 | -0.8 | -6.2 |
|  |  | +10 | 3.4 | 1.2 | 1.1 | 2.2 | 0.8 | 0.8 | 6.2 |
| Dapein 1 |  |  |  |  |  |  |  |  |  |
|  | Cement | -10 | -5.2 | -3.6 | -2.3 | -0.8 | -1.5 | -2.7 | -0.4 |
|  |  | +10 | 5.2 | 3.6 | 2.3 | 0.8 | 1.5 | 2.7 | 0.4 |
|  | Steel | -10 | 1.3 | -2.7 | -1.4 | -7.2 | -5.7 | -2.9 | -1.2 |
|  |  | +10 | -1.3 | 2.7 | 1.4 | 7.2 | 5.7 | 2.9 | 1.2 |
|  | Electricity | -10 | -2.1 | -1.7 | -2.3 | -2.0 | -0.7 | -2.0 | -6.8 |
|  |  | +10 | 2.1 | 1.7 | 2.3 | 2.0 | 0.7 | 2.0 | 6.8 |
|  |  | -10 | -3.5 | -1.1 | -1.1 | -2.1 | -0.9 | -0.9 | -6.1 |
|  | Diesel Fuel | +10 | 3.5 | 1.1 | 1.1 | 2.1 | 0.9 | 0.9 | 6.1 |
| Thuk Ye Khat 2 |  |  |  |  |  |  |  |  |  |
|  | Cement | -10 | -5.1 | -3.9 | -2.9 | -0.4 | -1.3 | -2.9 | -0.9 |
|  |  | +10 | 5.1 | 3.9 | 2.9 | 0.4 | 1.3 | 2.9 | 0.9 |
|  | Steel | -10 | -1.3 | -2.8 | 1.4 | -6.7 | -5.6 | -2.8 | -1.1 |
|  |  | +10 | 1.3 | 2.8 | -1.4 | 6.7 | 5.6 | 2.8 | 1.1 |
|  | Electricity | -10 | -1.9 | -1.9 | -2.2 | -2.1 | -0.8 | -1.8 | -6.6 |
|  |  | +10 | 1.9 | 1.9 | 2.2 | 2.1 | 0.8 | 1.8 | 6.6 |
|  | Diesel Fuel | -10 | -3.3 | -1.1 | -1.1 | -2.2 | -0.9 | -0.7 | -6.2 |
|  |  | +10 | 3.3 | 11 | 1.1 | -2.2 | 0.9 | 0.7 | 6.2 |

Table 7: Sensitivity analysis result

Conclusions

There is a wide-spread believe that smaller dams are more environmentally friendly than larger dams. As a consequence, many countries are encouraging construction of small hydropower plants with less strict planning and regulatory oversight compared with larger projects. However, smaller dams can pose a greater threat to ecosystems and natural landscapes, in particular when considered cumulatively. Our study on Myanmar confirms this (See Fig.5). A full LCA of environmental impacts of hydropower dams in Myanmar was conducted. In this context, the first-ever life-cycle inventory (LCI) data representative was developed for Myanmar. The results of our analysis suggest that there are substantial differences in the intensity of environmental impacts, depending on the size and installed capacity of the plants. Although all powerplants covered are large-scale, the power plants with above 500MW installed capacity perform environmentally better than those with between 300-100MW installed capacity. Impact intensities from previous reports are similar in magnitude to the findings for Myanmar.

It was demonstrated that construction and transportation phases of hydropower plants are the major contributors to environmental pressures associated with hydropower electricity generation in Myanmar. While large volumes of material and energy requirements in the construction phase are the leading cause of environmental burden, the remoteness of the hydropower plants in Myanmar is a crucial factor, contributing to environmental costs resulting from fossil-fuel consumption and combustion. Improving local production capacity for materials and equipment will significantly reduce the environmental impacts of the transportation sector. While larger-scale projects are environmentally more desirable, Myanmar needs to focus on responsible development of hydropower plants, especially those with foreign investment.

Despite wide-spread opposition to large-scale hydropower projects in Myanmar, hydropower is one of the most environmentally sustainable forms of electricity generation. This result supports the findings from previous LCA research (Asdrubali et al., 2015; Garcia et al., 2014). Hydropower usually generates the lowest impacts per electricity generation for all LCIA environmental impact categories when compared with other electricity production technologies (Brizmohun et al., 2015; Felix & Gheewala, 2012; Günkaya et al., 2016; Santoyo-Castelazo & Azapagic, 2014). For instance, GHG emissions from the full life-cycle of hydropower plants is 30-60 times less than that of fossil fuel used electricity generation, depending on the local climate (Varun et al., 2012). Although all renewable energy sources are considered environmentally benign, hydropower appears to have the lowest life-cycle environmental impacts even when compared with wind power (Siddiqui & Dincer, 2017). Particularly, run-of-river type large-scale hydropower dams can be an environmentally sustainable renewable energy option. Unlike reservoir type dams, run-of-river type hydropower plants do not require storage water and a significant amount of land area to be transformed and occupied (Fthenakis & Kim, 2009). Moreover, large dams potentially play an important role in irrigation and increasing cropland productivity (Strobl, 2013).

As a result of poorly planned projects, local activists and communities in Myanmar usually oppose larger sized hydropower plants while micro dams are often considered acceptable (Dapice, 2016). Environmentally and socially sustainable hydropower development in Myanmar will depend on the systematic planning, participatory decision making and, comprehensive environmental and social impact assessments (ESIA). Our results indicate that more rigorous assessment for cumulative environmental impacts of small dams are as necessary as for larger dams. The inadequate consideration of environmental effects of small hydropower projects and the exemption from EIA for those dams are a major concern (Erlewein, 2013). Generally speaking, current EIA practice in the hydropower sector in Myanmar is considered inadequate and ineffective (Aung et al., 2019). Analytical tools such as LCA have potential to improve the analysis of environmental impact in EIA reports by integrating regulatory compliance with environmental hazards. Liu et al. (2013) provide the methods to integrate LCA and EIA. Moreover, the use of remote sensing data has proven effective in quantifying land use in hydropower reservoirs (Dorber et al., 2018).

While hydropower projects can play an important role for solving Myanmar’s energy poverty, minimizing potential environmental damages and social problems is necessary. Sustainable development of hydroelectricity is necessary for adequate and reliable electricity supplies for Myanmar. It is important that the results from this study are for the installed capacity and that generalization of the results for future projects should be made with caution since hydropower is highly site-specific (Gagnon et al., 2002). More research is needed in understanding the cumulative environmental effects, in particular of small dams.

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