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LCA FOR ENERGY SYSTEMS

# Life cycle assessment of mini-hydropower plants in Thailand

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**Abstract**

*Purpose* The conversion of electricity in Thailand is mainly based on fossil fuels that account more than 90% of electricity generated in the country. The use of fossil fuels has large environmental impacts, and being largely imported, also affects the energy security of the country. From the oil shock situation in 1970s, there has been interest in renewable energy in Thailand resulting in the policy goal for the year 2020 to increase the portion of renewable energy to 20% of energy used in the country. Now, hydropower contributes a significant portion of the renewable energy in Thailand, and mini-hydropower (run-of-river type with capacity between 200 to 6000 kW) tends to be most attractive. This is particularly suitable for Thailand, and it is being applied at several locations. Thus, the overall life cycle assessment (LCA), from cradle to gate, of mini-hydropower plants needs to be assessed for quantitative evaluation.

*Materials and methods* There are five mini-hydropower plants in this study. The inputs and outputs of materials and energy used since before construction stage to demolition stage are inventoried and assessed via LCA using the CML 2001 baseline methodology for impact assessment. The impact categories considered in this study are global warming (GWP), abiotic depletion (ADP), acidification (ACP), fresh water aquatic toxicity (FWAP), human toxicology (HTP), photochemical oxidation (POP), and fossil fuel resource depletion (FRP) potential. The functional unit used is 1 MWh electricity produced from mini-hydropower plants in Thailand, and the life span of the power plants is 50 years.

*Results* For each of the environmental impact categories considered, the impact potentials were evaluated for each of the five mini-hydropower plants; 76.39–151.55 g Sb eq/MWh for ADP, 57.28–116.94 g $SO_2$ eq/MWh for ACP, 11.01–23.01 kg $CO_2$ eq/MWh for GWP, 23.01–52.05 kg 1,4-DB eq/MWh for HTP, 4.58–9.08 kg 1,4-DB eq/MWh for FWAP, 2.93–7.47 g $C_2H_4$ eq/MWh for POP, and 35.11–79.13 g Sb eq/MWh for FRP.

*Results and discussion* The main contributors to the impacts are the huge amount of materials used for construction of the mini-hydropower plant; sand, gravel, cement, reinforcement steel, pressure pipeline steel, iron, copper, and electric equipment and energy used for construction activities, construction equipment, and transportation. The remoteness of the mini-hydropower plants and the requirement of importing electric equipment technology from overseas are significant contributors to the environmental impacts.

*Conclusions and perspectives* The environmental "hot spots" are construction and transportation stage because of remoteness, huge amount of materials and energy use in construction period, and the use of imported equipment. Mini-hydropower plants do not only generate power, but being in hilly regions that are often quite scenic, can serve as public knowledge centers for renewable energy. Thus, the multiple purposes of mini-hydropower power plants should be utilized in the future. The proper management of

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environmental and social issues throughout the project cycle is essential taking into consideration the hydrological cycle and seasonal variations. Fresh water is a necessary resource for many living things and hence necessary to be managed wisely. These study results would serve as basic information for decision makers, environmentalists, and all stakeholders and provide a general picture of environmental impacts from mini-hydropower plants in Thailand.

**Keywords** Life cycle assessment (LCA) · Mini-hydropower plant · Renewable energy · Run of river · Thailand

## 1 Introduction

The production of electricity in Thailand is mainly from fossil fuels which account for more than 90% of electricity generated in the country, and a large portion (about 60%) of these are imported (http://www.dede.go.th/dede/). The value of imported fossil fuels is a large proportion of the national expenditure and increases every year due to increments of the country's activities and of the world price of fuel (Chamamahattana et al. 2004). The use of fossil fuels also has large environmental impacts and influences the energy security of the country.

From the time of the oil shock in the 1970s, there has been interest in renewable energy in the country. Thailand's policy goal for the year 2020 is to increase the proportion of renewable energy to 20% of energy used in the country (http://www.dede.go.th/dede/). The existing potential electricity produced by all renewable energy types is 1,750 MW as of 2008 and targeted to be 5,608 MW in 2020 out of which 324 MW is to be from hydropower. Renewable energy sources of interest in Thailand are biomass, solar, wind, and hydropower, with hydropower being an important contributor to the renewable electricity in Thailand. Hydropower plants do not have a fuel cost associated with their operation and in that sense are a cheap way to generate electricity. Also, there is very less emission of greenhouse gasses (GHGs) during the operation of mini-hydropower plants, especially run-of-river type, which require no dam construction and just have a small weir to divert water to generate electricity (Hondo 2005 and http://www.dede.go.th/dede/).

An important aspect is that almost three quarters of the earth's surface is covered with water, and the never ending movement of water can be used for energy (http://www.esha.be/index.php?id=44). In addition, water is a necessary resource that supports all forms of life on the earth. Unfortunately, it is not evenly distributed by season or geographical region. Hydropower projects also help to support other essential water services such as irrigation, flood control, and drinking water supplies. This is a process possible for the reasonable sharing of a common necessary resource (www.Hydropower.org). Hydropower plants are of various types and sizes which can lead to different environmental impacts.

Mini-hydropower is a technology to use energy from a small dam or weir. In Thailand, the capacity of mini-hydropower plants ranges between 200 and 6,000 kW (http://www.dede.go.th/dede/). Mini-hydropower can substitute fossil fuel-based power production and is especially useful in remote areas (having a river passing through that area) as it helps to counter power outages and support the grid electricity during peak demand. Mini-hydropower can be used to match the supply of generation capacity more closely with the electricity demand, reducing the costs of supplying electricity. Moreover, mini-hydropower projects use more local materials, equipment, and labor than large-scale projects (http://www.nreca.org/). Large dams have huge social impacts such as displacement of local communities which can be avoided if run-of-river type configuration is used. When a hydro reservoir is created, the newly flooded biomass will decay, and the process will gradually release some GHGs. The amount of GHG emissions associated with the decomposition of flooded biomass is site specific (Hondo 2005). As observed by Varun Bhat and Prakash (2009), life cycle assessment (LCA) of renewable energy for electricity generation systems by using mini-hydropower (run-of-river) tends to be the most attractive, but it is site dependent. It is particularly suitable for Thailand because there are many forests and mountains in the north and northeastern regions. Most of the people in those areas are farmers, so water is an important resource and is available in those areas. Mini-hydropower plants use the existing resources to generate electricity, and the water is still available for agriculture after the electricity is generated. However, the overall environmental impacts of mini-hydropower need to be assessed for quantitative evaluation. This research aims to assess the environmental impacts from construction to electricity generation from mini-hydropower plants in Thailand. The findings from this study will be good information for other countries in the same geographical region for designing and developing new mini-hydropower plants.

## 2 Materials and methods

### 2.1 Goal and scope of the research study

The goal of this research is to evaluate the environmental impacts of mini-hydropower plants in Thailand via LCA perspective and to provide the environmental information from cradle to gate of electricity production from existing mini-hydropower plants in Thailand. The resources consumption covers energy and ancillary substances needed from the construction stage to electricity generation of mini-hydropower plants. The raw material requirements, electricity, resources requirement, and transportation are considered for construction of weir, intake, headrace, penstock, and power house. The deterioration of electric equipment (replacement of turbines, seal plates, nozzles, and spear tips) from corrosion is also considered. The infrastructure of the background system is not included. The handling of wastes from demolition of mini-hydropower sites is included too.

### *2.1.1 Description of the study site*

The mini-hydropower plants chosen for this study are the ones operated by the Provincial Electricity Authority because they are representative of the average technology and capacity in use nowadays and trends in the future mini-hydropower development of Thailand. The five mini-hydropower plants considered in this study and their design capacities are Mae Thoei (2,250 kW), Mae Pai (two sets of 1,250 kW each), Mae Ya (1,150 kW), Nam San (two sets of 3,000 kW each), and Nam Man (5,100 kW), with a net efficiency of about 40–50% which is similar to that of similar-sized plants in Afghanistan (30–60%) (USAID 2006), whereas Malaysia reported a value of 60% (http://www.tops.lk/article-print-23966-panasian-power-makes-its-mark-in-local-mini-hydropower-development.html). Here, net efficiency is defined as the average efficiency through a year with which a mini-hydropower plant can produce electricity compared to the installed capacity, presented as a percentage. The two sets of machinery used for electricity generation at the Mae Pai and Nam Man mini-hydropower plants are both operating at the same time for 7 months and one operating-one standby for 3 months. All the mini-hydropower plants use technology from the UK and are located in remote areas. All of them use TwinJet Turgo Impulse Turbine type but with different sizes and synchronous generator type, except the Mae Ya mini-hydropower plant which uses induction motor generator. The Nam Man and Nam San mini-hydropower plants are located in the Northeastern region and the Mae Pai, Mae Thoei and Mae Ya plants in the Northern region of Thailand. The overall description of each individual mini-hydropower plant is provided in Table 1 and the location shown in Fig. 1.

### *2.1.2 System boundaries*

The basic system boundary of this study is separated into four parts that are preparation before construction, construction of mini-hydropower plant, operation and maintenance, and demolition. The preparation before construction of the mini-hydropower plant and transportation of materials to construct the plant is the first part considered in this study. The construction of mini-hydropower plant includes weir, intake, headrace, penstock, and power house construction. The operation and maintenance includes electricity generation and also overall maintenance activities through end of life of the mini-hydropower plants. After 50 years of operation, the mini-hydropower plants will be decommissioned. The basic system boundary of mini-hydropower for this study is shown in Fig. 2.

### *2.1.3 Functional unit*

The functional unit of this study is 1 MWh electricity production from a mini-hydropower in Thailand. The life span of the power plant is 50 years.

## 2.2 Life cycle inventory

The life cycle inventory data for this study are separated into two types, inventoried directly onsite and secondary data inventoried from literature or Ecoinvent database. The overall materials and energy used in each step of the life cycle are included since preparing for construction to demolition of the mini-hydropower plants. All transportations, in-country and overseas, are included in the inventory. The energy and materials used for operation and maintenance are compiled throughout the 50 years. For calculation of recycling of materials, the percentage of material deterioration for steel structure is assumed to be 20% of the original and 0% (no deterioration) for equipment steel except that which is in contact with water which will be reduced (due to corrosion) by 2% of the initial weight based on interviews with the plant engineers. The recycled materials included in this study are steel, stainless steel, copper, and iron. It is assumed that all the portions of the materials mentioned above that are not deteriorated will be recycled. This study also includes energy use for the demolition and transportation of recyclable materials to the recycling factory.

## 2.3 Life cycle impact assessment

The resources, materials, and energy used for whole life cycle of mini-hydropower plants are classified to environmental impact categories which are selected based on the environmental emissions and resources used as identified in the life cycle inventory. The impact assessment is conducted using the CML 2001 baseline methodology which is a problem-oriented (midpoint) approach (Guinée et al. 2002). The environmental impacts categories included in this study are listed in Table 2 along with the possible contributing environmental loads.

**Table 1** The description of the five mini-hydropower plants

| Description of the study site | Nam Man | Nam San | Mae Pai | Mae Thoei | Mae Ya |
|---|---|---|---|---|---|
| Project description | | | | | |
| - Geographic location | Dan Sai, Loei province | Phu Rua, Loei province | Pai, Mae Hong Son province | Om Koi, Chiang Mai province | Jom Thong, Chiang Mai province |
| - Installed capacity | 5,100 kW | Two sets of 3,000 kW | Two sets of 1,250 kW | 2,250 kW | 1,150 kW |
| - Proximity to population served | 1,558 households | 453 households | 6 villages | 940 households | 190 households |
| - Condition for electricity use | Local electricity grid and supply electricity for main transmission line | | | | |
| - Design of the system | Run-of-river (extra, tunnel 2.45 × 2.45 × 1,800 m) | Run-of-river (extra, tunnel 2.45 × 2.45 × 2,400 m) | Run-of-river | Run-of-river | Run-of-river |
| - Local river condition | The flow of rivers changes following seasons—having a rapid flow for 4 months in rainy season, medium flow for 4 months, low flow for 4 months, electricity is generated for only 10 months with varying capacity; for the calculations, annual electricity production data are used from the actual records. | | | | |
| - Responsibility for service and operation | PEA | PEA | PEA | PEA | PEA |
| - Project area | 7.3 ha | 9.6 ha | 23 ha | 12 ha | 6.4 ha |
| Project design description | | | | | |
| - Design flow rate | 6.0 $m^3/s$ | 4.36 $m^3/s$ | 1.39 $m^3/s$ | 2 $m^3/s$ | 1.73 $m^3/s$ |
| - Water head | 127 m | 95 m | 106.7 m | 137.1 m | 98.1 m |
| - Turbine type | 43 in. Twin Jet Turgo | 43 in. Twin Jet Turgo | 22 1/2 in. Twin Jet Turgo | 22 1/2 in. Twin Jet Turgo | 22 1/2 in. Twin Jet Turgo |
| - Generator type | Synchronous | Synchronous | Synchronous | Synchronous | Induction |
| - Weir | Mass concrete, 4 m height and 35.5 m long | Mass concrete, 4 m height and 55 m long | Mass concrete, 3.5 m height and 21.5 m long | Mass concrete, 2 m height and 18 m long | Mass concrete, 3.6 m height and 46 m long |
| - Penstock or pressure pipe line | Steel, 1.51 m diameter and 304 m long | Steel, 1.82 m diameter and 250 m long | Steel, 1.15 m diameter and 182 m long | Steel, 1 m diameter and 404 m long | Steel, 0.9 m diameter and 360 m long |
| - Water gate and screen | 17 sets | 19 sets | 15 sets | 14 sets | 13 sets |

## 3 Results and discussion

The results of life cycle inventory, impact assessment, and interpretation are presented separately as shown below.

### 3.1 Life cycle inventory

The inventory of the five stages—before construction, construction, transportation, operation and maintenance, and demolition of mini-hydropower plants—is shown in this section. The environmental exchanges for 1 MWh electricity production from mini-hydropower plant are shown in Table 3.

(a) *Before construction*: This section includes materials and energy used from clearance and land preparation for construction of mini-hydropower plants. The amount of materials was obtained from the bill of quantities and site visits to the mini-hydropower plants.

(b) *Construction of mini-hydropower plant*: The activities in the construction stage are foundation construction, formwork, and reinforced concrete structures, steel, stainless steel, copper for the electricity equipment installed, and all materials used for completing every section of the mini-hydropower plant (weir and intake, desander, tunnel, pipeline, power house, and tailrace). Only Nam Man and Nam San mini-hydropower plants have tunnel construction. Mae Ya, Mae Pai, and Mae Thoei mini-hydropower plants are in situ concrete on land for pressure pipeline. This stage includes electricity equipment installation. The energy and all materials used were calculated from bills of quantities, interviewing site engineers and operators, and site visits.

(c) *Transportation*: All transportations at every stage are considered in this phase. They consist of in-country transportation of materials to mini-hydropower plant construction site by road and transportation by ship of pressure pipelines and electricity equipment from overseas to the mini-hydropower plants. These data include transportation of materials for construction and maintenance stage (not including packaging of materi-

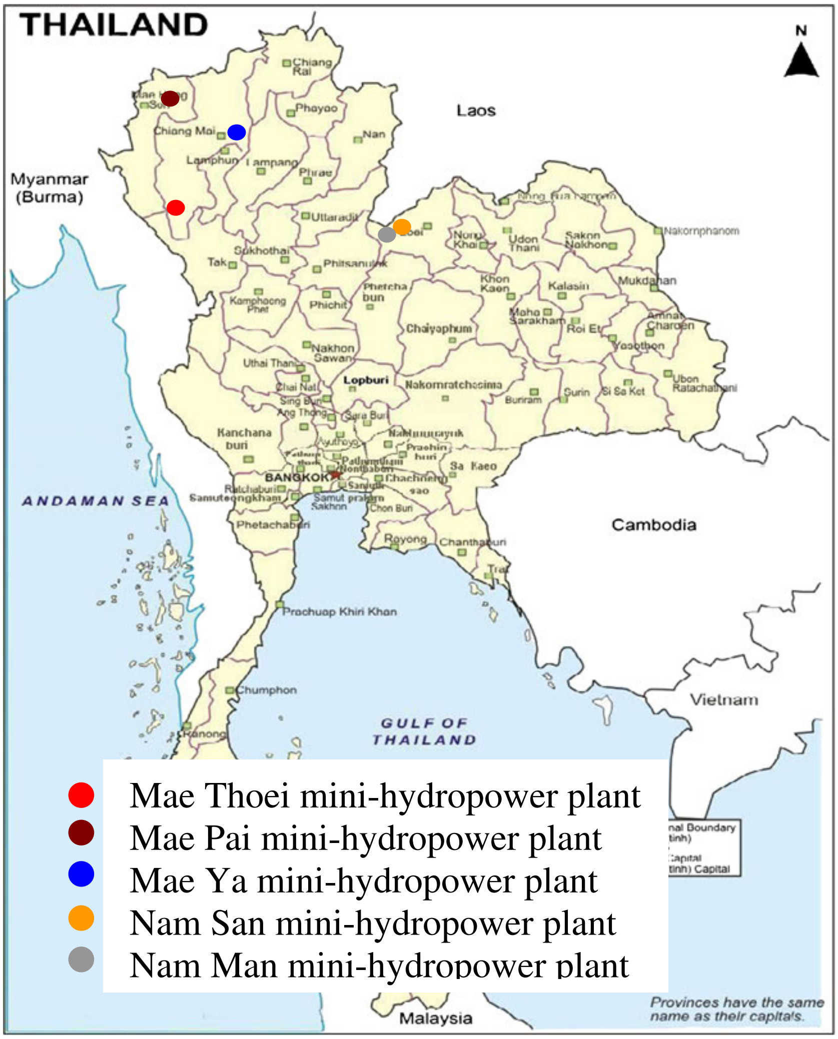

**Fig. 1** The location areas of the mini-hydropower plants

als for transportation) and transportation of materials from demolition of the mini-hydropower plants (including recyclable materials transported to recycling facilities by truck). The distances for transportation in this research were estimated from google map calculator and ship transportation from port world calculator (http://maps.google.co.th/; http://www.portworld.com/map/). Two-way transportation was assumed with empty return trips.

(d) *Operation and maintenance*: The data on electricity used for operation of Nam Man, Mae Ya, Mae Pai, and Mae Thoei mini-hydropower plants came from plant

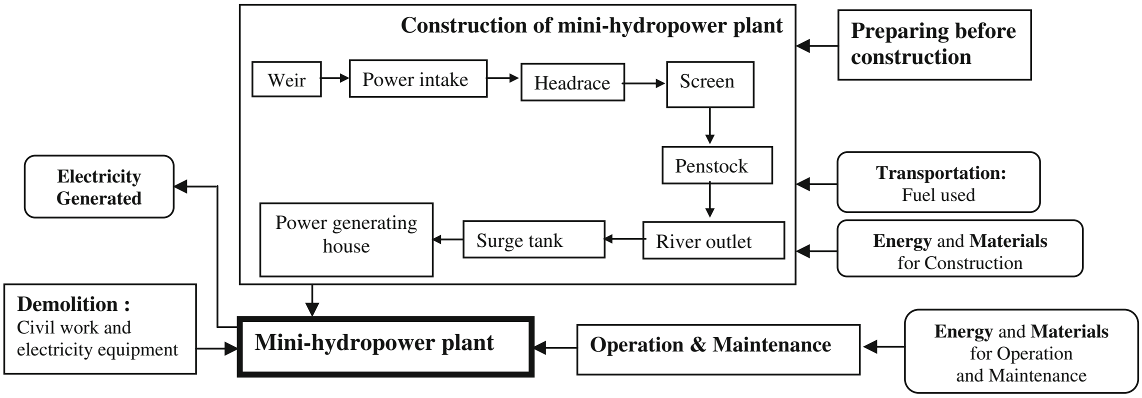

**Fig. 2** Life cycle inventory of the mini-hydropower plant

Table 2 The impact categories of characterization and their contributors

| Impact category | Abbreviation | Unit | Contributors to each impact category | Area impacted |
|---|---|---|---|---|
| Abiotic depletion | ADP | kg Sb eq. | Materials and nonrenewable energy | G |
| Acidification | ACP | kg $SO_2$ eq. | $SO_x$, $NO_x$, $N_2O$ | R |
| Global warming (100 years) | GWP | kg $CO_2$ eq. | $CO_2$, CO, $N_2O$, $CH_4$ | G |
| Human toxicity | HTP | kg 1,4-DB eq. | Dust, $SO_2$, $NO_x$, As, Pb, Mn, Hg, Ni, Se | R |
| Photochemical oxidation | POP | kg $C_2H_4$ eq. | CO, $NO_x$, $SO_x$ | L |
| Fresh water aquatic ecotoxicity | FWAP | kg 1,4-DB eq. | Heavy metal substances such as Cd, Pb, $PM_{10}$ | R |
| Fossil fuel resource depletion | FRP | kg Sb eq. | Nonrenewable energy | G |

*G* global impact, *R* regional impact, *L* local impact

records. Only for Nam San mini-hydropower plant, due to lack of records, the electricity use was estimated from data of other mini-hydropower plants. The maintenance of the five mini-hydropower plants is separated into two types, normal maintenance four times per year and major maintenance once a year. The major maintenance of electric machines in this research includes replacement of turbines, fixing spear tips and nozzles, changing lubricant oil, epoxy paint, and replacing seal plates. The lifetime of electric equipment is assumed to be 10–25 years.

(e) *Demolition:* As the development of mini-hydropower plants in Thailand is rather recent, not much data and documentation are available on demolition. The calculations are thus based on materials volume of the construction of mini-hydropower plants from the bills of quantities and energy used for demolition. The energy calculations are based on the electricity and energy used by the demolition machines such as electric hammers, cranes, and air compressors. There are major items which must be demolished such as concrete structures, powerhouse structures, pressure pipelines, and electricity machines. The recycling of high-value materials such as steel, stainless steel, and iron is included in this study. There are two kinds of steel, structural steel and equipment steel. The environmental burdens from recycling of metal waste are from the Ecoinvent database.

### 3.2 Life cycle assessment

All environmental loads from the life cycle inventory were translated to environmental impact potentials that mainly contribute to resource use, human health, and ecological consequences using the CML baseline 2001 method. From materials, energy used, and pollutant emissions for 1 MWh electricity production by the mini-hydropower plants, the results of life cycle impact assessment are presented in Table 4. The average in the last column of Table 4 is based on the weighted average of the five mini-hydropower plants considering the total amount of electricity produced by each.

### 3.3 Life cycle interpretation

The average contribution of the life cycle stages of the mini-hydropower plants to the various impact categories is presented in Fig. 3. Average values are used for discussion because the trends of percentage contribution of the various life cycle stages to each impact category are quite similar for the five power plants. However, the ranges of results are also presented in parentheses for some cases where the variation is significant. The contribution of impact potentials mainly comes from the mini-hydropower plant construction, transportation of materials, and operation and maintenance stages. The high impact potential of mini-hydropower plant construction comes from the huge amount of materials and energy used for the manufacture of cement, reinforcement steel, pressure pipeline steel, electric equipment steel as well as fossil fuels and electricity. Those factors can lead to high impact to the environment and human health. As seen from Fig. 3, the second largest contributor is transportation followed by operation and maintenance. The contribution of other processes—land preparation, demolition, and pre-construction—is very small.

Because of the site specificity of mini-hydropower plants and imported overseas mini-hydropower technology, transportation has a significant contribution. During the operation and maintenance of mini-hydropower plants, the main process is electricity production from water in the river, and there are relatively less emissions at this stage; it is thus less significant than the construction and transportation stages. More details of the various impact categories are described below.

#### *3.3.1 Abiotic resource depletion*

The contributions are mainly from the construction stage accounting about 55% (42–63%) of the total. The second is

**Table 3** The environmental exchanges for 1 MWh electricity produced from mini-hydropower plants in Thailand

| Item | Amount of environmental exchanges for individual plant | | | | |
|---|---|---|---|---|---|
| | Nam Man | Nam San | Mai Pai | Mae Thoei | Mae Ya |
| Materials | | | | | |
| Cement (kg) | 4.54 | 6.34 | 6.54 | 7.02 | 5.72 |
| Sand (kg) | 9.93 | 13.81 | 13.76 | 15.50 | 12.75 |
| Gravel (kg) | 14.41 | 20.13 | 20.60 | 21.73 | 17.59 |
| Dynamite (kg) | 9.32E−03 | 1.21E−02 | – | – | – |
| Filter fabric or Terram 1000 ($m^2$) | 7.12E−04 | 9.75E−03 | 3.15E−02 | 8.60E−03 | 1.06E−02 |
| Filter geotextile polypropylene ($m^2$) | 8.13E−03 | 1.47E−03 | 3.63E−03 | 8.96E−04 | 3.25E−04 |
| Reinforcement (kg) | 0.47 | 1.05 | 0.97 | 1.66 | 0.80 |
| Steel (kg) | 0.17 | 0.26 | 0.17 | 0.17 | 0.42 |
| Stainless steel (kg) | 4.72E−03 | 6.45E−03 | 8.38E−03 | 9.05E−03 | 1.47E−02 |
| Copper (kg) | 1.32E−04 | 8.85E−04 | 0 | 0 | 0 |
| Metal paint ($m^2$) | 7.14E−03 | 9.73E−03 | 3.96E−03 | 7.64E−03 | 1.18E−02 |
| Metal roof ($m^2$) | 8.54E−04 | 9.92E−04 | 4.37E−04 | 2.38E−04 | 4.60E−04 |
| Brick work ($m^2$) | 6.58E-04 | 8.04E−04 | 3.90E−04 | 2.76E−04 | 5.31E−04 |
| Paint surface of building ($m^2$) | 1.97E−03 | 2.41E−03 | 1.35E−03 | 8.95E−04 | 1.71E−03 |
| Battery HAP 13 (cell) | 5.25E−04 | 5.10E-04 | 1.94E−04 | 1.94E−04 | 3.68E−04 |
| Sulphuric aicd (liter) | 1.36E−03 | 1.32E-03 | 9.12E-04 | 9.13E−04 | 1.73E−03 |
| Timber ($m^3$) | 1.87E−02 | 4.21E−02 | 3.88E-02 | 6.63E−02 | 3.19E−02 |
| Iron wire and Iron round bar (kg) | 0.81 | 1.83 | 1.69 | 2.88 | 1.39 |
| Bolt (piece) | 7.01 | 15.77 | 14.55 | 24.87 | 11.97 |
| Lubricant oil (liter) | 0.02 | 0.03 | 0.05 | 0.02 | 0.04 |
| Land use ($m^2$) | 0.09 | 0.12 | 0.67 | 0.34 | 0.35 |
| Welding rod (kg) | 3.83 | 8.62 | 7.96 | 13.60 | 6.55 |
| Equipment | | | | | |
| Steel (kg) | 7.87E−02 | 1.41E−01 | 1.68E−01 | 9.10E−02 | 1.48E−01 |
| Stainless steel (kg) | 7.04E−03 | 1.37E−02 | 5.72E−03 | 2.87E−03 | 5.44E−03 |
| Copper (kg) | 1.21E−02 | 1.88E−02 | 4.11E−02 | 2.43E−02 | 3.64E−02 |
| Iron (kg) | – | – | 1.54E−03 | 7.73E−04 | 1.47E−03 |
| Aluminum (kg) | – | – | 1.14E−04 | 5.71E−05 | 1.08E−04 |
| Energy used | | | | | |
| Diesel oil (kg diesel) | 6.29E−02 | 6.25E−02 | 7.46E−02 | 2.84E−02 | 5.45E−02 |
| Electricity (kWh) | 1.30E−03 | 1.72E−03 | 1.61E−03 | 1.10E−03 | 1.41E−03 |
| Operation and maintenance | | | | | |
| Electricity use for operation (kWh) | 0.76 | 2.49 | 2.52 | 1.89 | 2.39 |
| Water use ($m^3$) | 7,310.16 | 10,392.86 | 4,996.33 | 7,200.12 | 11,824.58 |
| Transportation | | | | | |
| Diesel car (tkm) | 0.02 | 0.03 | 0.03 | 0.08 | 0.06 |
| 10-t Truck (tkm) | 10.18 | 18.45 | 15.18 | 3.11 | 5.14 |
| 20-t Truck (tkm) | 3.86 | 6.15 | 4.81 | 3.92 | 2.97 |
| 30-t Truck (tkm) | 0.13 | 0.18 | 0.20 | 0.18 | 0.16 |
| Trailer (tkm) | 2.39 | 3.15 | 0.76 | 1.28 | 1.72 |
| Ship (tkm) | 4.47 | 7.34 | 4.48 | 6.13 | 9.72 |

transportation stage accounting about 32% (18–50%) followed by operation and maintenance at 10%. The abiotic resources depletion mainly relates to the construction stage because this stage needs a big volume of materials for construction of mini-hydropower plants such as fossil fuels, cement, steel, iron, stainless steel, and gravel. A large

**Table 4** Life cycle environmental impact potentials of all five mini-hydropower plants in Thailand

| Powerplant location | Nam Man | Nam San | Mae Pai | Mae Thoei | Mae Ya | Average |
|---|---|---|---|---|---|---|
| Impact category | | | | | | |
| Abiotic depletion (g Sb eq) | 76.39 | 149.95 | 101.51 | 151.55 | 104.71 | 116.16 |
| Acidification (g $SO_2$ eq) | 57.28 | 116.94 | 76.58 | 110.39 | 80.41 | 88.49 |
| Global warming (GWP100) (kg $CO_2$ eq) | 11.01 | 23.01 | 16.28 | 22.71 | 16.49 | 17.62 |
| Fresh water aquatic ecotox. (kg 1,4-DB eq) | 4.58 | 7.62 | 6.57 | 6.97 | 9.08 | 6.46 |
| Human toxicity (kg 1,4-DB eq) | 23.01 | 39.94 | 33.17 | 28.25 | 52.05 | 32.65 |
| Photochemical oxidation (g $C_2H_4$ eq) | 2.93 | 6.49 | 4.61 | 7.47 | 4.45 | 5.02 |
| Fossil fuel resource depletion (g Sb eq) | 43.78 | 79.13 | 35.11 | 62.88 | 38.32 | 57.28 |

amount of energy (fossil fuels and electricity) is also used for constructing mini-hydropower plants. The second is related to the transportation stage because of the remoteness of the mini-hydropower plants. The operation and maintenance stage also contributes a significant amount as this activity occurs over a large period of time. The main natural resource used for operation is fresh water from the river which passes through the turbine to generate electricity and is returned to the river without contamination; only a little electricity is used for operation along with some lubrication oil, and there is some waste from replacement of electric equipment. However, the operation and maintenance stage has a lower contribution to abiotic resources depletion than the construction and transportation stages.

### 3.3.2 Global warming

The main contributors are mini-hydropower plant construction at 60% (48–72%), transportation at 32% (18–50%), and operation and maintenance accounting 8%. The significant emission is $CO_2$ contributing more than 83–88% of the total global warming (GWP), CO contributing 10–12%, $N_2O$ about 2–3%, and $CH_4$ from the cast iron production, cement production, and transportation by truck accounting 2–5%. The related activities are combustion of diesel oil used for construction equipment and transportation, electricity used for construction equipment, activities in the construction period, and operation of mini-hydropower plants. As the electricity generated in Thailand is based mainly on natural gas and coal, it has a significant contribution to global warming potential. The mini-hydropower plant construction stage uses high amount of cement, steel, and stainless steel which require a large amount of energy for production, thereby contributing to GWP. Also, the transportation of pressure pipelines and electric equipment from overseas is a significant contributor.

### 3.3.3 Acidification

The main contributions of acidification impact potential are from the construction of mini-hydropower plant accounting for 58% (38–70%) and transportation 40% (23–59%). The major acidifying pollutants are from the high amount of

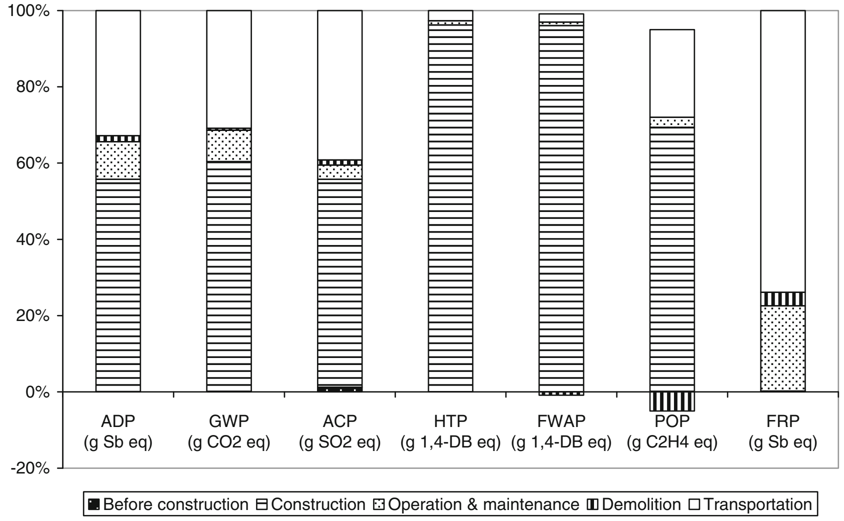

**Fig. 3** Life cycle environmental impact potentials (average data) of all five mini-hydropower plants in Thailand

diesel combustion in engines both for construction equipment and transportation vehicles.

### 3.3.4 Human toxicity

The main contributions of human toxicity are mini-hydropower plant construction and transportation, accounting 95% and 3%, respectively. Although quantitative data are not available for particulate matter, this issue is important as seen in the literature and from interviews during site visits and is thus mentioned here. The construction activities emit a huge amount of particulate matter especially from tunneling, but prevention steps are taken such as water spray in those areas and personal protection equipment for the workers.

### 3.3.5 Fresh water aquatic ecotoxicity

The main contributors are mini-hydropower plant construction (95%), transportation (2%), and operation and maintenance (2%). Credits from recycling of materials in the demolition stage reduce the overall impact by 3%. The main emissions contributing to this impact come from the extraction of minerals especially steel, iron, and stainless steel to build the mini-hydropower plant, fossil fuels used for construction equipment and transportation, electricity used for both construction and operation and maintenance stages. Besides that, fresh water aquatic toxicity could also be contributed by the total contamination of water from construction and operation period. However, the construction of mini-hydropower plant itself did not have a significant impact on toxicity as seen from the results of the water quality tests of three mini-hydropower plants which were similar before and after construction.

### 3.3.6 Photochemical oxidation

The main source of photochemical oxidation potential is the construction stage. About 70% is contributed by the mini-hydropower construction and about 25% by the transportation. Main related activities are the combustion of diesel oil for construction equipment and machines and electroplating for pressure pipelines.

### 3.3.7 Fossil fuel resource depletion

The fossil fuel resource depletion accounts for about 35–50% of the abiotic resource depletion. The maximum contribution, over 70% (55–82%), to this category is from transportation due to the remoteness of the mini-hydropower plants which results in large transportation requirement for all the materials used. About 20% (17–42%) is from operation and maintenance.

### 3.3.8 The characteristics of mini-hydropower plants and environmental impacts

The mini-hydropower plant construction stage is the major source of environmental impacts as seen in this study. The main activities are cement production, steel production, cast iron production and electroplating, copper production, gravel for concrete, high grade steel production, and diesel production. The different characteristics of the five mini-hydropower plants influence the different usage of materials.

Mae Thoei, Mae Pai, Mae Ya, Nam Man, and Nam San mini-hydropower plants have 137.1, 106.7, 98.1, 127, and 95 m of head height, respectively, which influences their construction design. Nam San and Mae Pai mini-hydropower plants have higher concrete consumption than other sites because there are two sets of electricity equipment. In addition, Nam San mini-hydropower plant has the biggest weir, 4 m high and 55 m long. This is followed by 3.6 m and 46 m for Mae Ya, 4 m and 35.5 m for Nam Man, 3.5 m and 21.5 m for Mae Pai, and 2 m and 18 m for Mae Thoei mini-hydropower plants. The size of weirs depends on the width of the river and the amount of water flowing through requiring different amounts of concrete for construction.

For the metals section, the cast iron requirement is mainly for iron wire and iron round bar for the concrete structure and iron composition in the electricity equipment; steel is used for the water gate and screen construction. Nam San has the highest amount of steel because this plant has 19 sets of water gates and screens followed by 17 sets for Nam Man mini-hydropower plant, 15 sets for Mae Thoei, 14 sets for Mae Pai, and 13 sets for Mae Ya. The electricity equipment have consumption of steel, stainless steel, and iron. Nam Man and Nam San mini-hydropower plants use more metal than Mae Pai, Mae Thoei, and Mae Ya mini-hydropower plants because Nam Man and Nam San mini-hydropower plants have higher capacity than the three mini-hydropower plants in the north. But Mae Pai mini-hydropower plant consumes more metal than Mae Thoei and Mae Ya mini-hydropower plants because it has two sets of electricity equipment installed. For the high grade steel pressure pipelines, a large amount of high grade steel is used; Nam Man and Nam San mini-hydropower plants account about $2.5\times10^5$ and $1.5\times10^5$ kg because of the large length of pressure pipelines.

Therefore, material usage in the whole life cycle is significant to the environmental impact assessment, but the whole material usage is shared by the overall electricity produced during the normal life span. Thus, the results of the environmental impacts of Nam San, Mae Thoei, and Mae Pai mini-hydropower plants are higher than the other plants. But Mae Ya mini-hydropower plant has higher environmental impacts per unit of electricity than Nam Man mini-hydropower plant because the electricity produced by the latter is more than five times that produced by the former due to higher capacity, although the materials used are not proportionately higher. To ameliorate the effects of the rapidity of water fall both at the weir and tail race on the fish movement, all of the mini-hydropower plants have fish stairs.

## 4 Conclusions and perspectives

In summary, the environmental "hot spots" are the stages of mini-hydropower plant construction and transportation due to the huge amount of materials required. The remoteness of mini-hydropower plant is a significant factor resulting in long transportation distances both in Thailand and overseas. Most of the materials used for construction are not available locally, and most of the mini-hydropower plants must exist in mountainous and remote areas. To put the results into perspective, the environmental impacts of mini-hydropower plant are compared with natural gas power plants that account more than 70% of overall electricity in Thailand. Comparing with the combined cycle natural gas power plants, the global warming potential of mini-hydropower is lower by more than 95% and acidification potential by almost 90% (Phumpradab et al. 2009). This is of course in addition to obvious savings in nonrenewable resources. For the specific conditions of mini-hydropower plants, not only environmental impact, the efficiency of energy, and materials usage but also the capacity, remoteness, geography, the stability of electricity production, base and peak load, and other things must be considered for deciding the proportion of electricity generation in Thailand.

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