https://dx.doi.org/10.1016/j.apenergy.2019.04.183

Life Cycle Assessment and Energy Payback Time of a Standalone Hybrid Renewable Energy Commercial Microgrid: A Case Study of Town Island in Hong Kong

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Abstract

Microgrid solutions can incorporate clean renewable energy and operate autonomously to power remote areas unreachable by the main grid. While microgrids have thus attracted the interest of many electricity operators, some suggest that renewable energy is not as environmentally friendly as it is claimed to be. This study investigates the life cycle environmental impacts and energy payback time (EPBT) of a microgrid through a life cycle assessment (LCA) case study of the Town Island Microgrid, the first standalone hybrid renewable energy commercial microgrid in Hong Kong. The environmental performance of the Town Island Microgrid was further tested against 2 electrification options, including an on-site diesel generator system and a grid extension. Our results indicate that the Town Island Microgrid is the least impactful in 8 impact categories out of 12. For instance, the global warming potential (GWP) of the diesel generator system and the grid extension is 4.3 times and 7.8 times greater than that caused by the microgrid, respectively. The EPBT found for the microgrid was 9.2 years, while the grid extension and the diesel generator EPBT values were 6.4 and 10.1 and times longer than that of the microgrid, respectively. In conclusion, the case study provides substantial evidence that a microgrid solution can deliver a significantly superior life cycle environmental performance than other common electrification options.

Keywords: Life-cycle Assessment; Microgrid; Energy payback time

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1. Introduction

The traditional centralized coal-fired electrical power generation system has generated increased environmental concern in recent years. Microgrids are believed to be a greener and more sustainable solution to serve the ever-growing energy demand [1]. In essence, microgrids are small-scale power systems which consist of distributed generators, a group of loads, energy storage and points of common coupling between the generator [2]. The heart of the microgrid concept is to decentralize the power generation system, reducing the need for centralized management and allowing more efficient energy management and a higher degree of control during the generation process [3,4]. There is no standard definition for microgrids, and different countries implement different types and structures [5]. The capacity of microgrids can have a very wide range, being able to serve loads with size stretching from small facilities to a large community. One major advantage of a microgrid is the ability to divide a traditional bulky power network into more easily controllable and operable small networks [6,7].

Microgrids can operate autonomously, which is known as "island mode". Under circumstances when the main grid fails, the generators in microgrids can maintain power supply to local users. Such an uninterruptable feature is especially important for critical loads that continuously require electricity, such as equipment in medical facilities or commercial computer systems [8]. The ability to undergo autonomous operation significantly improves energy security to areas exposed to high risk of blackouts caused by natural disasters, for instance in east California, USA. Microgrids as a supplement to the main grid can enhance reliability by switching to island mode if the main grid collapses. In addition to urban areas, due to their "micro" nature, microgrids can also enhance energy security in remote districts where it is difficult to erect large grid infrastructure. Around 20% of the global population does not have access to electricity and most of them live in rural areas. Also, it is not technically easy to erect grid connection to rural areas, and the economies of scale do not favour high investment for a usually small population in rural areas [9]. Therefore microgrids offer huge potential to provide these people with steady and secure access to electricity [10]. In addition to these technical advantages, microgrids are thought to be a more environmentally friendly electrification solution due to their higher ability to integrate renewable energy (RE). By reducing the scale of the grid, the unpredictable nature of renewable energy sources (eg. wind and solar) can be better coped with [3,11]. By 2015, there are already more than 1,400 microgrid projects undergoing planning, construction, and operation worldwide [12]. Despite this enthusiastic welcome, some suggest that renewable energy technology should not be perceived as sustainable as the public imagines it to be. Renewable energy technology can be associated with several adverse environmental impacts such as loss of habitat, the release of hazardous pollutants, noise pollution, and forest depletion [13].

So far, most studies are focused on operation control, optimization, and technology. An energy system should not be considered to comprise only technologies and infrastructures, it is also made up of environmental concerns, markets, its users and other factors affect how the energy system is developed and operated [14]. Currently, apart from technological solutions, the existing literature mainly focuses on optimizing systems cost reduction and carbon dioxide reduction [15]. The environmental performance of microgrids is seldom assessed, and there is a lack of case studies to prove that microgrids have superior environmental performance compared to traditional electrification means. As far as LCA and environmental impacts are concerned, most available studies focus on the component or product level, for instance, a photovoltaic (PV) module or a wind turbine. Only a few studies have investigated the environmental impacts of the entire microgrid including hybrid power generation means and battery system. A case study in Northern Italy [16] was conducted to evaluate its greenhouse gas emissions via LCA and to identify the least greenhouse gas intensive option to provide electricity to buildings in that region. It is reported that among 3 options for providing electricity: (1) a national grid, (2) a micro gas turbine, or (3) a hybrid PV microgrid and national grid, the 3rd option emitted the least amount of greenhouse gas. Another study conducted LCA to compare a hybrid diesel generator, PV and wind turbine remote microgrid, with 265 kWh electricity output per day, in Thailand against grid extension and home diesel generators [10]. Some previous studies also assessed microgrids using energy payback time (EPBT) as a key performance parameter. A grid-connected roof-top multi-crystalline PV system was reported to have an EPBT of 1.5 years, and another grid connected to a ground-mounted polycrystalline PV system was shown to have an EBPT of 2.2 years based on present-day technologies and irradiation of 1700 kWh/m^2/year [17]. Another study, which also did not include assessment of a battery system, reported that a grid-connected polycrystalline PV system for a hospital building in Malaysia has an EPBT of 5 years [18]. On the other hand, a study that focused on the EPBT of the storage system reported that a 27 kWp lead-based battery storage system linked with PV panels in India has an EPBT of 1.9 – 2.3 years [19]. Most studies have only focused on analysing the PV modules [20] and few studies include both PV panels and battery system in their EPBT calculation, not to mention a hybrid microgrid comprised of other renewable energy technologies such as wind turbines. A close reference found considered a decentralised hybrid PV solar-diesel in Nigeria, reporting an EPBT of 9.5 – 10.5 years, depending on the level of solar irradiation [21].

2. Study Aims

The aims of this study are to investigate the life cycle environmental impacts of a standalone hybrid renewable energy microgrid system and to test its environmental performance advantage by comparing the results against other electrification means. To achieve these aims, the present study explores the case of the Town Island Microgrid, which is the first standalone solar/wind hybrid renewable energy commercial microgrid in Hong Kong, through conducting an LCA on and calculating the EPBT of the microgrid. The LCA applies 12 life cycle impact categories to not only the as-built configuration of the Town Island Microgrid but also to compare its impacts against two other electrification means, specifically an on-site diesel generator system and a grid extension via a submarine cable. This approach provides extensive coverage on a system level instead of just on a product level. This paper represents the first comprehensive LCA study of the first standalone renewable energy commercial microgrid in Hong Kong. The findings will be valuable for future microgrid projects considered by electricity operators, researchers, and policy makers in Hong Kong and other regions interested in microgrid deployment.

3. Methodologies

3.1 Case Study: Town Island Microgrid

Background of Town Island Microgrid

Town Island is situated off the Sai Kung Peninsula. On the island, there is a drug rehabilitation center which serves around 80 people including recovering drug users. In 2008, China Light and Power (CLP), one of the two main electricity operators in Hong Kong, began to build a renewable energy system to provide electricity to Town Island. This became the first standalone commercial renewable energy system in Hong Kong. The implementation was divided into two phases. The first phase was completed in 2010, and in 2012 the second phase marked the completion of the entire renewable energy microgrid project. The Town Island Microgrid project was honored as one of the Hong Kong People Engineering Wonders in the 21st Century [22].

On the technical side, the Town Island Microgrid consists of two energy stations: Mount Carmel Renewable Energy Station (MCRES) and Living Spring Renewable Energy Station (LSRES). MCRES is made up of 96 200-W polycrystalline PV panels, 360 280-W polycrystalline PV panels. and a 6 kW wind turbine, with a capacity of 126 kW. LSRES is composed of 216 280-W polycrystalline PV panels and a 6 kW wind turbine, with a capacity of 66.48 kW. Operations at each renewable energy station are supported by a shared battery system, with a combined capacity of 1,105 kWh containing 576 pieces of lead-calcium alloy solar batteries, along with an invertor system that includes a solar inverter, wind invertor, and bi-directional invertor.

Prior to the installation of the renewable energy microgrid, electricity supplied to residents on Town Island was generated by diesel generators. This method was not only costly and time-consuming due to the necessarily frequent transportation of fuel, but it also led to adverse environmental impacts during operations on site.

Figure 1 - Diesel generator used to power Town Island before system upgrade (left) [22] and Town Island Microgrid (right) [23]

Alternative Scenarios

2 other electrification options are examined in this study, including (1) an on-site diesel generator system, and (2) a grid extension, according to the following rationales:

i. On-site diesel generator system: before the renewable energy microgrid was built, Town Island was powered non-continuously by a diesel generator, so it is reasonable to develop an alternative diesel generator scenario to relate the past and the present. Compared to a microgrid, diesel generators are easier to implement, with low capital costs options available and great ease of installation [24]. Although a study in 2003 [25] reported that it would take 15 years for PV technology to reach the same cost-effectiveness of a diesel generator, nowadays some remote islands in Hong Kong are still powered by diesel generators due to economic reasons. Overall, many benefits, including low investment and convenient installation, are harnessed at the early stage of the life cycle of a diesel generator.

ii. Grid extension: it has been suggested that grid extension to remote areas is a particularly cost-efficient electrification method. Previous studies indicate that, upon proper optimization, grid extension can be comparably environmental friendly as a renewable energy system [26,27]. Some remote areas, although isolated from the main grid, can still benefit from connecting to the main grid via extension [28]. Extension construction can be more complicated than setting up a diesel generator, but during the operation stage, grid extension seems to be a more secure and stable option.

3.2 Life Cycle Assessment (LCA)

LCA is used to investigate and identify the environmental impacts of products or services throughout their life cycle. This method has earned popularity in evaluating renewable energy systems such as solar energy and wind energy. Although these energy systems are emerging and are generally supported by government bodies and operators, specific scientific confirmation of their environmental performance is often not considered, particularly not through a life cycle approach [29]. Nevertheless, LCA has gained momentum as a systematic environmental impacts evaluation tool adopted to study the environmental performance of renewable energy systems in and of themselves and for comparing the environmental performance of different energy systems [30,31]. ISO standards (ISO 14040 and ISO 14044) were established to provide guidelines on how to conduct an LCA, which include 4 steps: (1) goal and scope definition, (2) life cycle inventory, (3) impacts assessment, and (4) results in interpretation. This study follows the procedures outlined in these standards.

In the present study comparative LCA was conducted to check whether the as-built configuration of the Town Island Microgrid is superior, from a life cycle environmental perspective to other possible electrification options.

System Boundary

This section presents an overview of the system boundary by illustrating the life cycle of each electrification option and highlighting the scope of the LCAs in this study (Figure 2). The general assumptions in the LCAs and details on the corresponding electrification option are presented in later sections.

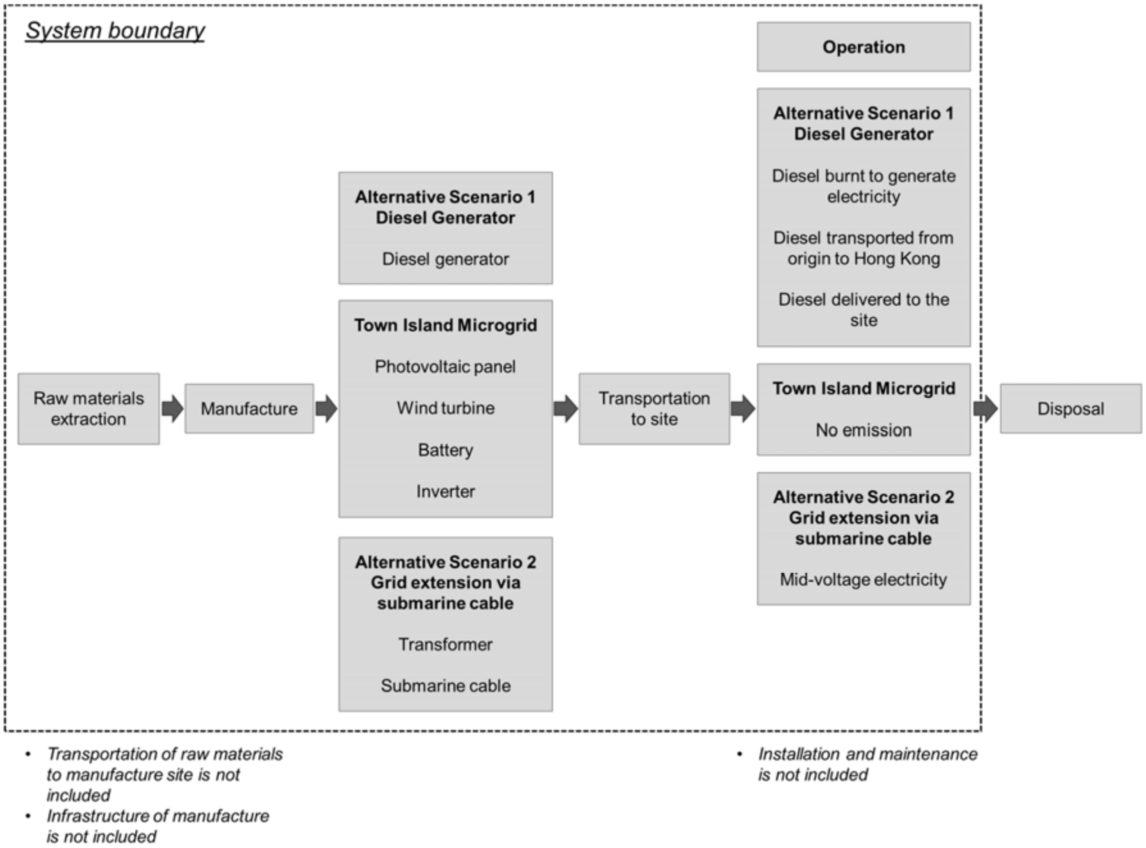

Figure 2 – Overview of the system boundary of the 3 electrification options

Functional Unit

For the sake of a fair and systematic comparison between the above 3 electrification scenarios, the annual electrical energy output of the Town Island Microgrid was estimated, and this electrical energy output was used as the functional unit. The timeframe of the LCA was set to be 20 years.

RETScreen, a clean energy management software developed by the government of Canada [32], is used to estimate the annual energy output by the PV panels. This software underwent validation and is equipped to conduct feasibility studies and energy assessments for renewable energy projects [33]. The software can estimate the annual solar energy output of a PV system based on the local solar radiation data. In this case data from the Hong Kong Observatory is referenced.

For a wind turbine, the below formula is used to estimate the annual energy generation, where ρ is air density, A is the swept area that the plane of wind intersected by the generator v is wind speed and C_p is the combined efficiency of energy conversion from kinetic energy to mechanical energy, then to electrical energy. A C_p of 0.41 is used for best design wind turbine [34].

$$P = \frac{1}{2} \times \rho \times A \times v^3 \times C_p$$

The wind speed data was obtained from the Hong Kong Observatory Sai Kung station, the closest wind station to Town Island. The daily mean wind data for 2 years (2014 and 2015) was used and the calculated power was averaged. Since the cut-in speed is 3.5 m/s, when the daily mean wind speed is lower than 3.5 m/s, it is assumed that there is no generation.

3.3 Life Cycle Inventory

General Assumptions

Conducting LCA requires a very comprehensive set of data throughout the life cycle of the targeted system. The best scenario is that every piece of data is specific to the system, for instance geographically, technically and temporally specific. However, in reality, not every piece of data is readily available. Therefore, to fill in data gaps, combined references of built-in the database in SimaPro, published academic journals, scientific reports, and manufacturer data are used, and adjustments to available data are made. These references will be stated in their corresponding sections.

The below general assumptions are made in the LCA of all 3 electrification options:

i. On Town Island, the power transmission system from the point of electrical supply to the building is similar for the three scenarios, therefore the transmission system from the supply point to the building, and the transmission system within the building are not considered in this comparison exercise.
ii. Since combined references are used and each reference has a different depth of detail, in order to avoid over-estimation or under-estimation in any one particular system equipment, a general rule [35] is applied in this study to normalize the depth of inventory data. If a system's equipment consists of less than 20 items on the inventory list, items with less than 1% of the weight of the equipment are neglected. If a system's equipment consists of 20 – 40 items on the inventory list, items with less than 0.5% of the weight of the equipment are neglected.
iii. A lifespan is allocated for each piece of equipment. After the lifespan is reached, the equipment is replaced.
iv. The emissions from installation, maintenance, and disposal are not considered. Previous LCA studies of renewable energy systems [36] have found that installation, maintenance, and disposal only contribute to 2%, 1%, and 0.5% of emissions respectively, hence the significance is considered negligible compared to other major stages. For batteries, due to the lack of relevant local data, the disposal is not considered

as well. Among existing literature, only a rare amount of LCA study covers the end of life, for instance, this study in Kenya [37], due to the lack of data.

v. The stages within a life cycle that are the focus in this study include: raw materials extraction and preparation; manufacture, transportation of assembled system equipment from the production site to Town Island; and operation.

vi. For items on the inventory list, the most applicable and relevant information is used. For instance, if the PV panels are assumed to be made in Asia, the inventory data in Asia will be referenced, if available. If data associated with a location is not available, data from other locations will be used.

Electrification Option 1: Microgrid (As-built Configuration)

The first LCA was conducted on the as-built microgrid system. The as-built configuration of the microgrid is described in Section 2. For the purposes of this LCA, it is assumed that the headquarters of a brand is the origin of equipment production and transportation. The inventory data for the extraction and processing of raw materials and manufacture is considered. Regarding transportation, the transportation of raw materials from the site of extraction to the headquarters is considered negligible; however, transportation from the headquarter to Town Island is considered.

A previous study [38] carried out an LCA for 1,000 W polycrystalline PV panels in China. This study is believed to be the most applicable available reference, and its LCI results were adopted in the present study. Instead of simply using a linear approach, the below non-linear economy of scale scaling law is applied to better reflect the industry reality. A scale factor of 0.6 is used, as it is often applied to the majority of energy and chemical plants [39]. The same method was adopted by an LCA study on wind turbines [36], which involved scaling down a 30 kW wind turbine to a 6 kW one. In the present study, the LCI of 1,000 W polycrystalline PV panels is scaled down to 280 W and 200 W, respectively.

$$C_2 = C_1 \left(\frac{S_2}{S_1}\right)^n$$

C represents the input into the process, n represents the scaling factor, and S represents the sizes of the process. The subscripts 1 and 2 refer to the respective process. The manufacturing location of the PV panels is in East Asia and it is assumed that they are transported to the final operation site by sea. The lifespan is assumed to be 20 years. The LCI of the PV panels is listed in Table 1.

Table 1 – Life cycle inventory of a 200 W PV panel and a 280 W PV panel

Input	**200 W**	**280 W**
Quartz / kg	13.65	16.70

Calcium oxide / kg	2.48	3.04
Silicon carbide / g	90.5	110.74
Glass / kg	25.03	30.62
Ethylene vinyl acetate copolymer (EVA) / kg	2.86	3.50
Steel / kg	6.51	7.97
Aluminum / kg	4.63	5.66
Polyethylene terephthalate part (PET) / kg	1.24	1.52
Polyvinyl fluoride film (PVF) / kg	1.24	1.52
Electricity / kWh	341.3	417.7

The LCI for 6 kW wind turbines was drawn from a wind turbine LCA study [36]. It is assumed that the wind turbines were manufactured in Northwest Europe and were transported to Hong Kong by sea, for which the sailing distance was estimated using online tools [40]. The turbines' lifespan is assumed to be 20 years. The life cycle inventory list is provided in Table 2.

Table 2 – Life cycle inventory of a 6 kW wind turbine

Input	
Cast iron / kg	101.96
Fiberglass reinforced plastic / kg	128.84
Low-alloyed steel / kg	5359.32
Stainless steel / kg	681.39
Synthetic rubber / kg	1.2
Aluminum / kg	5.47
Copper / kg	15.22
Epoxy resin / kg	14.00
Polyethylene / kg	10.23
Polyvinylchloride / kg	2.28
Electricity / kWh	219.68

No readily available literature presenting the LCI of lead-calcium alloy batteries has been found by the time of this study is conducted. Instead, the LCI of lead-calcium alloy batteries was derived from an LCA study comparing the environmental impacts of different types of batteries [41] and an LCA study on lead-acid batteries [42]. The LCI of a lead-acid battery and a lead-calcium battery are considered to be reasonably similar, as the composition of calcium in lead-calcium alloy battery is usually less than 0.1% wt. for anti-corrosion purposes. The batteries are assumed to have been produced in Central Europe and transported to Hong Kong by sea, and their lifespan is assumed to be 20 years. The LCI of a 960 Ah solar battery is listed in Table 3.

Table 3 – Life cycle inventory of a 960 Ah lead-calcium alloy (assumed to be lead-acid) solar battery

Input	
Lead / kg	17.00
Lead oxides / kg	23.80
Polypropylene / kg	6.80
Sulfuric acid / kg	6.80
Water / kg	10.88
Glass / kg	1.36
Antimony / kg	0.68
Electricity / kWh	345.22

The Balance of System (BOS) associated environmental impacts are considered negligible as the BOS was reported to contribute only a very small amount of emissions compared to the rest of the system. Also, the environmental impacts of maintenance are considered negligible [38].

Electrification Option 2: On-site Diesel Generators

Before Town Island was powered by the current renewable energy microgrid, electricity was supplied diesel generators which ran only for a few hours a day. In order to compare the current renewable energy microgrid solution against the previous diesel generator solution, an LCA of the latter is conducted as the first alternative method electrification.

For the sake of a fair comparison, the same capacity as the Town Island Microgrid is assumed for the diesel generator system configuration. Three 65 kW diesel generators, rather than a single 195 kW power system, are used. This is because the base load of a correctional facility is around one-third of its peak load [43] and therefore this configuration is closer to normal practice. It is assumed that each diesel generator has a 10-year lifespan [10]. Another assumption made is that the generators were produced in a city in South China and transported to Hong Kong by a lorry. During the operation stage, the diesel consumed by the generators is assumed to have been imported from Southeast Asia and was transported to Hong Kong by sea. Each diesel generator has an assumed combined efficiency of 55%. The LCI of a 65 kW diesel generator is drawn from a previous study [10] and is shown in Table 4. Unlike the Town Island Microgrid, which is automated during operation, the diesel generators require regular fuel delivery to the area. It is assumed that this refill takes place weekly and is delivered by a boat consuming 2 L/km of diesel.

Table 4 – Life cycle inventory of a 65 kW diesel generator

Input	
Steel / kg	558.00
Aluminum / kg	325.50
Copper / kg	18.60
Electricity / kWh	4133
Lubricating oil / kg	872.50

Electrification Option 3: Grid Extension

Given that Town Island is a remote area isolated from the main CLP electricity grid, the previously presented options are considered to power the island as on-site standalone systems. In addition to these unconnected systems, it is worthwhile to study whether it is environmental advantageous to extend the main grid electricity supply to the remote island. Typically extension can take place in two forms: overhead cable or submarine cable. The nearest substation of CLP is located on High Island. Extension via a submarine cable is believed to be a more technically and economically viable means compared to overhead cables. Therefore the second alternative scenario is set to be a grid extension via a submarine cable. The approximated distance from this substation going along the coast of High Island to Town Island is 6.7 km.

In this scenario, several assumptions are adopted. Firstly, no major upgrade is required for the main grid nor the High Island substation. Secondly, the submarine cable starts from the High Island substation, with a distance to Town Island assumed to be 6.7 km. Thirdly, an additional stepdown transformer is installed in Town Island to reduce the voltage from 11 kV to 220 V for end use. Given the power capacity and the voltage of transmission, the current of transmission is worked out and the corresponding cable is chosen from the manufacturer's catalog. It is assumed that the submarine cable was manufactured in South China and was transported to Hong Kong by trucks. The LCI of the transformer and submarine cable are shown in Table 5 and Table 6, respectively. This LCA adopts a generalized electricity mix in China, for which data is available in SimaPro, to represent the operation stage. The data refers to a country-specific electricity mix including production.

Table 5 – Life cycle inventory of a transformer

Input	
Steel / kg	571.33
Aluminum / kg	226.67
Mineral oil / kg	133.20
Electricity / kWh	146.94

Table 6 – Life cycle inventory of the 6.7km submarine cable

Input	
Copper / kg	7950.18
Polypropylene / kg	9895.60
Polypropylene fibres / kg	2860.00
Steel / kg	34447.57
Wire drawing of copper / kg	7950.18

3.4 Life Cycle Impact Categories

In this study, Simapro was employed to carry out the LCA. It is a professional LCA software program supported by ecoinvent database, which contains a compliant data source for studies and assessments based on ISO 14040 and ISO 14044. The ReCiPe (midpoint) framework, with a hierarchies perspective, was used to express the level of environmental impact for each category [44]. Following the methodology guidelines on Life Cycle Assessment of Photovoltaic Electricity [45], the below impact categories are primarily focused on in this study:

i. Climate change, measured in kg CO_2 eq: When using a midpoint methodology, climate change represents the global warming potential (GWP) – the amount of energy absorbed by the greenhouse gases emitted, with CO_2 as a reference. The higher the climate change factor is, the stronger the climate change impacts will be, meaning that the gas warms the Earth more.

ii. Fossil fuel depletion (FFD), measured in kg oil: This category describes the cumulative energy demand along the life cycle of the object being studied. The default fossil fuel in Simapro is crude oil (42 MJ per kg). With the mass of fossil fuel multiplied by this factor, the cumulative energy demand in energy units can be worked out.

iii. Particulate matter formation potential (PMFP), measured in kg PM_{10} eq: This indicator measures the sum of particulate matter directly emitted and objects that transformed into the particulate matter in the air.

iv. Terrestrial acidification potential (TAP), measured in kg SO_2 eq: This indicator measures the change in acidity in soil caused by sulphates, nitrates, and phosphates deposited from the atmosphere.

v. Ozone depletion potential (ODP), measured in kg CFC-11 eq: This indicator measures the thinning of the stratospheric ozone layer caused by anthropogenic emissions.

vi. Human toxicity potential (HTP), measured in kg 1,4-DB eq: This category measures the harmful impacts on human health caused by the chemicals that are released and to which humans are exposed via a channel, for instance, inhalation of the chemical in the air. 1,4-dichlorobenzene is used as a reference.

vii. Ecotoxicity (measured in kg 1,4-DB eq): This indicator measures the impacts on ecosystems, including freshwater ecotoxicity potential (FETP), marine ecotoxicity potential (METP) and terrestrial ecotoxicity potential (TETP).

viii. Land use and Water use: This category of indicators measures the use of land, including agricultural land occupation (ALO) and urban land occupation (ULO), measured in m^2a, and land transformation (LT), measured in m^2. However there is insufficient data to accurately reflect the water use of all 3 electrification scenarios, thus water depletion is considered beyond the scope of this study.

In addition to the midpoint methodology, an endpoint methodology was also used to aggregate all impact categories to result in a final single score for each electrification option, enabling an overall comparison to be carried out.

3.5 Energy Payback Time (EPBT)

In addition to the above life cycle impact categories, the energy payback time (EPBT) is a commonly used parameter to measure the payback period of a system in terms of its input and output energy. The below formula may be used:

$$\mathrm{EPBT/year} = \frac{\text{Total primary energy demand}}{\text{Annual energy output}}$$

Based on the FFD results, the total primary energy demand can be deduced. In Section 4, the estimation of the annual energy output of the Town Island Microgrid will be illustrated. By considering the total primary energy demand and the annual energy output, the resulting EPBT can be interpreted to reflect the efficiency from an energy investment and generation point of view.

4. Energy Output and Functional Unit

4.1 Estimated Energy Output of Town Island Microgrid

RET Screen is used to estimate the annual energy output of the PV system. Figure 3 shows the energy output generated by the PV panels in the Town Island Microgrid. The 280 W PV panels in MCRES contribute the most due to their higher capacity and the greater number of installations. The second-highest output contributor is the 280 W PV system in LSRES, and the third is the 200 W PV panel system in MCRES due to its lower capacity and lower number of installations. Combining the PV panels of both the MCRES and LSRES, the annual electrical energy output of the panels is therefore 204.5 MWh.

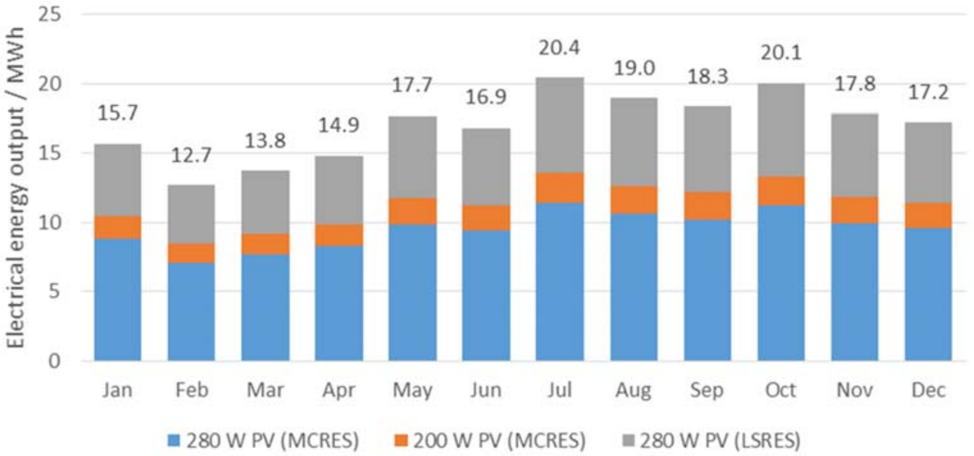

Figure 3 – Electrical energy output of the Town Island Microgrid PV panels

The annual electrical energy outputs of the 6 kW wind turbines of the two renewable energy stations are shown in Figure 4. The annual electrical energy output is estimated to be 100.2 kWh. The number of windy days (wind speed larger than 3.5 m/s cut-in speed) is also presented.

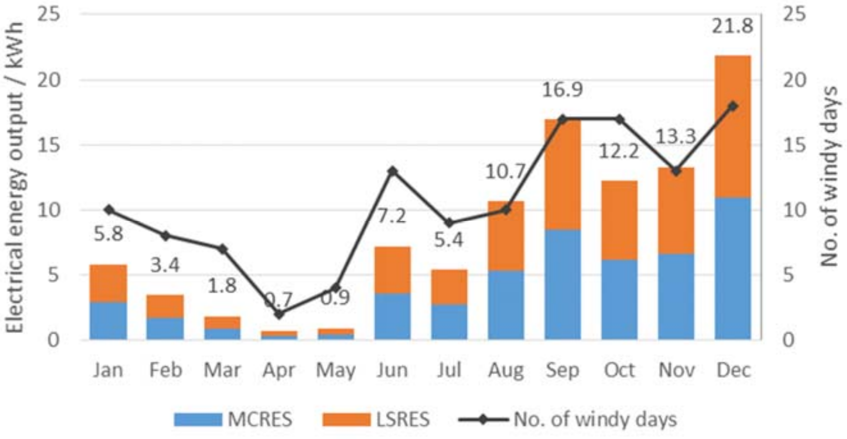

Figure 4 – Electrical energy output by the wind turbines in Town Island Microgrid

4.2 Functional Unit

By combining the values in the above two figures, the annual energy output of the entire microgrid system is found to be 204.7 MWh. Thus, the functional unit for this comparative LCA is an annual electrical energy output of 204.7 MWh for 20 years. With the functional unit confirmed, the details of the two alternative electrification options can be further developed. For the on-site diesel generators option, it is assumed that almost 30,000 kg of diesel is required each year to generate the same amount of electrical energy output as the Town Island Microgrid, based on a calorific value of diesel of 40 MJ/kg and a combined efficiency of 55% of a diesel generator. In addition, for the grid extension option, the amount of electrical energy output will be based on medium-voltage electricity generation.

5. Results and Discussion

5.1 Life Cycle Environmental Impacts of the Town Island Microgrid

The life cycle environmental impacts of the major components, including the 200 W and 280 W PV panels, the 6 kW wind turbines, and the 1,105 kWh battery system, are shown in Figure 5. The PV panels, 200 W and 280 W combined, contribute to more than 50% in climate change (GWP), fossil fuel depletion (FFD), particulate matter formulation (PMF), terrestrial acidification potential (TAP), ozone depletion potential (ODP), terrestrial ecotoxicity potential (TETP), agricultural land occupation (ALO), urban land occupation (ULO), and natural land transformation (NLT). The battery system also contributed to more than 50% in human toxicity potential (HTP), freshwater ecotoxicity potential (FETP), and marine ecotoxicity (METP). Since only 2 wind turbines were installed on site, their associated environmental impacts are not particularly significant compared to the PV panels and the battery system. The results of these impact categories are further broken down into different stages of the life cycle and are discussed in the next sections.

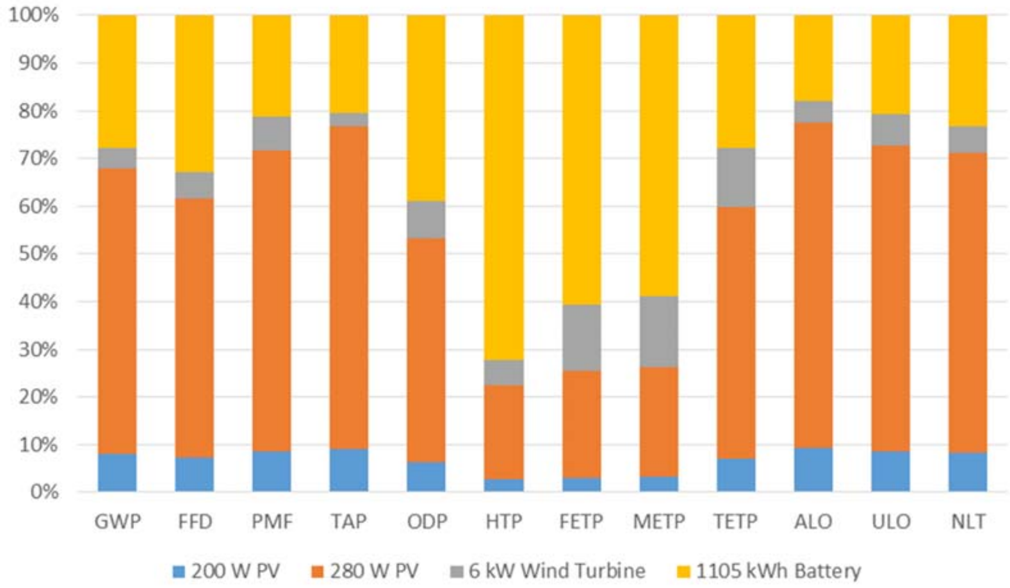

Figure 5 – Life cycle environmental impacts of major components of the Town Island Microgrid

5.2 Life Cycle Environmental Impacts per Unit of Electrical Energy Output

Although the life cycle environmental impacts of the 2 wind turbines may seem small due to their relatively small installed capacity, this does not imply that wind turbine technology has a better environmental performance than PV technology. To further illustrate this, the environmental impacts of 1 kWh of electrical energy output generated by a PV panel (combined 200 W and 280 W) and a wind turbine are calculated. The life cycle environmental impacts of the battery system, which is essential to support the operation of the energy system, are weighted according to the corresponding electrical energy output of the two renewable energy technologies. The life cycle environmental impacts of PV panels and wind turbine are shown in Table 7 and the results are compared against each other across impact categories.

It can be reasoned that a wind turbine is not necessarily more environmentally friendly than PV panels based on Hong Kong climate data. In fact, PV panels demonstrate better environmental performance in all impact categories by a large margin. This is because wind power cannot be fully harnessed from relatively low wind speeds. Mathematically, environmental impact diminishes as the electrical energy output decreases, given the fixed environmental impacts associated with the raw materials stage and manufacturing stage of a PV panel. Hence the lower electrical energy output by a wind turbine leads to a less promising environmental performance compared to PV panels. The aim of this analysis is not to prove that wind energy is not environmentally friendly, but to simply demonstrate that the PV panels on Town Island lead to less life cycle environmental impacts per unit of electrical output compared to the wind turbine. Nevertheless, the two wind turbines only take up a small portion of the installed power capacity in this pilot project. Instead of solely focusing on the life cycle environmental impacts and energy efficiency of the renewable energy microgrid, the wind turbines can serve educational and research purposes, particularly in testing the complementary effect of hybrid renewable energy resources.

Table 7 – Life cycle environmental impacts of PV panels and wind turbine, with battery, factored in, based on 1 kWh electrical energy output

Impact Categories	**PV Panels**	**Wind Turbine**
Global warming potential / kg CO_2 eq	2.940	282.441
Fossil fuel depletion / kg oil eq	0.746	90.950
Particulate matter formation / kg PM_{10} eq	0.007	1.050
Terrestrial acidification potential / kg SO_2 eq	0.204	1.161
Ozone depletion potential / kg CFC-11 eq	0.000	0.000
Human toxicity potential / kg 1,4-DB eq	1.812	215.840
Freshwater ecotoxicity potential / kg 1,4-DB eq	0.310	10.292
Marine ecotoxicity potential / kg 1,4-DB eq	0.030	10.671
Terrestrial ecotoxicity potential / kg 1,4-DB eq	0.001	0.037
Agricultural land occupation / m^2a	0.066	6.698
Urban land occupation / m^2a	0.020	2.921

Natural land transformation / m^2	0.0003	0.032

5.3 Life Cycle Impact Category Comparisons by Life Cycle Stages

This section presents the results of the comparative LCA. The results of each electrification option are broken down into life cycle stages and discussed per impact category.

Global Warming Potential (GWP)

The GWP caused by the diesel generator system and the grid extension is 4.3 times and 7.8 times higher than the GWP caused by the microgrid, respectively (Figure 6). This makes the microgrid the least climate-change causing electrification option. For the Town Island Microgrid, the comparatively high GWP during the manufacturing stage is mostly due to multiple energy-intensive treatment processes, including the purification of quartz to generate metallurgical grade silicon and solar grade silicon. These processes can be powered by mainly non-renewable energy resources. On the other hand, the raw materials of the other 2 electrification options are less energy intensive to extract from their original sources and to process during the manufacturing. However, although the earlier stages of these two options contributed relatively less to GWP, both of their operation stages took up 98% of life cycle GWP due to their heavy reliance on fossil fuel.

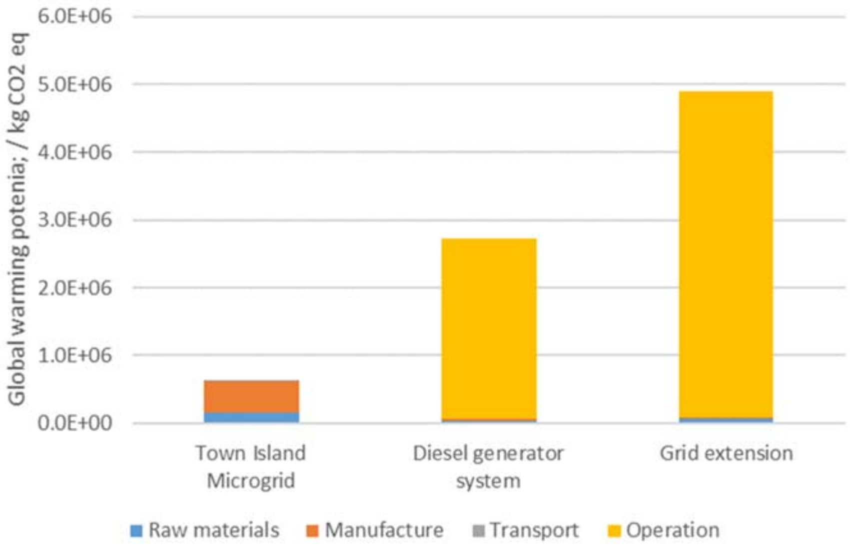

Figure 6 – Global warming potential / kg CO_2 eq

Fossil Fuel Depletion (FFD)

The FFD caused by the diesel generator system and the grid extension is 10.1 times and 6.4 times greater than the FFD caused by the microgrid, respectively, as shown in Figure 7. The microgrid is shown to be the least fossil depleting option out of the three electrification options.

As similarly seen in Figure 6, the microgrid option shows the least FFD due to its zero emissions during operation. In contrast to the climate change impacts presented above, the FFD of the diesel generators is higher than that of the grid extension. This is because the operation stage of the diesel generator involves two major contributors to FFD: (1) the production of diesel fuel and (2) the burning of diesel fuel to generate electricity on site, both of which are activities that consume a lot of fossil fuel, whereas the operation of the grid extension only involves the generation of medium-voltage electricity. The operation stage carries the highest portion of life cycle FFD, 99% and 96% for the diesel generator and grid extension, respectively.

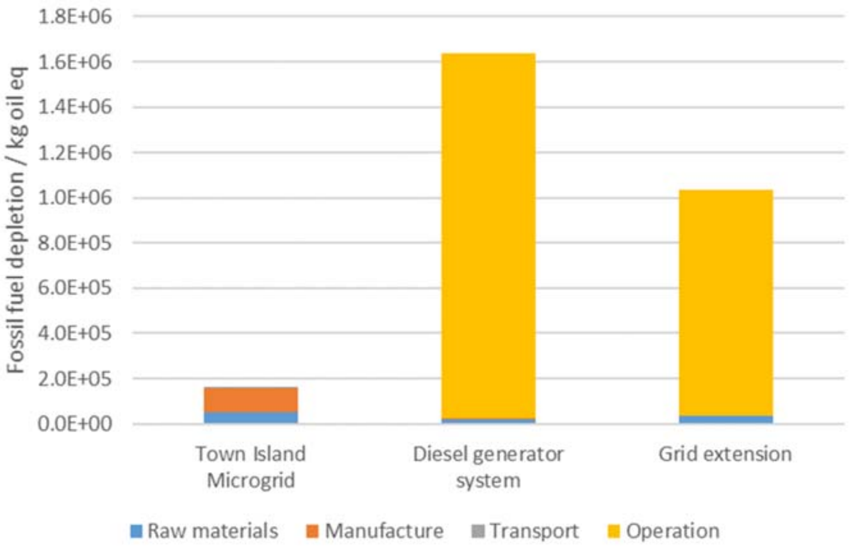

Figure 7 – Fossil fuel depletion / kg oil eq

Particulate Matter Formation Potential (PMFP)

The PMFP caused by the diesel generator system and the grid extension is 10.1 and 9.0 times greater than the PMFP caused by the microgrid, respectively (Figure 8). The microgrid generates the least particulate matter among the 3 electrification options. Some degree of correlation is observed between the GWP, FFD, and PMFP in the case of the microgrid, and this is because of the use of fossil fuel during raw materials extraction, treatment, and manufacture. For the other 2 options, it should be apparent that the high particulate matter formation is also due to the combustion of fossil fuel during the operation stage, through which particulate matter is directly emitted into the atmosphere. For the diesel generator system, most of the particulate matter is emitted during the burning of diesel on site. In contrast, the PMFP caused by the grid extension option is not on site and the particulate matter released most likely takes place in a controlled environment with mitigation to reduce emissions into the atmosphere. On the other hand, little control can be imposed when a diesel generator is used and residents on Town Island are more directly exposed to the emissions.

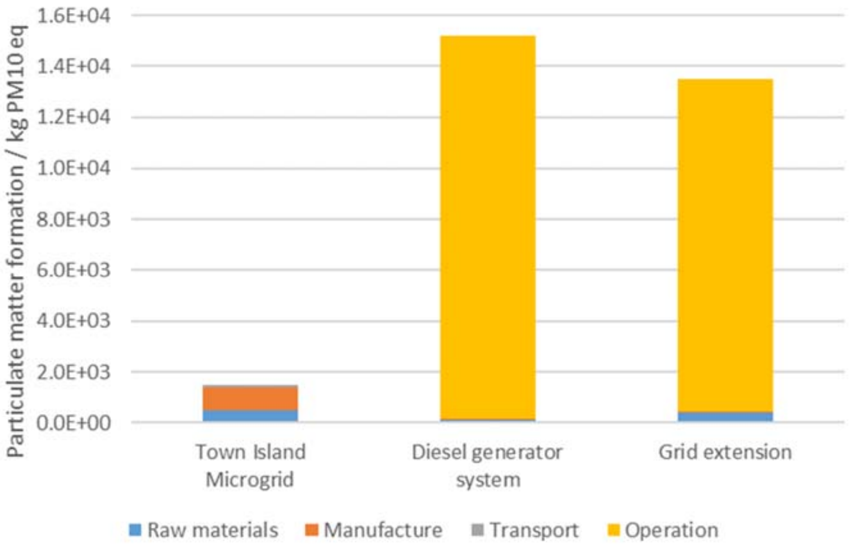

Figure 8 – Particulate matter formation / kg PM_{10} eq

Terrestrial Acidification Potential (TAP)

The TAP of the diesel generator system and the grid extension is 7.0 times and 9.9 times greater than the TAP caused by the microgrid, respectively (Figure 9). The microgrid option leads to the lowest level of TAP among the 3 options. The TAP is related to the use of fossil fuels from China, which are particularly rich in sulphur dioxide and nitrogen oxides [38]. The lower level of reliance on fossil fuels can help reduce the life cycle TAP of the electrification option.

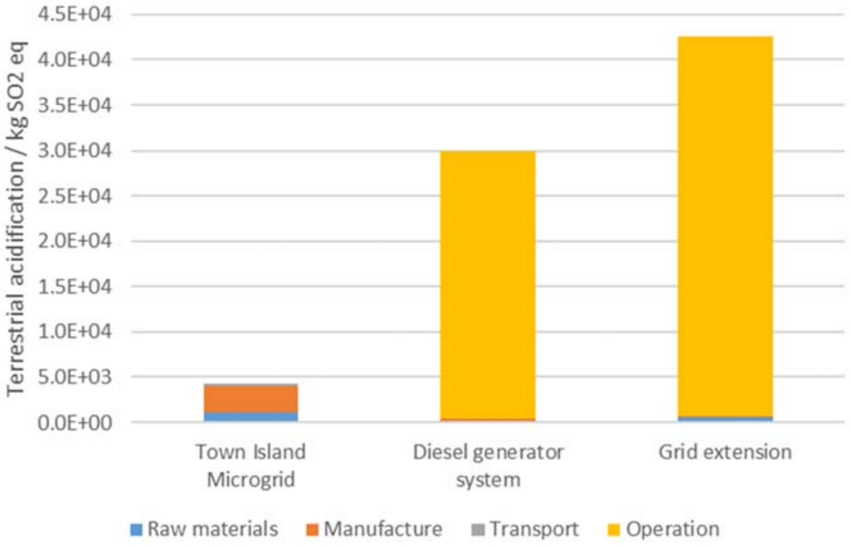

Figure 9 – Terrestrial acidification potential / kg SO_2 eq

Ozone Depletion Potential (ODP)

The ODP caused by the diesel generator system and the grid extension is 32.4 times and 1.7 times greater than the ODP caused by the microgrid, respectively (Figure 10). The microgrid is the least ozone depleting of the 3 electrification options. The ODP resulting from the microgrid may be due to the fuel used to extract raw materials and manufacture. For the diesel generator system, the significant ODP is largely due to the emission of Halon-1301, which is an organic halide. The activities responsible for the Halon-1301 emission during operation include the production of diesel (48.5 %) and burning of diesel (51.5 %). On the other hand, since the major energy resource in China is coal, the grid extension option generates far fewer Halon-1301.

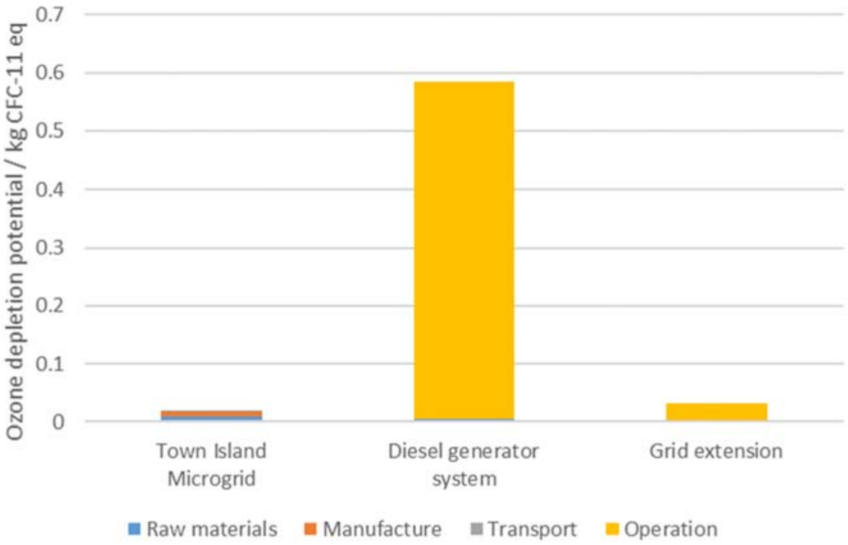

Figure 10 – Ozone depletion potential / kg CFC-11 eq

Human Toxicity Potential (HTP)

The two major contributors to HTP in a microgrid are the PV panels (200 W and 280 W), contributing 22.3%, and the batteries, contributing 72.2% (Figure 5). These are due to the use of heavy metals, such as manganese, arsenic, selenium, barium, cadmium, and lead, during the raw materials extraction and processing stage, and manufacture stage. The heavy metals emissions take place through various paths, including the release of impurities (manganese) in crystalline silicon, the discharge of cadmium through fossil fuel use, and the use of arsenic as a semi-conductor [46]. The grid extension option features the highest life-cycle HTP, 29.2% of which is caused by the submarine cable and 68.5% of which is caused by electricity generation during operation. Within the HTP associated with the submarine cable, 83.2% is due to the use of copper as a conductor, while copper is toxic to humans upon consumption [47]. The generation of human toxicity during the operation stage, for both the diesel generator system and the grid extension, is due to the use of fossil fuels. Despite the same electricity output during operation stage, the generation of medium-voltage electricity emits almost 10 times more heavy metals through grid extension compared to the amount emitted when burning diesel therefore exhibiting significantly higher HTP.

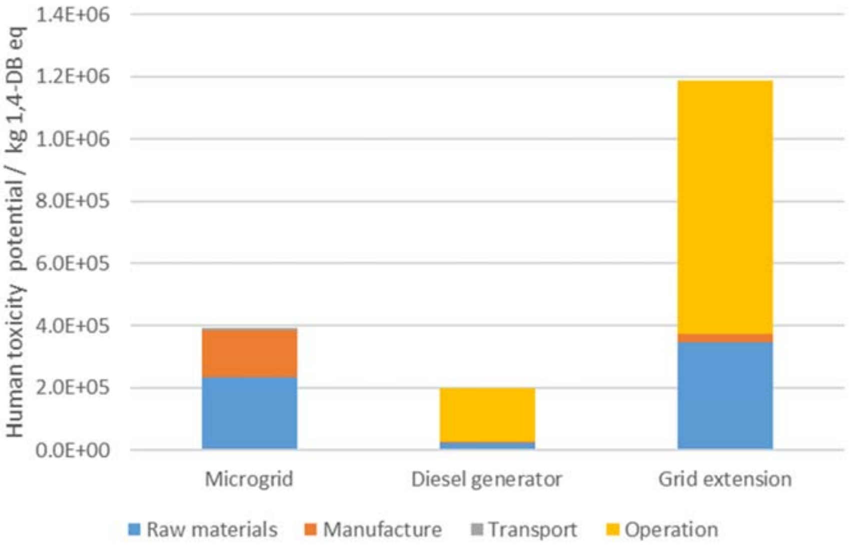

Figure 11 – Human toxicity potential / kg 1,4-DB eq

Ecotoxicity

The levels of freshwater ecotoxicity potential (FETP) and marine ecotoxicity potential (METP) are shown in Figure 12 and Figure 13, respectively. The major contributor to the FETP and METP for the Town Island Microgrid is the battery system, contributing 60.7% and 58.9%, respectively. This is primarily due to the use of antimony, despite the small quantity used, which contributed to 43.37% of FETP and 42.06% of METP caused by the battery system. The processing of antimony involves two heavy metals: manganese and zinc. 36.2% of the antimony-associated FETP and 37.1% of the antimony-associated METP are due to the emission of manganese, whereas 27.9% of the antimony-associated FETP and 24.2% of the antimony-associated METP are due to the emission of zinc. Firstly, antimony often naturally occurs as an antimony compound bound with manganese oxides. When antimony is extracted, manganese is also extracted and released [48]. Since manganese ions are soluble in water, the release of manganese into the environment will cause harm to both the freshwater environment and marine environment. In freshwater, the affected species include crustaceans, fish, algae, and bacteria, while in marine habitats, the affected species include crustaceans, algae, and molluscs. The release of manganese is not only harmful to the environment, but also to human life, by playing a role in, for instance, neurotoxicity, hepatotoxicity, and infant mortality [49]. In addition to the manganese released during antimony refining, zinc is also another major contributor to FETP and METP, which may due to zinc poisoning of wildlife [50]. The release of zinc is also due to the extraction of antimony, which in ores is often bound with zinc [51]. Furthermore, substantial life cycle FETP (48.90%) and METP (50.1%) is emitted during the manufacturing stage. This is associated with nickel released during electricity production [52], which affects the survival and reproduction of wildlife including Oligochaeta, Crustacea, and Arthropods [53].

For the diesel generator system, the FETP and METP are mainly due to diesel production (43.6% of the operation stage FETP and 54% of the operation stage METP) and diesel burning on site (39.8% of operation stage FETP and 58.2% of operation stage METP). For operation stage FETP, diesel production and burning result in the release of bromine and nickel. Bromine is soluble in water and is harmful to freshwater fish and aquatic invertebrates [54]. Nickel, as explained earlier, is released during the combustion of fossil fuels. Bromine and nickel account for 38.3% and 26.3% of the diesel fuel production-associated FETP, respectively, whereas bromine and nickel account for 33.1% and 29.2% of the diesel fuel combustion-associated FETP, respectively. The METP generated during the production of diesel fuel is mainly due to heavy metals including zinc (32.2%) and nickel (22.7%), whereas the METP generated during diesel fuel combustion is mainly due to heavy metals including zinc (24.6%), nickel (21.3%) and copper (16.3%). For grid extension, the major contributor to both raw material stage FETP and METP is the production of copper. During this process, heavy metals including manganese, zinc, and nickel are emitted. For the operation stage, the significantly high FETP and METP values are caused by the emissions of fossil fuel combustion, including the emission of nickel (41.9% of operation stage FETP and 40.3% of operation stage METP) and vanadium (22.6% of operation stage FETP and 22.1% of operation stage METP).

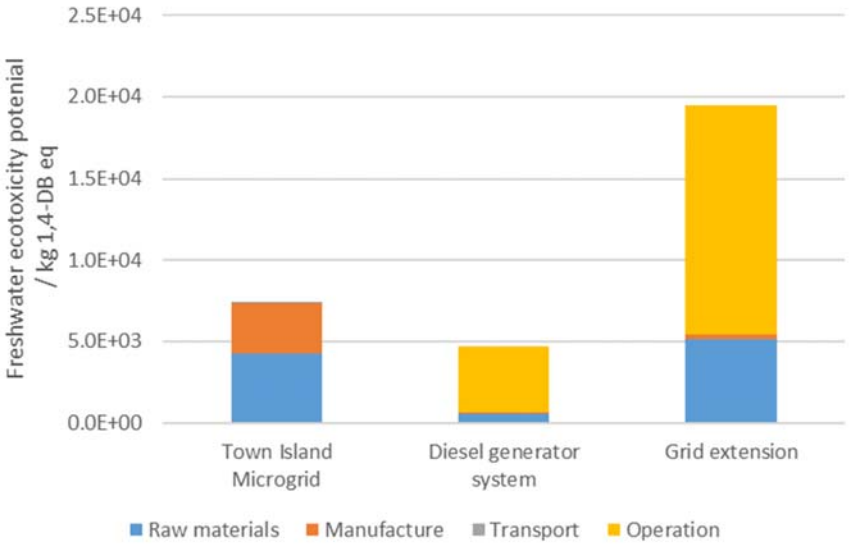

Figure 12 – Freshwater ecotoxicity potential / kg 1,4-DB eq

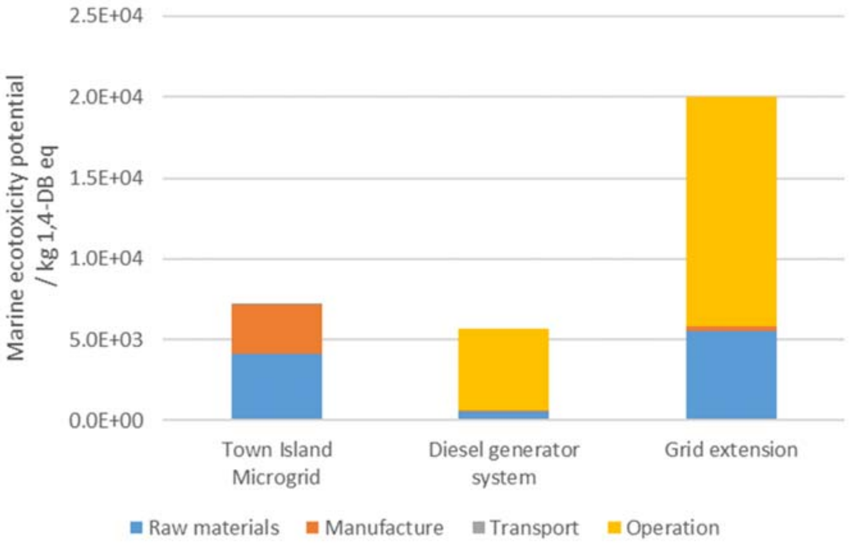

Figure 13 – Marine ecotoxicity potential / kg 1,4-DB eq

The terrestrial ecotoxicity potential (TETP) caused by the diesel generator system and the grid extension is 12.0 times and 5.4 times greater than the TETP caused by the Town Island Microgrid, respectively (Figure 14). The microgrid solution is the least terrestrial toxic option. The high TETP emitted by the operation of diesel generators is due to the emissions of phosphorus as the exhaust of diesel fuel and fossil fuel combustion [55]. This is similarly the case for the grid extension scenarios. Provided that the operation of the Town Island Microgrid does not rely on fossil fuels, the life cycle TETP is significantly lower than the other two options.

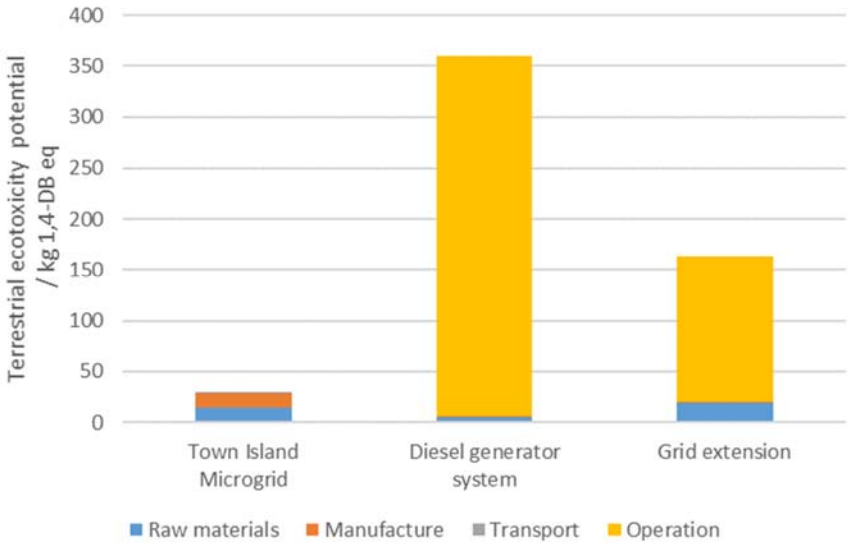

Figure 14 – Terrestrial ecotoxicity potential / kg 1,4-DB eq

Land use

78.2% of the agricultural land occupation (ALO) associated with the Town Island Microgrid occurs during the manufacturing stage (Figure 15). The ALO can be correlated to the consumption of fossil fuels [56]. Since the production of microgrid equipment requires more electricity than the diesel generators and the submarine cable, the Town Island Microgrid features higher ALO. Grid extension operation involves off-site electricity generation, with a consequently significant ALO.

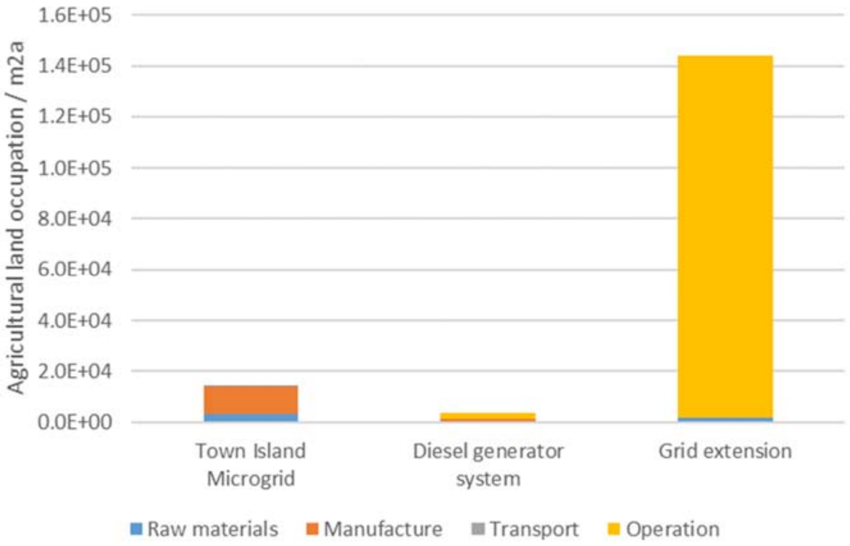

Figure 15 – Agricultural land occupation / m^2a

The urban land occupation (ULO) required for the diesel generator system and the grid extension is 1.7 times and 9.4 times greater than the ULO caused by the microgrid, respectively (Figure 16). The microgrid solution is the least urban land occupying option. For the manufacturing stage of the microgrid and the operation stage of the grid extension scenario, the is mainly a function of the dump site associated with electricity generation. On the other hand, during the operation stage of the diesel generator system, the urban land occupation is needed for diesel production and diesel combustion.

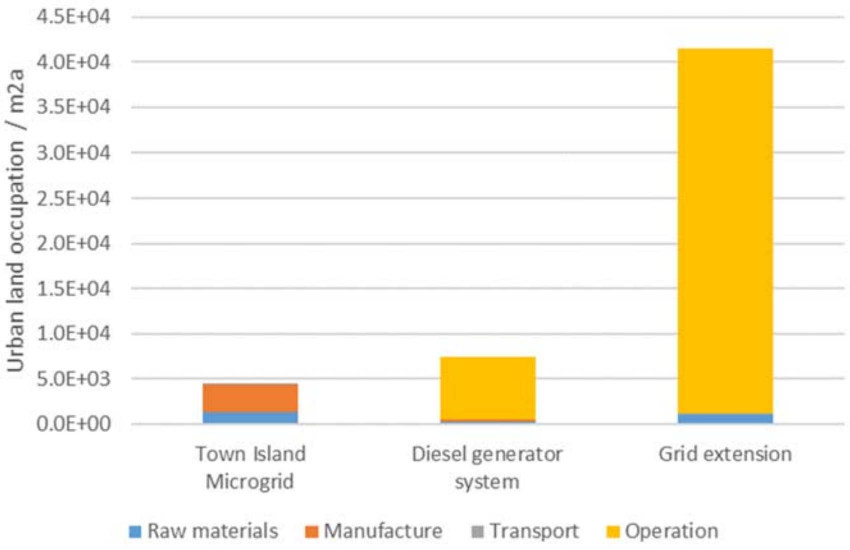

Figure 16 – Urban land occupation / m^2a

The natural land transformation (NLT) required by the diesel generator system and the grid extension is 40.9 times and 5.7 times greater than the NLT caused by the microgrid respectively (Figure 17). The microgrid solution leads to the least amount of natural land transformation. The production and combustion of diesel fuel are the two major contributors to NLT. NLT caused by grid extension involves transforming forest from extensive to intensive.

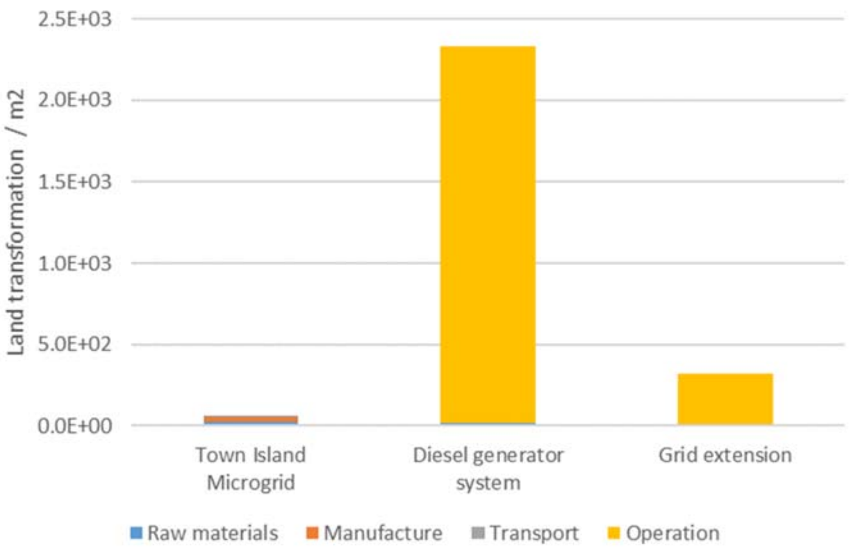

Figure 17 – Natural land transformation / m^2

5.4 Overall Life Cycle Environmental Performance of the Town Island Microgrid Compared to Other Electrification Options

Summarising the results of the comparative LCA based on midpoint methodology, the Town Island Microgrid is found to be the least impactful in 8 out of the 12 studied impact categories, and for no impact categories are the Town Island Microgrid found to be the poorest performer. In addition, the endpoint methodology is used to aggregate the impact categories to construct a single score to compare the three options (Figure 18). The significant impacts on human health include mainly particulate matter formation, global warming potential, and human toxicity, whereas the noticeable impacts on resources involve mainly metal depletions and fossil fuel depletion.

Overall, this study suggests that the microgrid is the most favorable option. This is consistent with previous studies, which have found a microgrid to be a more environmental friendly electrification solution compared to other conventional electrification solutions [10]. In contrast, the diesel generator system option imposes the most significant environmental impacts, which can be attributed to the continuous diesel fuel production and emissions from diesel fuel combustion during operation that characterizes this system. The grid extension option performs slightly better; however, it still imposes significantly more life cycle environmental impacts than the microgrid solution. The results of this study highlight the importance and merit of using LCA as a comprehensive environmental impact evaluating tool in order to identify under which impact category a solution can be further improved. For instance, as described in earlier sections, the relatively high HTP, FETP, and METP emitted by the microgrid are largely due to heavy metals. Now that these LCA results are published, equipment manufacturers can introduce technological improvements in treating the heavy metals, such as chemical precipitation and ion exchange or absorption [57].

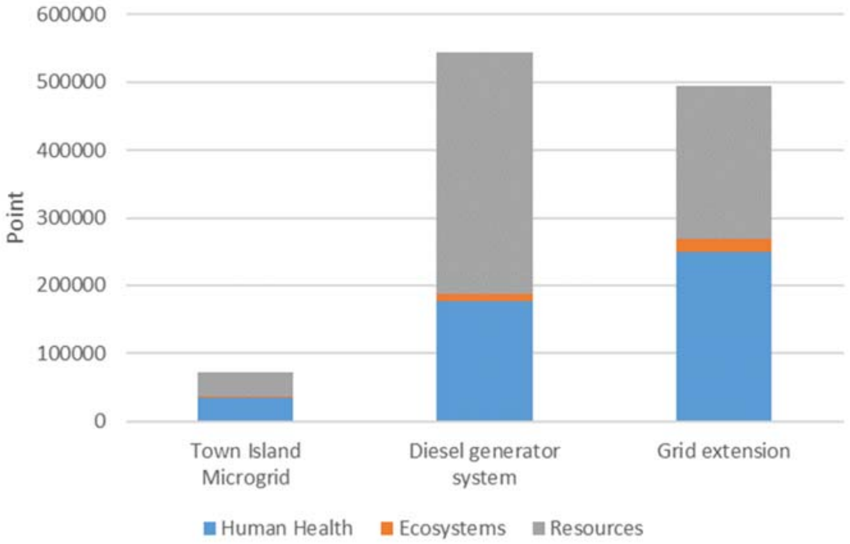

Figure 18 – Aggregated single score of the three electrification options assessed using endpoint methodology

5.5 EPBT of the Town Island Microgrid

The EPBT values for each of the three scenarios are shown in Table 8. It is estimated that the Town Island Microgrid has an EPBT of 9.2 years, meaning that it will take this period of time for the system to generate enough energy output to compensate for the primary energy required to develop the system. The EPBT of the diesel generator system is about 10 times greater than that of the Town Island Microgrid, and the EBPT of the grid extension option is 6.4 times greater than that of the Town Island Microgrid. As mentioned in the introduction, few studies have considered all the microgrid components, including the renewable energy generators and the battery system. Nevertheless, the EPBT calculated for the Town Island Microgrid in the present study is comparable to the value found in a previous study that suggested it would be 9.5 to 10.5 years [21].

Table 8 – Total primary energy demand and energy payback time of the three electrification options

Electrification Option	Total Primary Energy Demand / MWh	Energy Payback Time / Year
Town Island Microgrid	1886.95	9.2
Diesel generator	19085.76	93.2

Grid extension	12074.62	59.0

5.6 Other Aspects of Sustainability

The concept of sustainability covers environment, economics, and society. In addition to environmental sustainability, the other two aspects of sustainability are equally important. For instance, social sustainability is believed to be significantly enhanced by using microgrid systems because of the improved energy security that they provide. Prior to the microgrid installation, Town Island was powered non-continuously by diesel generators. Emissions and pollutions from the generators negatively impacted the lives of Town Island residents, but with the implementation of the clean renewable energy microgrid, these negative impacts have been significantly mitigated. Also, the frequent delivery of diesel fuel is costly and time-consuming, and sometimes uncertain if sea traffic conditions are adverse. A study [58] suggested a framework to evaluate the overall sustainability of an energy system, not only the different aspects have to be considered, they have to be compared against each other in order to effectively identify the tradeoffs. This framework may be applied when more data is available.

6. Conclusions

This study assesses the life cycle environmental impacts of the microgrid. An LCA case study was carried out on the Town Island Microgrid, the first standalone hybrid renewable energy commercial microgrid in Hong Kong. To comprehensively review its environmental performance, 12 LCA impact categories were considered and the system's EPBT was calculated. The PV panel system (composed of both 200 W and 280 W panels) is the major contributor to several impact categories including GWP, FFD, PMF, TAP, ODP, TETP, ALO, ULO, and NLT, whereas the battery system is the major contributor to HTP, FETP, and METP. The system EBPT is calculated to be 9.2 years, which is comparable to previous studies. The environmental performance of the microgrid was further tested against two alternative electrification options, including an on-site diesel generator system and a grid extension via a submarine cable. Among the 12 LCA impact categories, the Town Island Microgrid has been demonstrated to be the least impactful in 8 categories, and for no impact, category was the microgrid found to be the most impactful. The EBPT of the diesel generator and the grid extension is 10.1 and 6.5 times greater than the EBPT of the Town Island Microgrid. It can thus be concluded that the case study supported the microgrid as a more environmental friendly solution compared to other common electrification options.

For future works, the scope of study could be expanded by also taking into account the end of life for an energy system. Given that recycling data in Hong Kong is not readily available, it was decided not to include the end of life in the LCA at the current study. Future LCA research could factor in the impacts of recycling and disposal if the data becomes more accessible. In addition, for microgrid projects undergoing the initial planning and design stage, smart grid features such as demand response can be considered for further optimization and to harness benefits from possible enhanced efficiency. The associated environmental performance improvement can then be quantified by LCA.

Acknowledgments

Technological data was shared between CLP Power (CLP) and the authors. The authors wish to express our most profound gratitude to CLP for making this study possible. This paper represents independent and neutral findings by the authors and the responsibility of clarity and accuracy belongs to the authors only.

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