Renewable Energy 36 (2011) 2227–2237

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

LCAs of a polycrystalline photovoltaic module and a wind turbine

Z.W. Zhong [a,*], B. Song [b], P.E. Loh [a]

[a] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Republic of Singapore
[b] Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075, Republic of Singapore

ARTICLE INFO

Article history:
Received 17 August 2010
Accepted 18 January 2011
Available online 15 February 2011

Keywords:
Life-cycle assessment
Photovoltaic module
Wind turbine
Recycling

ABSTRACT

This study compares the environmental impacts of a polycrystalline photovoltaic (PV) module and a wind turbine using the life cycle assessment (LCA) method. This study models landfill disposal and recycling scenarios of the decommissioned PV module and wind turbine, and compares their impacts to those of the other stages in the life cycles. The comparison establishes that the wind turbine has smaller environmental impacts in almost all of the categories assessed. The disposal stage can become a major contributor to the environmental impacts, depending on disposal scenarios. Recycling is an environmentally efficient method, because of its environmental benefits derived from energy savings and resource reclaimed. The end-of-life recycling scenario for a wind turbine has a significant part on the environmental impacts and should not be ignored. However, many factors also influence the degree to which recycling can be beneficial. With the wind turbine recycling scenario, when large quantities of waste are recycled, the potential savings can be quite large, while with the PV module, small quantities of recycled waste mean that the benefits of recycling are not fully reaped.

1. Introduction

There has been increased interest in environmentally friendly technologies and in processing hazard-free materials. The public is increasingly aware of climate changes and many people re-consider their lifestyle and energy usage choices [1]. Renewable energy has won legislative supports in many countries [2]. There is rapid growth in wind and solar energy for sustainable development [3,4].

Renewable energy has many advantages, but there is a concern that many renewable energy technologies are also polluting [5]. The wind turbines on farm sites require infrastructure construction, and grid connections may affect the natural habitat of wildlife around the area [6]. While newer designs with blades of slower rotation rates reduce bird mortality rates, older turbines still present a threat but are less destructive to birds, compared with fossil fuels, which destroy habitats during oil spills, acid rain and mining activities [7,8]. Although power generation using a photovoltaic (PV) system is free from greenhouse gas emissions and fossil fuel use, the energy and emissions involved in the manufacturing, transport and disposal of its elements must be considered [9]. The worst environmental problems with solar technologies are from the manufacturing processes of solar cells because of the large amount of energy consumed and the use of toxic chemical and scarce minerals [7].

Using of so-called “green technologies” does not always automatically guarantee sustainable production. Therefore, life cycle assessment (LCA) of the technologies is needed.

LCA is a useful tool for assessing the environmental impacts of a product or process and has been applied to many fields. The most extensive data for LCAs of PV technologies were obtained in 1992, but they were based on the technologies of the 1980s [10–13]. Updating the data was attempted, but it was mostly based on estimates and data derived from secondary sources [11,13]. A study of ten PV plants was performed recently, which produced inventory data for the PV technology of that period and also used adjustments to estimate data for PV technologies up to 2010 [14].

However, many LCA studies of PV technologies focused on the manufacturing and installation stages, and the end-of-life scenario is often excluded, as PV technologies have very long life cycles and thus any disposal data collected are based on outdated technologies [15]. The common approach to dealing with the decommissioning of PV modules is to assume that they are disposed at landfills [15], incinerated or both [16]. As the disposal of PV modules is a vital part to complete the full cradle-to-grave life cycle and increasingly used solar energy increases the waste of decommissioned PV modules, its environmental impacts should be studied [17,18]. The amount of materials that can be recovered through recycling has been compiled with the data collected across Europe and compiled for the year 2007 [19].

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* Corresponding author. Tel.: +65 6790 5588; fax: +65 6791 1859.
E-mail address: mzwzhong@ntu.edu.sg (Z.W. Zhong).

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doi:10.1016/j.renene.2011.01.021

Most of LCA studies of wind turbines show that the main contributor to environmental loads is the production phase of the turbine [20]. A study of 72 LCAs found that all of them studied the manufacturing phase, 70% studied the installation, 56% included maintenance and repair inventories, but only 19% included the decommissioning phase [21]. The low percentage of studies analyzing the disposal and recycling stages of a wind turbine is largely because of many disposal methods and lacking of good data [22]. Some studies on the disposal or scrapping of a wind turbine measure the effects in energy terms only, by assessing the energy amount used to dismantle the turbine and subtracting the energy amount saved from the recycled materials [23]. There are studies that give possible recycling scenarios for a decommissioned wind turbine, but only the main components are accounted for waste treatment [24,25].

This study models landfill disposal and recycling scenarios of a decommissioned polycrystalline PV module and a wind turbine, and compares their impacts to those of the other stages in their entire life cycles.

2. The methodology

LCA assesses the environmental impacts of the processes over the entire life cycle of a given product from raw materials and manufacturing processes to its operational life and disposal or recycling [26]. The processes are constantly refined and streamlined, and are repeatedly evaluated to reduce uncertainties and ensure good final results [27]. An LCA study consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation. The LCI (life cycle inventory) analysis phase is related to the calculations and collection of data [28]. In this work, models were established using a SimaPro software system with the database Ecoinvent.

The life cycle impact assessment (LCIA) converts LCI results to the collection of indicator results for different impact categories [29]. In this work, the Eco-indicator 99 methodology [30] was chosen to be used. The impact categories used are carcinogen, respiratory inorganics, respiratory organics, climate change, radiation, ozone layer, acidification/eutrophication, ecotoxicity, land use, mineral use, and fossil fuels. The interpretation phase evaluates the results of the LCIA of the product system [28].

3. A PV module

3.1. End-of-life scenarios for a PV module

The goal is to model two end-of-life scenarios (burying waste at a landfill and recycling of waste) and complete the life cycle of a polycrystalline silicon PV module converting solar energy to electricity. The models are built using the data of the PV technologies in literature [11,13]. After the PV assembly is decommissioned, it is disassembled into the module and BOS (balance of system) components. In the first model, the materials are not incinerated or recycled, and the module and BOS components are buried at a landfill. In the second model, after dismantling the PV assembly, the glass, plastic and metal components and other waste materials are sent to their respective recycling processes. The amount of waste recycled is taken from literature [25].

3.1.1. LCI analysis of the PV module

The PV module is mounted on a slanted roof as it has the lowest environmental impact [20]. A BOS consisting of an inverter, cabling and frames is added for the assembly and installation of the PV module. The data for the BOS are from SimaPro Ecoinvent database. The data are used as a control reference for the generation of the new model using the ECN (Energy Research Centre of the Netherlands) data released in 2007 reflecting changes in PV technology since 2003.

First, the polycrystalline silicon ingot is created, followed by the fabrication process of the ingot into wafers and then the slicing of wafers into PV cells. The PV cells and other inputs are combined together to create the PV module as a sub-assembly, which is then assembled together with the BOS components to create the PV module with BOS.

In this study, all of the impact scores were divided by a reference score for each impact category to investigate whether the impacts calculated would be significant, and this benchmarking step is known as normalization. Normalization calculates the relative contributions of a product/process to each of the environmental impact potentials, by dividing the environmental impact potentials of the product/process with a reference score for each impact category [26]. In the Eco-Indicator 99 methodology used in this study, normalization is based on European person equivalents per year [30,31], meaning the reference score used is that of one average European person per year for an impact category [32].

Fig. 1 shows normalized impact assessment results of the PV assembly process. The most relevant impacts are fossil fuels, respiratory inorganics, minerals, ecotoxicity, climate change and carcinogens in the highest-to-lowest order. The high fossil fuel score is due to the large amounts of fossil fuels used in energy generation, and they are also partly responsible for the scores in respiratory inorganics and climate change. PV modules require the use of scarce metals, which accounts for the minerals score. The disposal of process waste generated during the manufacturing processes is the main cause for carcinogens and ecotoxicity.

3.1.2. LCI analysis of the landfill disposal scenario

In the disposal phase, the PV module is first separated from the BOS. The PV module sub-assembly and the BOS components are then processed by a landfill disposal scenario that breaks them down into individual components based on the waste types, which are then sent to different waste treatment processes. The analysis reveals that after disassembly, the BOS components have no significant contributions to the environmental impacts. Most of the impacts come from the disposal of plastic waste at a sanitary landfill (51.2%). The PV cells make up the largest portion of the disposed module in terms of weight. The PV cells are disposed as solid waste at an inert landfill [16], which is the main reason for the contribution of the inert landfill waste treatment process (17.7%). The treatment of Al waste contributes 7.8% of the impacts, coming from the disposal of the module frame.

The highest impact category for the disposal phase is fossil fuels, mainly due to the use of crude oil (76.1%) and natural gas (17.1%). The use of fossil fuels is also responsible for climate change (22.6%) and respiratory inorganics (60.1%). The disposal of plastics at the sanitary landfill is the main contributor to the impacts of carcinogens (83%) and ecotoxicity (56.9%), due to the degrading of waste that releases toxic chemicals and pollutants into the atmosphere or leaches into ground water and rivers. However, the normalized overall impacts of the disposal phase are relatively small, as shown in Fig. 2.

3.1.3. LCI analysis of the recycling scenario

The PV module with BOS is first disassembled and the PV module is sent to the recycling scenario based on the data shown in Table 1 [19]. All non-recycled materials are disposed at a landfill, except for polyethylene terephthalate waste which is incinerated based on the Ecoinvent PV data. The recycling process of copper is created based on a literature source [25]. The other materials are recycled using default recycling processes in the SimaPro Ecoinvent database according to the amount in Table 1. The energy input for the process is calculated as 26% of the total energy required in the manufacturing process [16]. After a preliminary analysis, it is found

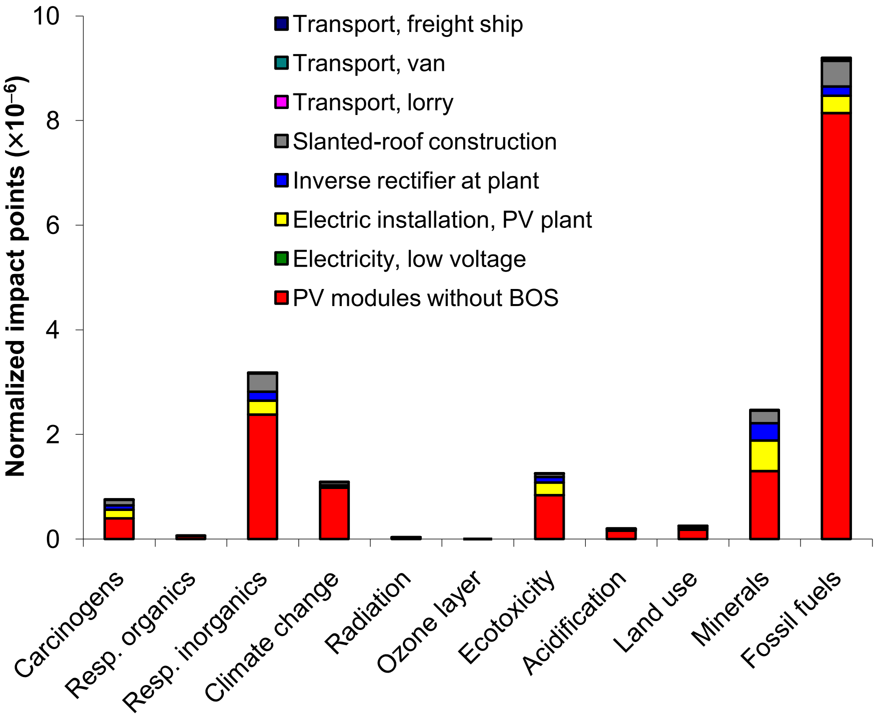

Fig. 1. Normalized impact assessment results of the PV assembly process.

that the recycled amounts of silver and lead waste are small and therefore the impacts are not significant. Therefore, these materials are removed from the model.

The analysis reveals that the BOS components have very little contribution to the environmental impacts. The major contributor is the transportation of waste by lorry. The largest benefits are from the recycling of glass and aluminum with relatively high recycling rates.

The comparison between the landfill disposal and recycling waste scenarios indicates that except for respiratory organics, ozone layer, acidification/eutrophication and fossil fuels, recycling has reduced the impacts on the environment. After normalization, these impacts are greatly reduced such that they are almost negligible, except for carcinogens and fossil fuel use as shown in Fig. 3. The disposal of plastics is the main contributor to carcinogens as only a small amount is recycled.

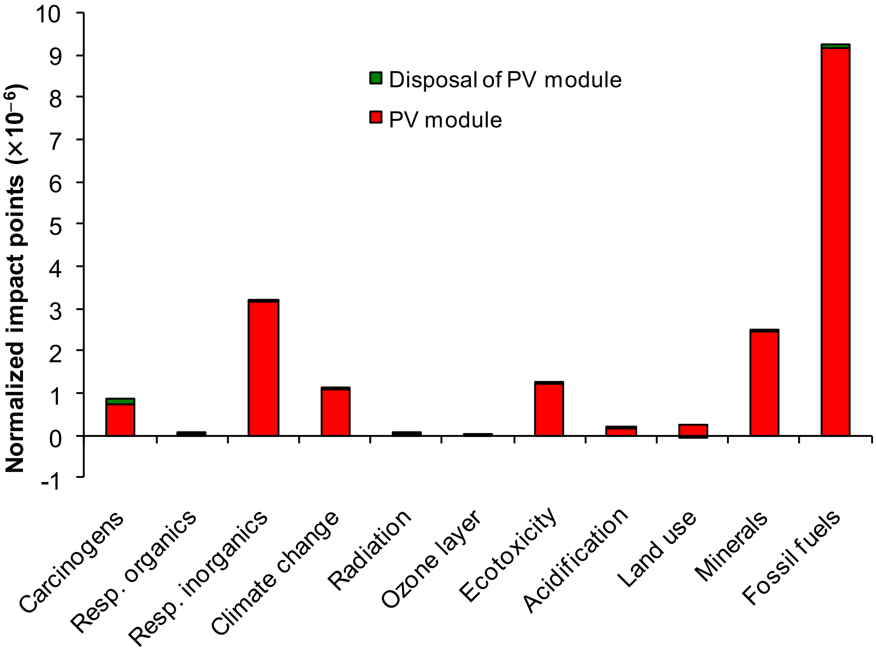

Fig. 2. Normalized impact assessment results of the disposal of the PV module over the life cycle.

Table 1
Recycling of the decommissioned PV module [19].

Material	Recycled (%)
Glass	74.16
Aluminum frame	10.30
EVA	6.55
Solar cells	3.48
Back foil (plastics)	3.60
Copper	0.57
Silver	0.08 (mean value)
Tin	0.14 (mean value)
Lead	0.035 (mean value)
Silicon	3

However, the recycling of plastics helps to reduce some of the impacts. The recycling processes also require energy inputs, leading to a higher fossil fuels score. The manufacture of PV cells requires the use of scarce metals such as nickel, bauxite, copper and tin. Through recycling, these minerals can be reclaimed for re-use, shown by the minus score of the impact of recycling on minerals. The reduction in the impact of respiratory inorganics is because of the recycling of glass.

3.2. Comparison of PV solar power and grid power

In the manufacture of the silicon wafers and subsequently the processes to fabricate the PV cells in solar panels, large quantities of electrical power and heat energy are used, large portions of which currently are supplied by burning natural gas or fossil fuels. These fossil fuels indirectly affect the impacts of fossil fuel use, climate change, acidification and respiratory inorganics. However, solar technology can also generate electricity and heat.

The analysis described in this section is a supplemental analysis to study whether using PV technology to supply the heat and electricity needed for PV cell manufacturing and assembly processes results in lower environmental impacts compared to using electricity from grid. The analysis uses the ECN data for the PV module and the data from the SimaPro Ecoinvent database for the BOS, assembly and energy production processes. The data may be valid representations of Western European technology [3]. Only the manufacturing and installation processes are analyzed because these phases consume the most energy and require the most fossil fuels. The end-of-life impacts are relatively small and thus are not compared in this section.

Fig. 4 shows the main processes for the manufacturing of the PV module. To evaluate the effects of using solar energy to power the processes, a PV production mix is used for electrical power (this represents an average of 10 PV plants [20]), and solar thermal energy supply for housing is used to approximate the heat input to the PV module manufacturing process. Thus, the manufacture of the PV panel is completely powered by solar.

The normalized impact assessment results of the conventional grid power and PV power scenarios are shown in Fig. 5. Of all the impacts, the use of fossil fuels has the highest influence on the environment. The burning of fossil fuels also releases gases such as sulphur dioxide and nitrogen oxides, which contribute to the impacts of respiratory inorganics and acidification. The use of solar power can reduce the environmental impacts of fossil fuels by over 20% and also indirectly reduce the effects of respiratory inorganics and acidification. But much more solar cells are needed to power the manufacturing process purely using solar energy. The use of toxic chemicals and metals such as lead and cadmium in PV cells and increased manufacturing wastes are responsible for the increase in carcinogens and ecotoxicity. The increased amounts of copper and silicon also give a higher mineral score. Overall, the total environmental impact of the manufacturing phase is reduced when it is powered by solar energy instead of fossil fuels.

4. A wind turbine

4.1. End-of-life scenarios for wind turbine

Much like the LCAs for PV technologies, the disposal and recycling phases of wind turbines are often neglected. However, these phases are important because of their environmental impacts. An end-of-life phase can be modeled with a disassembly of a turbine

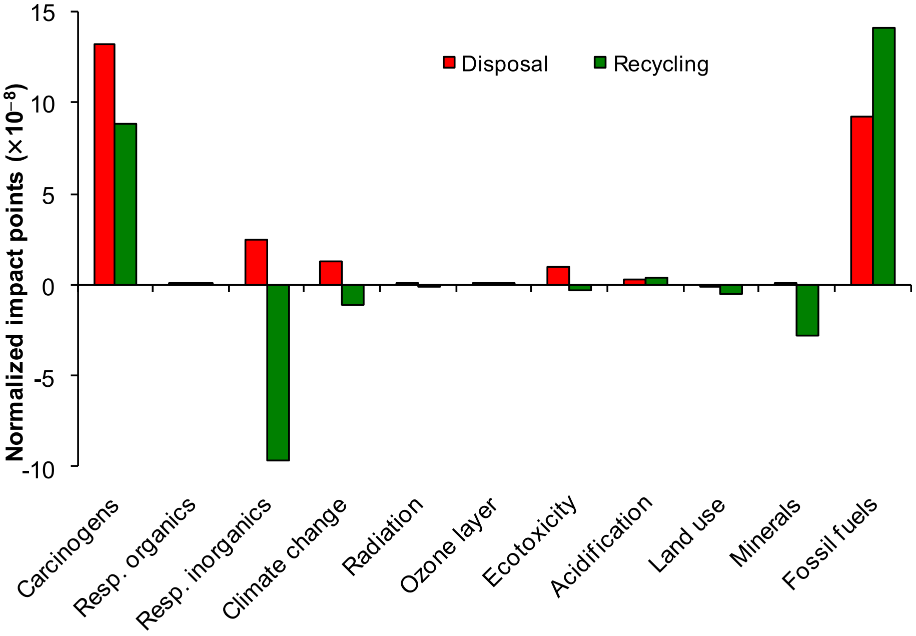

Fig. 3. Normalized impact assessment results of the landfill disposal and recycling stages of the PV module.

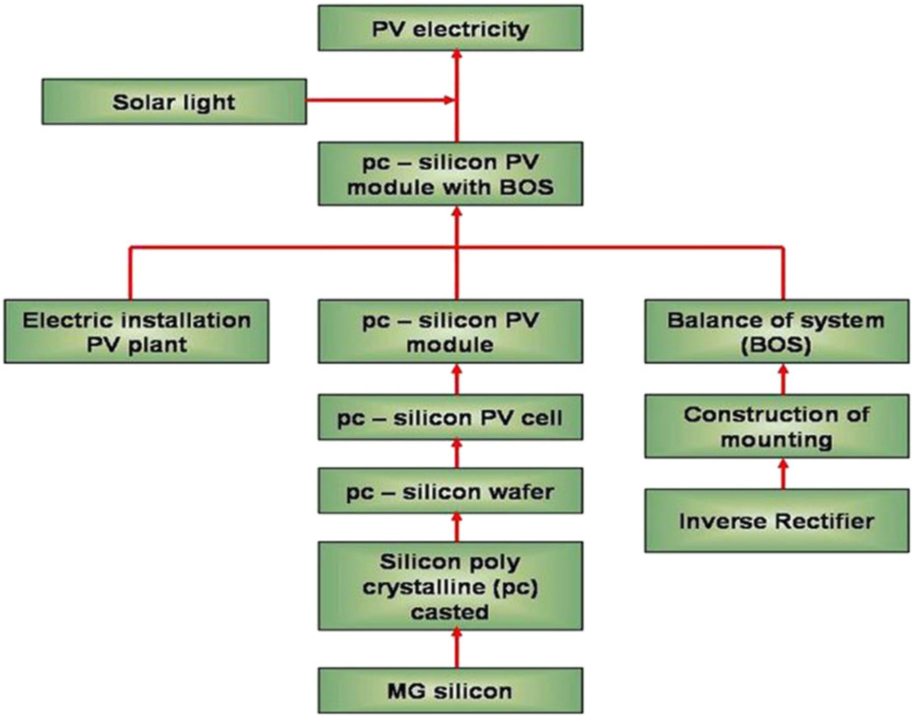

Fig. 4. The main processes for the manufacturing of the PV module [33].

and then disposal or recycling of its parts. The simplest way to model the disassembly of the turbine is to reverse the process of installation [25]. After disassembly, the parts are recycled, incinerated or buried at a landfill.

The goal is to model two end-of-life scenarios for a wind turbine upon decommissioning. The first model is for burial at a landfill and the second is for waste recycling. The product analyzed is a 600-kW wind turbine. Although 600-kW turbines may be no longer in mass

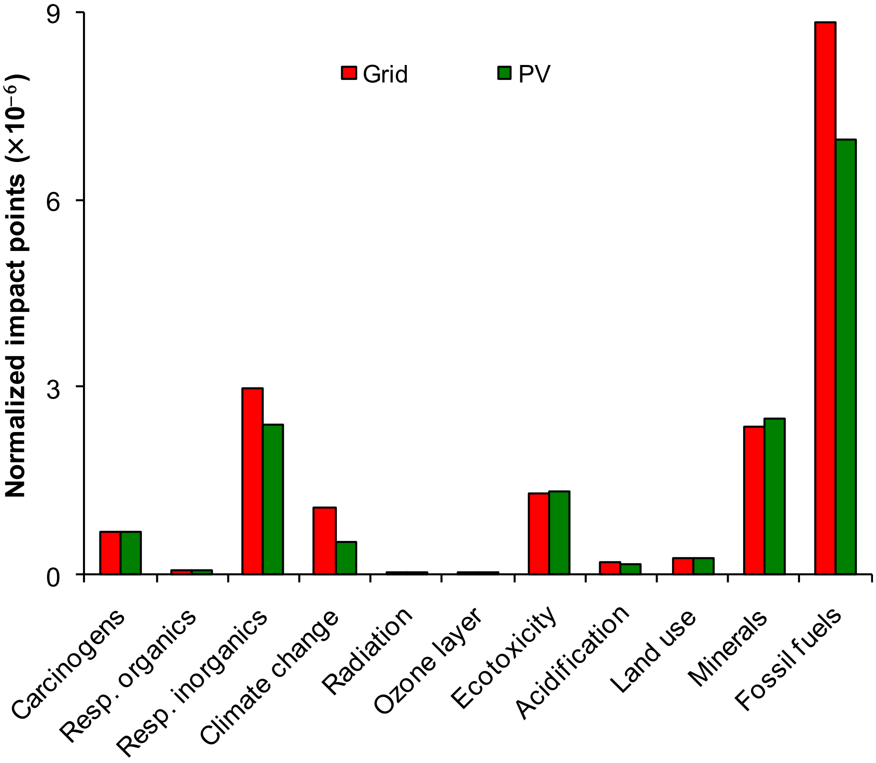

Fig. 5. Normalized impact assessment results of the conventional grid power and PV power scenarios.

production, this size was chosen for the study in this work because of the availability of the data and also the following reasons. Although the wind turbine data were collected in Switzerland, they can be approximated for use as Western European technology [20]. The data were published in 2003 based on the technology in 2000, and may still be representative of 2004/2005 600-kW wind turbine technology because of the operating life of 20 years. To model a disposal phase without recycling is an indicator of the worst case scenario in terms of environmental impacts. In the recycling model, the data are collected from the literature [24,25] to evaluate potential environmental benefits of recycling waste compared to disposal.

4.2. Comparison between the assembly phases of PV module and wind turbine

The inventory data for the assembly processes of the wind turbine are based on those of a 600-kW onshore wind turbine from the SimaPro Ecoinvent database. The environmental impacts of the assembly processes of the wind turbine are compared to that of the PV module studied in section 3. Fig. 6 shows the normalized impact assessment results of the comparison, and the measurement unit is the amount required to produce 1-kWh electricity. The impacts of the assembly processes for the PV module are higher than those of the wind turbine in all categories except those of land use and minerals. The laying of the foundation for the wind turbine requires the land to be altered, and the building of infrastructure such as roads also affects the score of land use. Wind turbines also require the use of larger amounts of copper, iron and steel, which is responsible for the higher impact score of minerals use. However, after normalization, the differences between these impacts become insignificant. Large impact differences are associated with fossil fuel usage, respiratory inorganics, climate change and carcinogens. The high score for fossil fuels is because the fabrication of a PV module consists of many processes requiring electricity and/or heat generated from fossil fuels. The burning of fossil fuels also releases air pollutants, the causes of the impact scores for respiratory inorganics and climate change. The carcinogen impact is due to the processing of slag waste generated during the fabrication of solar cells.

4.3. LCI analysis of landfill scenarios

The disassembly of the wind turbine is approximated by reversing the process of assembly and installation [25]. Therefore, the energy inputs required to power the disassembly process is assumed to be the same as that for the assembly. The turbine is assembled using a crane to stack up the parts. In disassembly, a similar crane is used to remove each part, but the order is reversed. After disassembly, each of the sub-assemblies (moving parts such as gears and rotor mechanisms, and fixed parts) is allocated a landfill scenario created using waste treatment processes within SimaPro.

The analysis reveals that the disposal of plastics (57.3%), the transportation of waste by lorry (18.4%) and the power inputs (18.2%) are the main contributors to the environmental impacts. As shown in Fig. 7, the disposal of the turbine moving parts contributes heavily to carcinogens, fossil fuels and ecotoxicity. The electricity inputs also contribute a large part of the impacts of fossil fuels, climate change and respiratory inorganics. The disposal of plastics at the landfill is the main cause of the high scores for ecotoxicity (60.9%) and carcinogens (92.5%). The environmental impact of fossil fuels is due to the energy used to disassemble the turbine as this power is supplied mainly using crude oil (69.6%) and natural gas (24.8%). The impact of respiratory inorganics score is also due to the burning of fuels such as diesel (8.1%), coal (10.1%) and other fossil fuels like ignite (19.0%), which release harmful gases. Fossil fuels are also largely responsible for climate change (59.8%). The transportation of waste by lorry also contributes to the impacts of climate change (20.1%) and respiratory inorganics (34.8%).

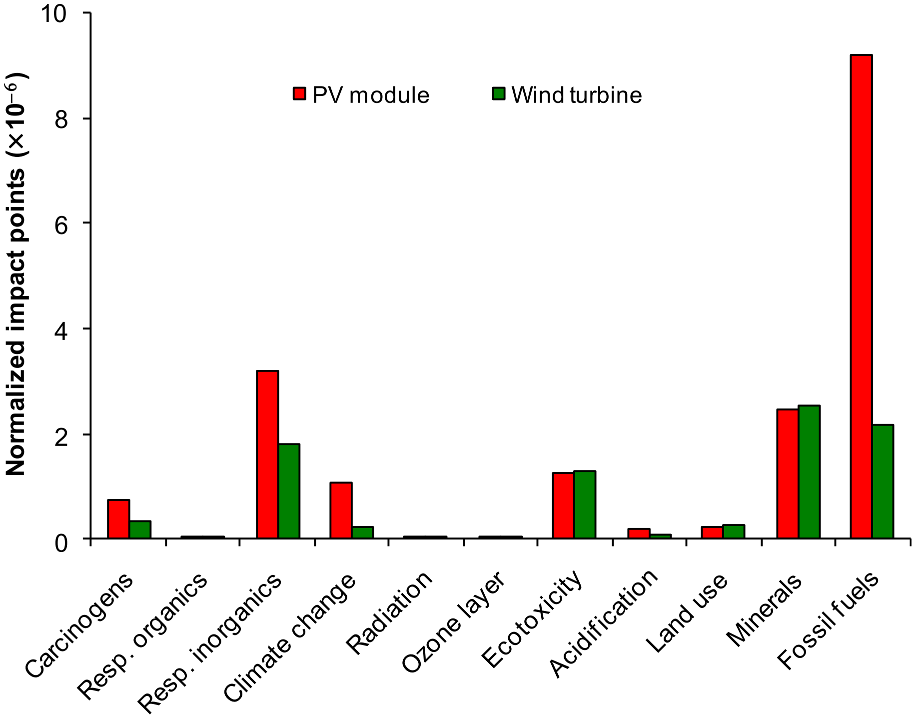

Fig. 6. Normalized impact assessment results for the comparison between the assembly phases of the PV module and wind turbine.

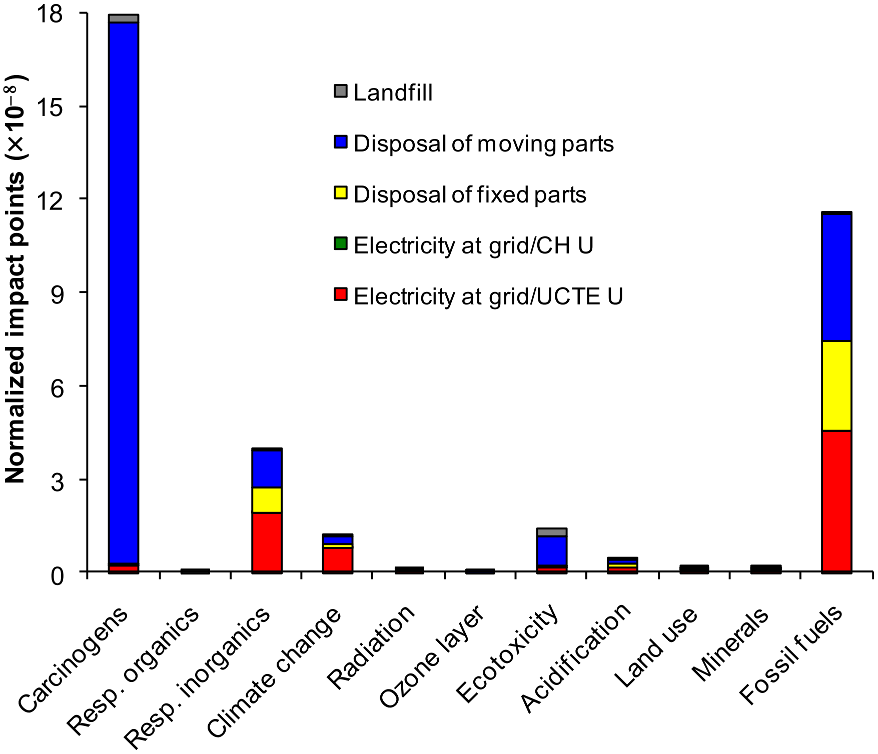

Fig. 7. Normalized impact assessment results of the disassembly and disposal stage of the wind turbine.

4.4. LCI analysis of recycling scenarios

The wind turbine data used in the assembly and disassembly are reused, but the landfill scenario is replaced with a recycling scenario having the sub-assemblies materials recycled. The recycling data are shown in Table 2 [24,25]. All plastics are sent to incineration processes.

The analysis reveals that the moving parts of the turbine are the more significant contributor to the environmental loads than the fixed parts, and recycling of copper, and iron and steel contributes to the environmental benefits in all the impact categories except radiation whose impact is also reduced by more than half. Upon normalization, as shown in Fig. 8, the most significant benefits of recycling are in the impact categories of carcinogens, respiratory inorganics, ecotoxicity and minerals. The beneficial impact on mineral use is because of the recycled metals such as copper (−83.8%) and iron (−11%). As a large percentage of the waste is recycled or incinerated, the waste amount sent to the landfill is greatly reduced. Carcinogen scores are also reduced due to the effects of recycled copper (−62%) and iron (−49%). Ecotoxicity is reduced by copper recycling (−95%). The biggest difference between disposal and recycling is in the category of respiratory inorganics, where the recycled iron (−50%) and copper (−19%) are also the main beneficial contributors. The waste not recycled is mostly incinerated, and the heat produced from incineration is used to generate electricity. This leads to a beneficial impact on the environment and minimizes the amount of energy inputs into the turbine life cycle. Using recycled materials also results in energy savings, reducing fossil fuels consumption.

Table 2
Recycling data for a 600-kW wind turbine.

Materials	Recycle (%)	Disposal	Source
Steel and cast iron	90	10% landfill (ETH-ESU 96)	[25]
Copper	90	10% inert landfill (ETH-ESU 96)	[25]
Glass fiber and plastics	0	100% incinerate (Ecoinvent)	[25]
Concrete	0	100% inert landfill (ETH-ESU 96)	[25]
Rubber	0	100% incinerate	[24]
Aluminum	90	10% assumed disposal to landfill	[24]
Lead	90	10% loss during recycling	[24]

Note: items in parenthesis are the databases the data are extracted from.

5. LCA comparison of the PV module and wind turbine

5.1. Goal and scope of the LCAs

The goal is to compare the complete life cycles of the PV module with BOS and the 600-kW wind turbine and to assess which is more environmentally sustainable. The complete life cycles of these technologies can be modeled including one of the models created for the end-of-life scenarios: disposing of all waste at a landfill and recycling of waste materials.

5.2. The complete LCA models of the PV module and wind turbine

A simplified model of the complete life cycle of the PV module is shown in Fig. 9. The contribution of the disposal scenario to the environmental impacts is small, 1.77% of the total contribution of the complete life cycle to the environmental impacts. The recycling scenario can reduce the contribution from 1.77% to 0.26%.

A simplified model of the complete life cycle of the wind turbine is shown in Fig. 10. The analysis reveals that the recycle phase can reduce the contribution to the environmental impacts by 37.1%. This means that the end-of-life recycling scenario for a wind turbine has a significant part on the environmental impacts and should not be ignored. End-of-life scenarios can contribute to the total impacts of wind turbines, depending on waste treatment methods and amount of waste processed.

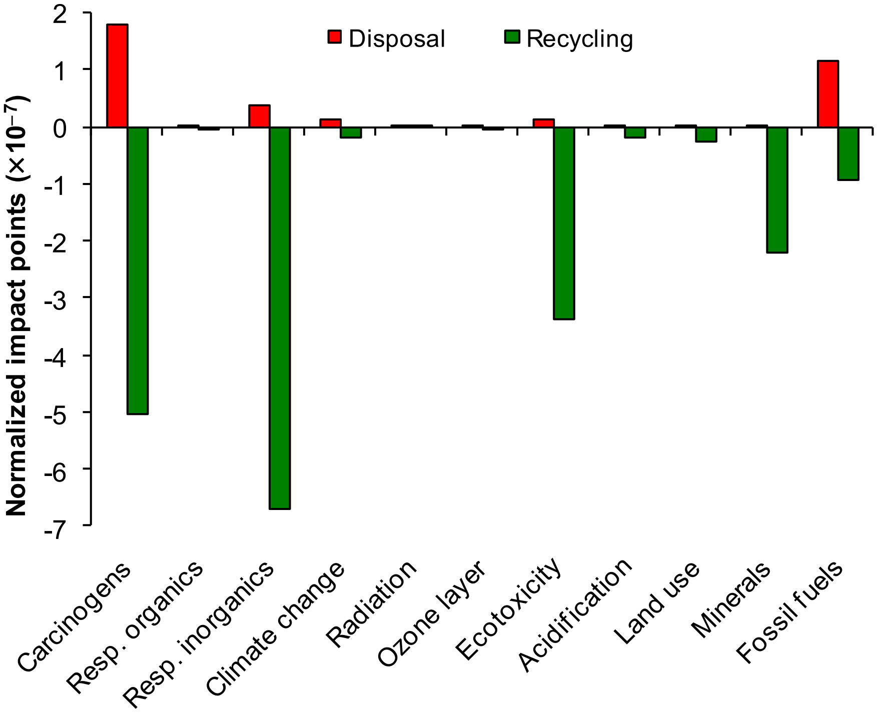

Fig. 8. Normalized impact assessment results of the disposal and recycling of the wind turbine.

5.3. *LCI analyses*

As shown in Fig. 11, the PV model has higher relative-impact-scores in almost all categories than the wind turbine model, except for minerals, ecotoxicity and land use categories. The largest difference is in the amount of the fossil fuels consumed in the life cycle of the PV module, because the PV module manufacturing process is more energy intensive. The wind turbine has large amounts of iron,

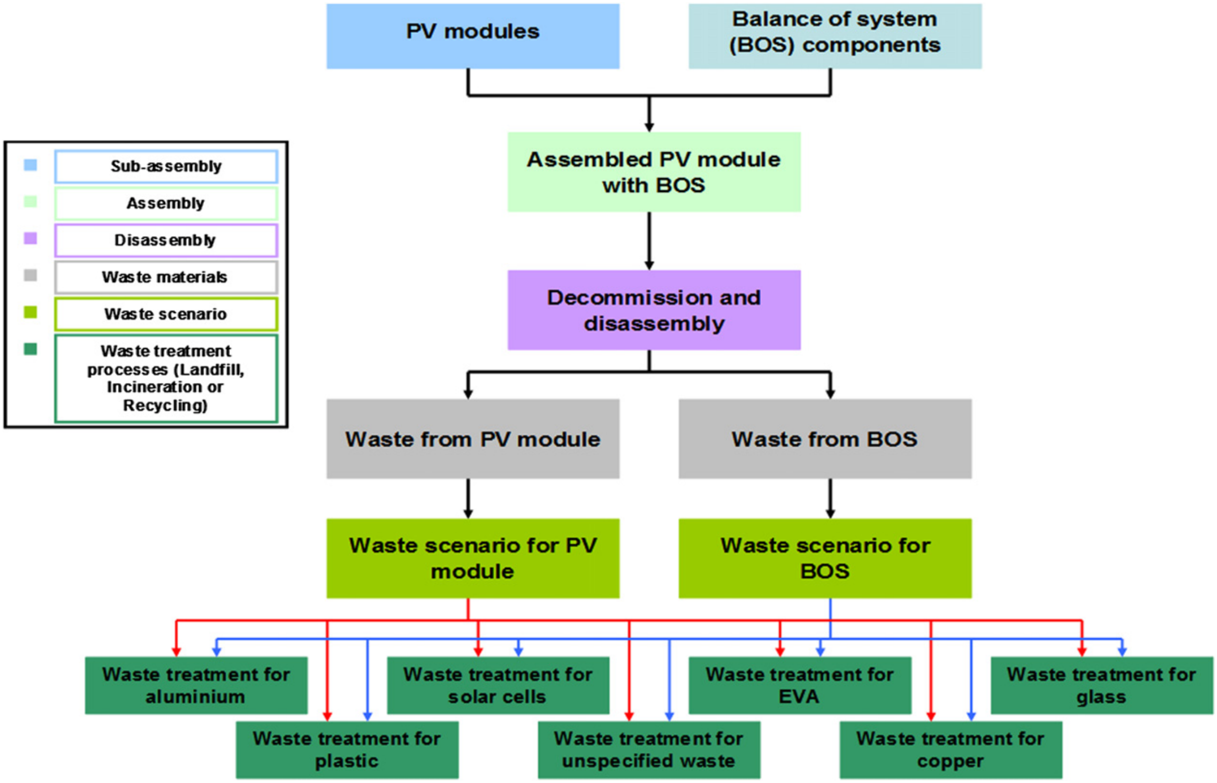

Fig. 9. Simplified model of the complete life cycle of the PV module [33].

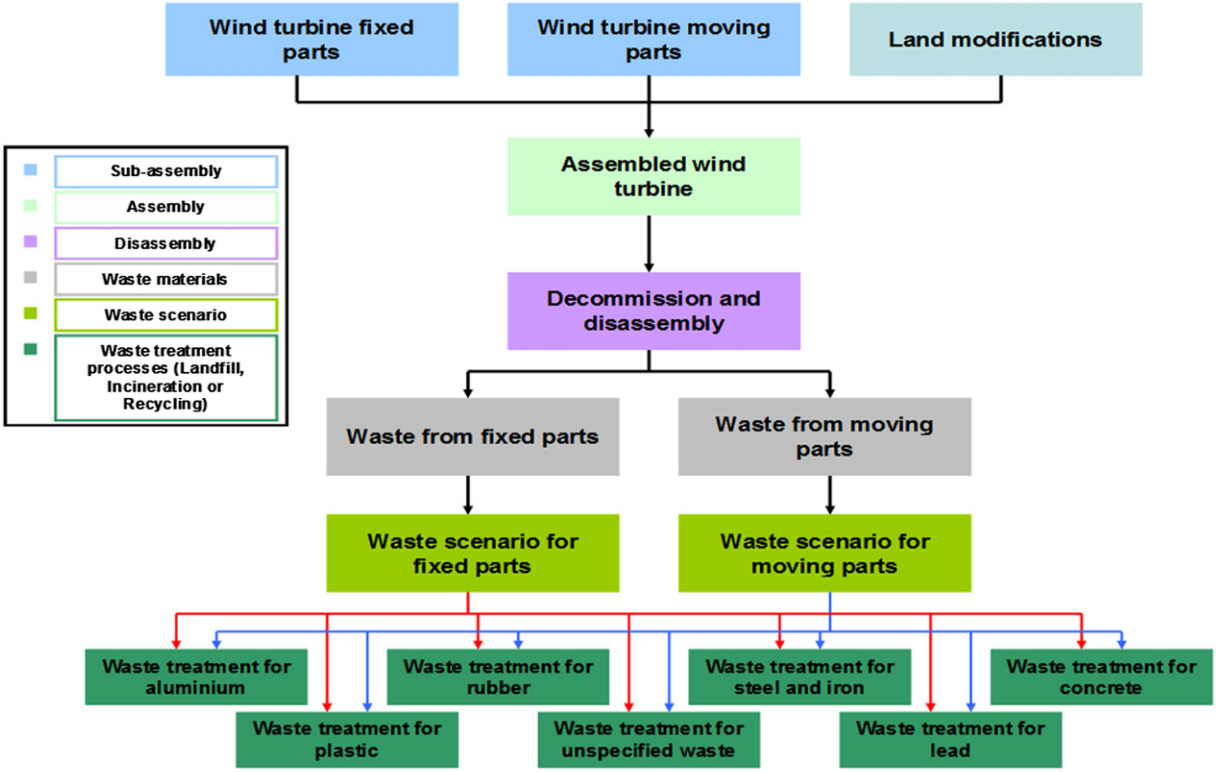

Fig. 10. Simplified model of the complete life cycle of the wind turbine [33].

steel, copper and lead, resulting in a higher minerals score. It has a higher land use impact because of the need to modify land area to build the foundations. After normalization, as shown in Fig. 12, the impacts of the models differ largely in the categories of fossil fuels, respiratory inorganics, climate change and carcinogens due to the large amounts of fossil fuels consumed in the assembly stage of the PV module, the differences in the impacts of mineral use are minimized, and the differences in land use are not significant.

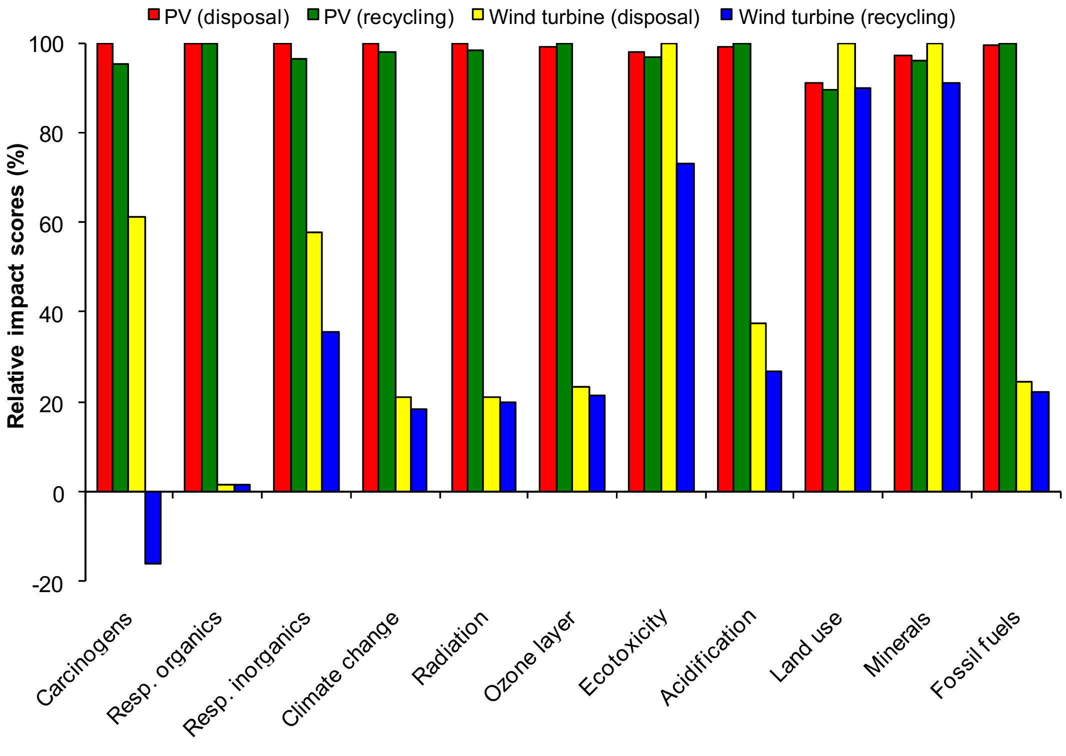

Fig. 11. Characterization of impact assessment results for the PV and wind turbine models.

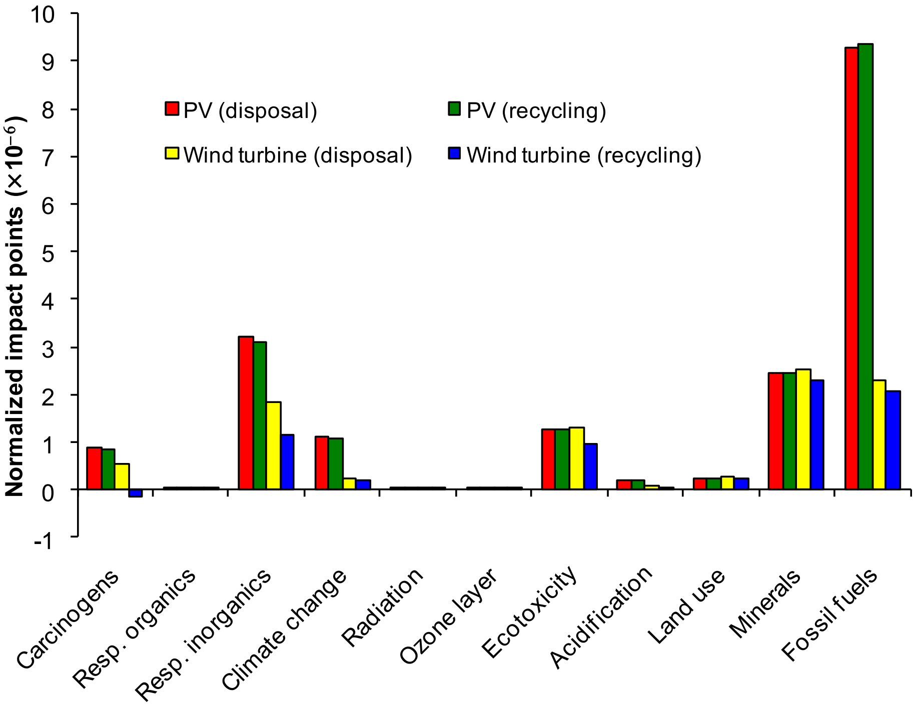

Fig. 12. Normalized impact assessment results of the PV and wind turbine models.

The wind turbine model with the recycling end-of-life scenario is the least environmentally damaging in all categories among the four models/scenarios. The high recycling amounts of the waste result in reduced environmental impacts. The PV model with recycling, however, only recycles a low amount of the waste materials, and most of the waste is disposed at the landfill. As a result, the PV model with recycling still scores higher in many impact categories than the wind turbine model without recycling. With the present technological standards, the wind turbine technology is much more sustainable than the PV technology over their entire life cycles.

6. Conclusions

The comparison of life cycles of a PV module and a wind turbine clearly shows that the wind turbine technology has less environmental impacts in almost all of the categories assessed. The impacts of fossil fuels have the most significant difference. Using the PV energy to power processes in the assembly phase can help to minimize some of the impacts, but it is still not a penalty-free solution. The disposal stage can become a major contributor to the environmental impacts, depending on disposal scenarios. The worst case would be when waste is disposed at a landfill. The heat generated during incineration can be used to produce useful energy, and this offsets some of the energy inputs into the life cycle and can reduce energy related impacts. Recycling is an environmentally efficient method, because of the environmental benefits derived from energy savings and resource reclaimed. The end-of-life recycling scenario for a wind turbine has a significant part on the environmental impacts and should not be ignored. However, many factors also influence the degree to which recycling can be beneficial. As seen with the wind turbine recycling scenario, when large quantities of waste are recycled, the potential savings can be quite large, while with the PV module, small quantities of recycled waste mean that the benefits of recycling are not fully reaped.

Acknowledgements

The authors would like to thank Mr. Ng Rui Sheng, Mr. Chua Sheng Long, and Mr. Tan Tze Li for their assistance.

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