Life cycle impacts for electricity generation from wind source

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Abstract

Wind power is a renewable energy source, which is relatively evenly distributed over many regions of the world. Wind power plant requires no fuel input to produce electricity, thus, wind energy is emission free during its conversion process. However, manufacturing of wind power plant components such as turbine requires several materials, processes, energy, transports, natural resources, and disposal stages during its whole life cycle stages. For a complete understanding of impacts of electric energy generation using wind turbine, it is necessary to analyze the emissions and other impacts over the entire life cycle stages of a wind turbine. This study makes a complete Life Cycle Analysis (LCA) of wind energy to determine the impacts for each functional unit (i.e. 1kWh of electric energy) over the entire life cycle of a wind turbine. LCA tool SimaPro has been employed to define the scopes and goals of the analysis and to perform inventory and impact assessment. Data has been collected from Ecoinvent database sources. This study found that overall negative impacts for electric energy generation are 1.58 *Pt* (Pt is a unit for environmental loading) and 339.8 *Pt* for wind source and energy mix in Malaysia, respectively. This study results mean that electric energy generation using wind turbine has much less negative impacts than fossil based energy mix.

Keywords
SimaPro, Wind turbine, LCA, Characterization, Damage

1. Introduction

The burning of fossil fuels for electricity generation releases greenhouse gases (GHG) into the environment. Electricity generation from fossil fuels accounts for major part (more than 50%) of CO_2 emissions (Bravi et al., 2007). It has also been appeared in the literatures that energy sector has a huge contribution to the total anthropogenic activities (Rahman et al., 2014). Wind, photovoltaic, and biomass are the predominant renewable energy resources in the world accounted for 95% of the renewable based electricity generation (excluding hydro) (REN21, 2015). However, electricity costs from renewables are generally high owing to their higher capital investments (ESMAP, 2007). Among these three major sources, interests in wind is particularly high due to their availability and huge potential (Dolan and Heath, 2012). Despite wind resource is relatively evenly distributed all over the world and have capabilities to counteract environmental challenges, its dissemination is still limited primarily due to the lack of life cycle consideration (Saidur et al., 2011).

Several studies assessed life cycle emissions and water consumptions for different fossil and renewable energy sources for power generation(Cameron and van der Zwaan, 2015; Frondel et al., 2010; Li et al., 2012; Rajaei and Tinjum, 2014; Saidur et al., 2011; Simas and Pacca, 2014; Warlick, 2009; WNA, 2011). These mentioned studies compared emission and water savings for electricity generation from renewable sources with conventional energy sources. Despite life cycle impacts for different products have been reported by many researchers, there is a clear lack of life cycle analysis of wind energy in Malaysia. In this work, we perform a life cycle assessment (LCA) for wind power generation in Malaysian context to make a comparison with that of Malaysian energy-mixes for electricity. The LCA is a well-known approach for performing evaluation of a product's environmental impacts throughout its life cycle, i.e. from a cradle-to-grave stages of the product (Baharwani et al., 2014; Dolan and Heath, 2012). Several softwares have been developed to assist and facilitate life cycle assessments, through the utilization of extensive databases. One of the most popular LCA softwares is SimaPro (Oebels and Pacca, 2013). In this work, we have used SimaPro software version 8.0.4.30, and Ecoinvent database 16 (SimaPro, 2017) to model electricity generation from wind energy and energy-mixes. The objective of this study is to determine the life cycle environmental impacts for Malaysian wind energy and energy mix to facilitate their unbiased comparison.

2. Methodology

2.1 Life cycle approach

Understanding of impacts for any product or service necessitates looking over the whole production lines. The production lines include raw materials extractions, refinery, blending, milling, waste management as well as transportation and other services. In traditional energy analysis, assessment of energy production takes account only the immediate inputs in the production line with ignoring the impacts from raw material extraction, material transportation, ultimate products, and disposal scenarios. To allow a fair comparison, impacts (e.g. global warming, resource depletion etc.) of electricity generation from various fuel sources for the whole life-cycle stages are essential. Life cycle assessment is a cradle-to-grave approach for assessing impacts for products or services. Cradle-to-grave approach begins with the gathering of raw materials from the earth to create the product (functional unit) and ends at the point where all materials are returned to the earth (Hendrickson et al., 2013). Life cycle values comprise all processes and environmental releases beginning with extraction of raw materials and the production of energy through the final disposition of the products. The life cycle impacts encompass activities under three major stages namely-upstream, spot, and downstream stages. Upstream impacts originate from raw materials extraction, processing, component manufacturing, component assembling and transportation. Spot impacts are the direct impacts from activities such as combustions, and operation and maintenance of the plants. Downstream impacts are ascended from activities such as transmission, consumption, disposal and recycling and reuse (Dolan and Heath, 2012). The major stages of a typical LCA study are raw material acquisition, component manufacture and assembling, production of functional unit, and deposal of the product.

Life cycle assessment technique utilizes the following methodology which is presented here in a generic approach. The major steps of a life cycle analysis are: Goal definition and scoping, life cycle inventory, life cycle impact assessment, and life cycle results and interpretation (Herrmann and Moltesen, 2015; Raadal et al., 2011; SimaPro, 2006). A brief outline of the life cycle analysis approach for this study is presented in Figure 1.

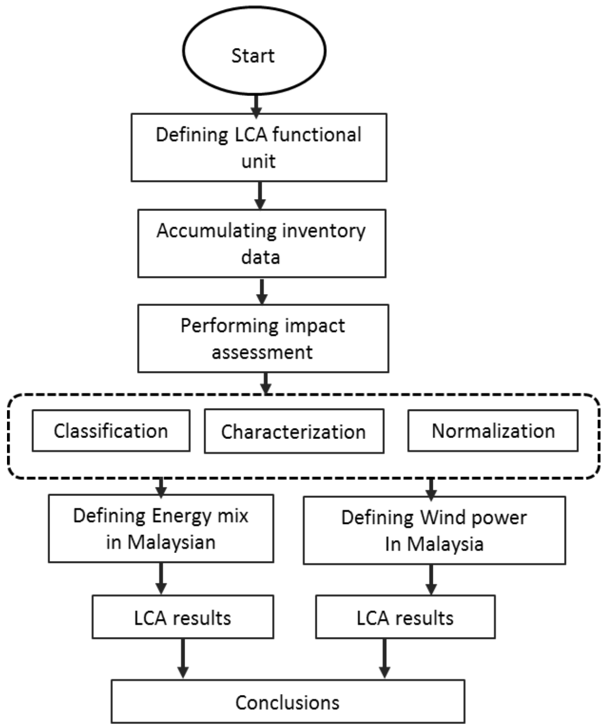

Figure 1. Life cycle assessment steps

2.2 Goal definition and scoping

Goal definition and scoping in LCA describe the purpose and procedure of determining life cycle impacts. The main goal of life cycle process is to provide the assessment of the environmental impacts of a process, product or service. LCA aims to select the best possible options with least possible impacts on human and environment (João Vasco de Oliveira Fernandes Lopes, 2010). The following issues are addressed while defining the goal of the LCA-

a) What are the reasons for conducting the LCA
b) The purpose of the study
c) The product's functional unit or function
d) To whom the results are aimed at
e) The definition of system boundary

The scopes of the LCA include the following things:

i. Product's function or service
ii. Temporal and spatial boundary within which the product evolves during the whole life cycle
iii. Data for the system's characterization
iv. Study assumptions
v. Study limitations
vi. Quality of the expected results
vii. Critical revision and validation of the results
viii. Structure of the final report.

2.3 The Functional Unit

The functional unit represents the main output of the process under LCA study. The input and output data are determined in light of the functional unit. When comparing of different products or services, the basis of comparison should be the same unit and this is called functional unit. In this study, the basis for determining the impacts for electricity production from wind source and energy mix is one unit of electricity (i.e. 1 kWh of electricity).

2.4 Life Cycle Inventory (LCI)

In the life cycle inventory process, input and output data are collected for a particular output of the whole system under consideration. The input output data may regard to energy, raw materials, or other physical inputs, co-products, and wastes that are released to or from water, air, and soil. The data are collected and organized in a prescribed structure.

The life cycle inventory composed of the following steps:

a) Development of flow diagram representing the system boundary of the study
b) Collection of the data
c) Data processing
d) Assessment and analysis of the results
e) Brief descriptions of each LCI
f) Impact assessment

2.5 The Life Cycle Impact Assessment (LCIA)

The life cycle impact assessment steps consist of assessment of results obtained in the inventory assessment. The life cycle impact results provide environmental significance by taking into account resource depletion, human health, and environmental impacts. The LCIA connects a product or process into the corresponding consequence in terms of potential human and environmental impacts. The LCIA consists of three basic steps as given below.

2.5.1 Selection of Impact Categories

This includes identification of impact categories. The impact categories depend on goal and scopes of the LCA e.g. global warming, acidification etc. The impact categories determine the types of data to be collected during inventory process.

2.5.2 Classification

The classification assigned each environmental flow into each impact category. For example, emission of methane is classified as global warming impact category. Any environmental flow can classify into more than one category as they contribute many impact categories. For example, emission of CFC can be classified as global warming as well as ozone layer depletion impact category.

2.5.3 Characterization

Characterization provides magnitude of the environmental flow for each environmental impact category. The contribution of each environmental flow is quantified into each category. Through science-based conversion factors, the LCI results are converted and combined into representative indicators to human and ecological health. To convert each environment flow into corresponding impact category, an equivalence factor is used which is called characterization factors.

2.5.4 Normalization

Normalization is achieved by dividing the impact results with a reference number. Without normalization, it is not possible to get idea how severe an impact category is in compare to other categories. Normalization provides comparability between the results from different impact categories. Normalization results are denoted by Pt, where 1 Pt represents one thousandth of the yearly environmental load of one average European inhabitant. An average European inhabitant emits around 11 tons of CO2 equivalent and 22 grams of CFC11 equivalent, as well as 0.415 kg of Phosphate equivalent.

2.6 Energy Mixes for Electricity in Malaysia

The energy mixes are the groups of different primary energy sources from which secondary energy is produced for consumption. The primary energy sources include fossil fuels (e.g. oil, natural gas and coal), nuclear energy, waste and the many types of renewable energy (biomass, wind, geothermal, hydro etc.). These primary energy sources are used to generate electricity, fuels for transportation, and heating and cooling for residential and industrial buildings. The term energy mix (electricity) refers the proportion of different primary energy sources to generate electricity in a given geographical region or country. Energy mix for electricity varies significantly from one country to another, globally fossil fuels account for over 65% of the energy mix for electricity generation. Malaysia employed significant amount of renewable hydropower for its electricity generation (12.5%). Other primary sources for electricity generation are natural gas (53.2%), Coal (30.4%), Crude oil (3.8%), and small scale renewable sources (0.5%). This study used above energy mix for electricity generation in Malaysia.

2.7 Wind Power

Research shows that Malaysia has a huge potential to generate electricity from offshore wind source (Samsudin et al., 2016). In this study, we have considered a typical 2000 kW offshore wind turbine for electricity generation with an expected life of 30 years. This study determines the life cycle impact of electricity generation at plant site from wind turbine installed at offshore Malaysian territory. The assumed system boundary for this analysis is shown in Figure 2.

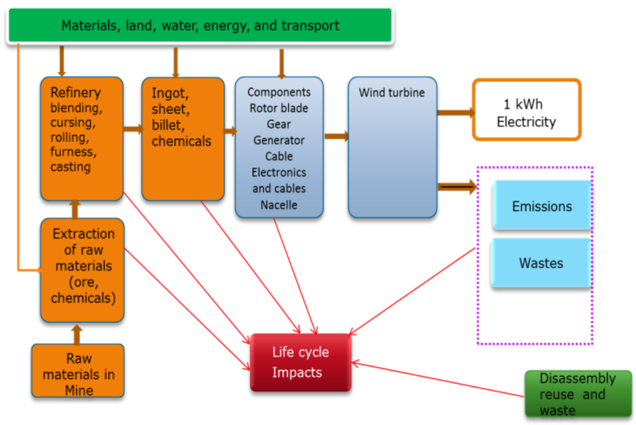

Figure 2. Boundary for determining life cycle impact for one kWh of electricity from wind source

3. Results and discussions

3.1 Characterization Results

The characterization results for both wind power and energy-mix are presented in Table 1. The characterization results aggregate impact categories into different damage categories. The characterization result for global warning impact category is 0.81469623 kg CO2eq. This means that the impacts of different emission species such as CO2, CH4, NO2, and CFC would result global warming that equivalents to 0.81469623 kg of carbon dioxide. For different greenhouse gas species, an equivalency factor/characterization factor was used to transform them into a single impact category. One hundred grams of CH4 emissions contribute global worming that equivalent to 2.5 kg of carbon dioxide.

Table 1. Characterization results

Impact category	**Unit**	**Energy mix Malaysia**	**Wind power**
Mineral extraction	MJ surplus	5.56E-05	0.0012225
Non-renewable energy	MJ primary	9.608121	0.0843175
Global warming	kg CO2 eq	0.8146962	0.0063516
Aquatic eutrophication	kg PO4 P-lim	0.0001564	5.72E-07
Aquatic acidification	kg SO2 eq	0.0037909	2.56E-05
Land occupation	m2org.arabl	0.0043347	0
Terrestrial acid/nutri	kg SO2 eq	0.0096017	8.22E-05
Terrestrial ecotoxicity	kg TEG soil	3.0451075	0.0298588
Aquatic ecotoxicity	kg TEG water	16.223849	0.0310478
Respiratory organics	kg C2H4 eq	6.91E-05	3.55E-06
Ozone layer depletion	kg CFC-11 eq	9.35E-09	0
Ionizing radiation	Bq C-14 eq	0.0837653	0.0535304
Respiratory inorganics	kg PM2.5 eq	0.0018540	2.85E-06
Non-carcinogens	kg C2H3Cl eq	0.0029821	0.0001506
Carcinogens	kg C2H3Cl eq	0.0184320	3.18E-05

The descriptions of each of the above impact categories are provided below.

- *The ozone layer depletion* represents the destruction of the stratospheric ozone-layer by anthropogenic emissions of ozone depleting substances such as CFCs.
- *The climate change* impact represents the global worming potential from greenhouse gas emissions.
- *Agricultural and urban land occupation* impact means the amount of land occupied for the functional products or services.
- *The human toxicity and ecotoxicity* represents the environmental persistence and accumulation in the human food chain, and toxicity of a chemical.
- *The ionizing radiation* represents the level of exposure to radioactive materials.
- *The photochemical oxidant formation* represents the marginal change in average concentration of ozone due to a marginal change in emission of a substance.
- *The particulate matter formation* is the intake fraction of PM10.
- *The marine eutrophication* represents the environmental persistence of the emission of Nitrogen containing nutrients.
- *The freshwater eutrophication* represents the environmental persistence of the emission of Phosphorus containing nutrients.
- *The fossil fuel depletion* is the amount of fossil fuel extracted and used for this purpose based on the lower heating value.
- *The freshwater depletion* is the amount of freshwater that is consumed for producing functional unit.

3.2 Damage Results

From the characterization results, it is not clear the severity of impacts to the human health and the environment. The purpose of damage assessment is to present the anticipated damage that may cause to the environment and human health. The damage results combine a number of impact categories into different end-point damage categories (also called area of protections). In the damage assessment step, impact category indicator with a common unit is to be sum up to one category. For example, all impact categories that refer to human health are expressed in DALY (disability adjusted life years). In this method, DALYs caused by carcinogenic substances are added to DALYs caused by climate change.

Human health is obtained by modeling the cause-effect chain of water deprivation for agricultural users (lack of irrigation water) leading to malnutrition. Ecosystem quality is obtained by modeling the cause-effect chain of freshwater consumption on terrestrial ecosystem quality with units of potentially disappeared fraction of species (PDF). Different damage categories for both the energy sources are presented in Table 2.
Energy resource damages, for example, are 0.0855400299 MJ for wind energy. This means that 0.0855400299 MJ of primary energy is consumed for the whole process of the 1 kWh of electric energy generation from wind source.

Table 2**.** Damage assessment results

Damage category	**Unit**	**Energy mix Malaysia**	**Wind power**
Energy resources	MJ primary	9.6081766	0.085540029
Climate change	kg CO2eq	0.81469623	0.006351638
Ecosystem quality	$PDF \cdot m^2 \cdot yr$	0.039611868	0.000323275
Human health	DALY	1.36E-06	2.52E-09

3.3 Normalization Results

The characterization and damage results are appeared in incompatible units for total aggregation. We see that each impact category has its own unit, and thus the overall results cannot be compared. The normalization solves the incompatibility issue and provides the results in a single unique unit (Pt). The normalized environmental impacts for these two energy options are presented in Table 3. These normalization results mean that total impacts are only 1.5834908 µPt for wind energy, whereas total impacts are 339.8694 µPt for energy mix.

Table 3. Impact per impact category in a single score

Impact category	**Unit**	**Energy mix Malaysia**	**Wind power**
Total	µPt	339.8694	1.5834908
Mineral extraction	µPt	0.000365571	0.00804411
Non-renewable energy	µPt	63.221436	0.55480928
Global warming	µPt	82.28432	0.64151548
Aquatic eutrophication	µPt	0	0
Aquatic acidification	µPt	0	0
Land occupation	µPt	0.34491264	0
Terrestrial acid/nutri	µPt	0.72896338	0.006243933
Terrestrial ecotoxicity	µPt	1.7583364	0.017241395
Aquatic ecotoxicity	µPt	0.059453916	0.000113778
Respiratory organics	µPt	0.020760333	0.001066188
Ozone layer depletion	µPt	0.001384334	0
Ionizing radiation	µPt	0.002480292	0.001585036
Respiratory inorganics	µPt	182.99267	0.28082732
Non-carcinogens	µPt	1.1773383	0.059478003
Carcinogens	µPt	7.2769757	0.012566222

3.4 Damage Results in Normalized Unit

The Table 4 shows the damage results for each of the four damage categories namely Climate change, Resource depletion, ecosystem quality and human health. The results means that total impact is much lower for wind based electricity (i.e. only 1.58 µPt) than current energy mix (i.e. 339.8 µPt. The damage results also mean the level of severity for a damage category compared to other categories. For instance, human health damage category is much severe with 191.47161 µPt than other categories for energy mix option.

Table 4. Impact per damage category in a single score

Damage category	**Unit**	**Energy mix Malaysia**	**Wind power**
Total	µPt	339.8694	1.5834908
Resource depletion	µPt	63.221802	0.56285339
Climate change	µPt	82.28432	0.64151548
Ecosystem quality	µPt	2.8916663	0.023599106
Human health	µPt	191.47161	0.35552277

4. Conclusions

This study evaluates the life cycle impacts for electricity production from renewable wind source and electricity from Malaysian energy mix. Life cycle impacts provide a comprehensive view of the environmental aspects of the product (i.e. electricity) and a more accurate picture of the true environmental trade-offs in selecting resources. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product's whole life cycle (e.g. raw material extraction, material transportation, ultimate product disposal etc.). This study first determined characterization results against 15 different impact categories for electricity generation from both wind and energy mix. All the impact categories are found to have much lower negative impact for wind based electricity than energy mix. The resultant damages for these impacts are consequently lower for wind electricity. For example, damage to human health is 2.52E-09 DALY for wind based electricity whereas this damage for electricity mix is 1.36E-06 DALY. We have also normalized the impacts into a single unit, for a comparison. Total environmental impacts for wind based electricity are 1.58 Pt whereas it is 339.8 Pt for energy mix. Among the damages, climate change has the major impacts with 82 Pt for energy mix and 0.64 Pt for wind electricity. This analysis will help decision-makers select the resources or their mixes that results in the least impact to the human health and environment with same amount of output.

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