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Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique

Md. Shazib Uddin [a,b,*], S. Kumar [a]

[a] Energy Field of Study, School of Environment, Resources and Development, Asian Institute of Technology, Pathumthani 12120, Thailand
[b] Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi 6204, Bangladesh

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ABSTRACT

Wind turbine used for electricity generation is known as clean and renewable energy technology. The worldwide increasing trend of wind turbine installation present and future projection addressing the issue of energy required for manufacture and environmental impact due to energy consumption. The life cycle energy and environmental impact of wind turbine has been studied in many literature, but some studies are based on average data, the life cycle stages are incomplete of some study, most of the literature are horizontal axis type and the literature for Asian developing countries are rare. In addition, the life cycle study of vertical axis wind turbine is unusual. Since, the life cycle assessment (LCA) study varied from location to location due to industrial performance, countries energy mix and related issues, a life cycle embodied energy, emissions and environmental impacts analysis were undertaken for two grid connected rooftop wind turbines (vertical axis and horizontal axis) considering the industrial performance, applications and related issues in Thailand. The life cycle assessment was done using SimaPro 7.3.3 software from cradle to grave for base case and for alternative cases. The result showed that, wind turbine installation in Thailand at Chiangmai is reliable to deliver wind energy over the year compared to Phuket and Surat Thani Island. The vertical axis wind turbine is energy and emission intensive per kWh/year energy delivered compared to horizontal axis wind turbine for base case system. The embodied energy and environmental impact could be possible to reduce by more than 60% and 50% respectively using reuse of materials strategy. The embodied energy of vertical axis wind turbine could be possible to reduce by 36% with thermoplastic and 40% with fiberglass plastic turbine instead of aluminum turbine, while the environmental impact reduction more than 15% has been observed. The energy intensity, CO_2 emission intensity and energy payback time found to be lower when compared with literature.

1. Introduction

The energy availability and environmental threat due to combustion of fossil fuel (Natural gas, oil and coal) is the exciting issues for the researchers now a day. The world population in 2007 was 6.6 billion and is expected to about 8.2 billion in 2030, which indicates the importance of energy requirements in near future (World Nuclear Association, 2012). Currently, fossil fuels are the major sources of energy and its share is about 87% of global total energy consumption in 2011. The present reserve of fossil resources are limited (gas 29,400 billion m^3, oil 260,000 million barrels and coal 49,600 million tons) (Meindertsma and Blok, 2012). Based on current consumption rate (10,600 million ton oil equivalent in 2011) (Dudley, 2012), the proof reserves are not sufficient to meet the future energy demand. Conversely, environmental impacts are other issues due to presence of green house gases (GHG) in the atmosphere comes from the combustion of fossil fuel. The world GHG emission in 2010 was 54 Gt CO_2-eq (Parry, 2012) and is projected to 70 Gt CO_2-eq in 2050, which is significant and danger for human living in near future (Akashi et al., 2012). Global electricity generation has been increased by 3.1% in 2011 referring to last 10 years average (BP Statistical Review, 2012), but still two billion people of the world have no access to electricity (World Nuclear Association, 2012).

Because of the aforementioned issues, renewable energy technologies (RETs) are playing an important role and its applications increasing worldwide. Renewable would be the world largest second power generation sources by 2015 (World energy outlook, 2012).

* Corresponding author. Department of Mechanical Engineering, Rajshahi University of Engineering & Technology, Rajshahi 6204, Bangladesh. Tel.: +88 (0) 1782369498; fax: +88 (0)721750319.
E-mail addresses: shazib0397@gmail.com, p_k_m_shazib@yahoo.com, msu0397@yahoo.com (Md.S. Uddin).

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Wind turbine is one of the widely used renewable energy technologies worldwide for electricity generation. It is a clean energy technology. Countries worldwide are providing taxes and incentives to promote wind turbine (KPMG International cooperative, 2011). Global wind turbine installation capacity was 18 GW in 2000 and is increased to 238 GW in 2011 (IEA, 2012). Thailand current electricity generation capacity using wind turbine is 7.28 MW and the generation target is 1200 MW by 2021 for the reduction target is 76 million ton CO_2/yr (Cheokul, 2012). However, the wind turbine does not produce emission in the environment during its operation stage, but it produce harmful emission during manufacture, transport, disposal, etc.

Life Cycle Analysis (LCA) is a technique that quantifies the energy consumption, emissions and environmental impacts of a product or system throughout the life cycle stages (Cradle to gate or cradle to grave) namely, extraction of raw materials, transportation, manufacture, installation and disposal with recycling (Pehnt, 2006). The LCA study provides the useful information to developers, designers, policy makers and researchers, to develop and promote the technology. The environmental regulatory team can benefit to establish benchmarks in national and international level.

The life cycle assessment of wind turbine has been published. The environmental impacts were published for a wind firm located in Spain (Martinez et al., 2009). In this study, foundation is the major contributors to the environmental impacts. The recycling of materials reduced the impacts significantly. The energy and carbon emissions of rooftop wind turbine in New-Zealand have been studied (Mithraratne, 2009). In this study, the rooftop wind turbine installation have the potential to reduce the energy and carbon intensity by 81% and 26% respectively compared to wind firm using large turbine. The emissions of 141.5 MW wind firm in Brazil have been studied (Oebels and Pacca, 2013). The study showed that, more than 50% emissions come from the manufacture of tower, where the transportation is responsible for 6% only. The CO_2-emission intensity found to 7.10 g CO_2/kWh in Brazil. The energy and environmental performance of an Italian wind firm for the generation of 1 kWh electricity using the average European data have been studied (Ardente et al., 2008). In this study, energy intensity varies from 0.04 to 0.07 kWh_{prim}/kWh_{el} and CO_2 emission intensity varies from 8.8 to 18.5 g/kWh. The payback indexes found to lower than 1 year.

The literature shows that, material recycle/reuse, complete life cycle stages, extraction of raw materials were not taken into account in some studies (Crawford, 2009; Ardente et al., 2008), The detail life cycle analysis considering all the aspects (energy, emission and environmental impacts) are not taken into account in most of the studies (Martinez et al., 2009; Mithraratne, 2009; Oebels and Pacca, 2013; Crawford, 2009; Ardente et al., 2008). Furthermore, the sizes of the systems in the literature are different and the LCA studies were conducted at different location and conditions. Most of the LCA study of wind turbine reported for horizontal axis type and the literature are other than Asian developing countries (Lenzen and Munksgaard, 2002). In addition, the vertical axis wind turbine is relatively new and currently under developing mode (Parsons and Chatterton, 2011). The LCA study of vertical axis wind turbine is rare. The advantages of vertical axis wind turbine over horizontal axis wind turbine are, lower noise and vibration, reliable for multidirectional wind velocity, easy to install, simple design, can captured turbulent wind and no gear box is required (Clean field Energy Company Limited, 2012).

The objectives of this study are to estimate the life cycle energy consumption, emissions and environmental impacts of vertical axis and horizontal axis wind turbine over all the life cycle stages. The study was conducted for base case and alternative cases for possible improvement to promote the wind turbine. Since, the countries industrial performance, energy policy, transportation, etc greatly influence the LCA results, the novelty of this study lies in the national industries data, transportation, country energy mix and application in Asian developing country Thailand. The LCA study for vertical axis wind turbine is an extended novelty of this study. The inventory stages namely, extraction of raw materials, transportation, manufacture of component parts, distribution, installation, use and disposal were considered to conduct LCA study. The life cycle embodied energy consumptions (MJ-eq), emissions (air, water) and environmental impacts of wind turbine from cradle to grave were estimated. The alternative cases namely, reuse of materials and alternative materials were considered for the potential reductions of energy consumption and environmental impacts. The life time of the wind turbine was considered 20 years based on the data provided by the wind turbine seller in Thailand. The application of the wind turbine for energy generation was considered at three wind potential sites (Phuket Island, Surat Thani Island and Chiangmai) in Thailand. The comparative study with other literature has been also studied. The capital goods, building construction, vehicle manufacture, machine manufacture, etc were excluded for the estimation of embodied energy consumption, emissions and environmental impacts.

2. Methodology

The methodology to estimate the life cycle (cradle to grave) embodied energy (MJ_{eq}); emissions in air namely, carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrogen oxide (NO_x) and sulphur dioxide (SO_x); emissions in water namely, chemical oxygen demand (COD), dissolve organic carbon (DOC), suspended solids, phosphate (PO_4) and sulphate (SO_4); environmental impacts namely, global warming potential (kg CO_2-eq), acidification (kg SO_2-eq) and eutrophication (kg PO_4-eq) of selected wind turbine is presented in this Section.

According to International Organization for Standardization (ISO), the methodological framework of LCA study consists four phases namely, goal and scope, inventory analysis, impact assessment and interpretation the results. Goal and scope describes the objectives of the study and selection the product to be considered for LCA study. Inventory analysis is the key phase for LCA study. It includes the life cycle stages from cradle to grave and data to be collected for the estimation of LCA results from each stage within the system boundary. The description of wind turbine, system boundary, data and estimation, presentation the results and analysis are described as follows:

2.1. System description

Two types of grid connected wind turbines were considered (300 W vertical axis and 500 W horizontal axis) for the estimation of life cycle embodied energy, emissions and environmental impacts. The descriptions of the wind turbine systems are given as follows:

- *Vertical axis wind turbine*

The component part of the vertical axis wind turbine includes turbine, rotor, three frame, tower, generator, switchboard and inverter. The turbine made of aluminum support and 12 slice of aluminum fan set at a certain angle to receive the wind. Rotor is made of galvanized steel set at the centre of the turbine and joint with aluminum support. Three frames made of aluminum acts as an external support for the turbine. A 6 m height and 25 cm outside diameter hollow galvanized steel tower were considered for rooftop installation. Disc generator without iron core inside,