Exergetic Evaluation of Renewability for Renewable Electricity Generation in Thailand

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Abstract

In 2021, the target of renewable energy production of Thailand is 25%. Therefore the installation of renewable power generation systems has been increasing. In order to promote the sustainable development of renewable power generation, the environmental impacts of the system have to be considered. In this paper, the environmental sustainability of solar and wind power generation were evaluated by using life cycle assessment (LCA) framework together with exergy concept as exergy-based indicator, exergetic efficiency and renewability, throughout the life cycle from procurement of materials as well as transportation to the power generation system. According to the results, renewable power generation systems consume the greatest amount of exergy in the construction phase, wind power generation was considered as a sustainable system. Wind power generation is also more easily renewable than solar power generation.

Keywords: Exergetic Efficiency / Renewability/ Renewable Power Generation

1. Introduction

The electricity demand in Thailand is increasing continuously. The majority of electricity generation in the country is produced by fossil fuels, especially natural gas, whereby fossil fuels account for 67% of the total. In 2012, natural gas was most commonly used fuel in power generation, holding a share of 60% of the total consumption. Domestic natural gas production accounted for a share of 80%, with the remaining 20% being imported from Myanmar since 1999 to the present day (Department of Energy Policy and Planning Office, 2013). In addition, the natural gas market is expected to continue, with higher natural gas prices leading the government having to deal with the security of electricity production. The Thai government has a target of 25% renewable energy production by 2021 (Ministry of Energy, 2011). This plan includes power generation, using renewable resources such as; solar, wind, small hydropower, biomass and biogas. Presently, in 2013, the renewable power generation was 3,788 MW or 11.1% of the total power generation (Department of Alternative Energy Development and Efficiency, 2014). However, renewable power generation technologies involve a high consumption of materials during the construction and transportation phases. Thus, it is essential to assess the environmental impacts of electricity production throughout the production chain of renewable electricity generation system.

Energy cannot be created or destroyed, so energy is always conserved in every process. Energy analysis has been evaluated and identified as the quantity of energy and heat losses. However, energy analysis cannot give information about the quality of using energy sources. Exergy analysis is a more powerful tool than energy analysis for the identification of improvement in the process. Exergy is defined as the maximum work which can be extracted from the system when it deviates from reference state to equilibrium with the environment (Velásquez et al., 2013). Exergy analysis has been evaluating the performance of the process especially in energy systems (Dincer and Rosen, 2013; Kaushik et al., 2011; Koroneos et al., 2003; Pandey et al., 2013; Park et al., 2014; Tyagi et al., 2013). In addition, the concept of exergy has been developed as a tool for the accounting of resources (Wall, 1977). Currently, the awareness of environmental problems is continuously drawing attention, especially the utilization and depletion of resources. Exergy has been used coupled with the life cycle thinking concept as an indicator to assess the resource consumption of the process or system. The concept of cumulative exergy consumption (CExC) was proposed by Szargut, the first to study exergy based on a life cycle approach, the method has been expressed the total of primary exergy consumption of all resources in all the processes of the system. This method was also applied as a primary indicator to measure the resource quality in LCA (Bösch et al., 2007). Cornelissen and Hirs (2002) use exergy analysis together with the concept of the life cycle assessment (LCA) namely exergetic life cycle assessment (ELCA) to quantify the consumption of natural resources by measuring the irreversibility over the product life cycle. The exergy-based method has been applied in various processes and systems by many researchers in recent publications (Davidsson, 2011; Dewulf et al., 2007; Liao et al., 2012; Moya et al., 2013; Talens Peiró et al., 2010; Wall, 2011).

Exergy has been used as a sustainable development by an applied cumulative exergy

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consumption approach to identify the renewability of various processes, such as biofuel, ethanol and biodiesel (Berthiaume et al., 2001; Sorguven and Özilgen, 2010; Yang et al., 2009). Neelis et al. (2004) defined the renewability of renewable resources as the proportion of exergy from renewable resource consumption to the total exergy consumption in the process, thus, incoming exergy resources should be divided into renewable parts and non-renewable parts (Neelis et al., 2004; Yang and Chen, 2014), whereas the renewability performance indicator was defined as the proportion between exergy output (product) and total exergy input except exergy from renewable resources (Velásquez et al., 2013).

The aim of this work is to apply exergy concepts with life cycle thinking to evaluate the sustainability of renewable power generation systems using resource efficiency as well as the renewability of solar and wind power generation in Thailand. Additionally, comparisons with coal power generation systems are presented.

2. Methodology

2.1 System boundary and functional unit

This study is focused on evaluation of solar and wind power generation in Thailand. System boundaries of the evaluation consist of: raw material extraction, transportation of materials for use in producing the required equipment, transportation of said equipment to site. For power generation, the system has been divided into three phases consisting of: construction phase, operation phase and dismantling phase, however, the dismantling phase evaluation was excluded due to a lack of data. Energy used in the construction phase and exergy of emission was also excluded in this calculation. The operation phase includes materials for maintenance as well as the replacement parts of the system throughout the life span which is assumed to be 25 years (NSTDA, 2012), figure 1 shows the system boundary of this study.

2.2 Data sources

The material and energy inputs as well as the transportation data in this study were retrieved from the literature (NSTDA, 2012). In order to calculate the exergy in transportation, characterization factors in domestic transportation have to be known. The fuel consumption data (Sampattagul, 2008) and exergy content of fuel (Gleich et al., 2006) were used, the characterization factor of oceanic transport were obtained from a database (Ecoinvent, 2007).

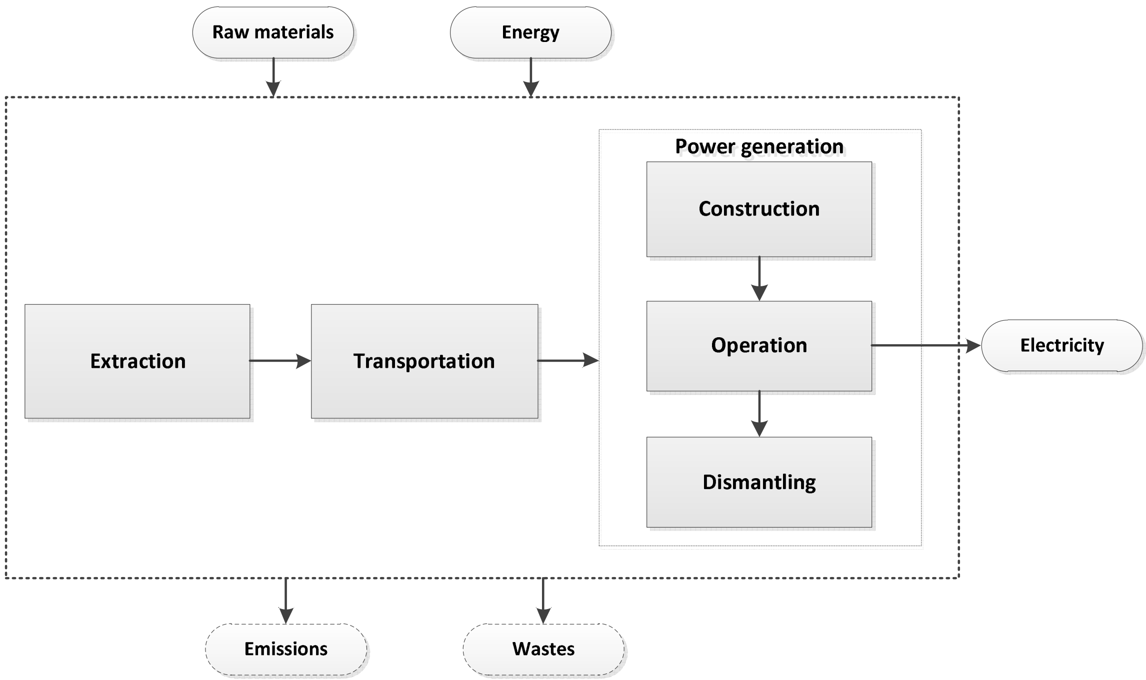

Figure 1: System boundary of power generation systems.

2.3 Calculation of exergy

The material and energy inputs of the system over the entire the life span are converted into exergy units. The calculation of different resource types is described. The exergy consumption of the material resources are related to the chemical exergy which can be calculated follow by the Szargut's method (Szargut et al., 1988). The exergy of many compounds can be retrieved from the prior references (Szargut et al., 1988; Gleich et al., 2006; De Meester et al., 2006). When the exergy of the compounds cannot obtainable, the chemical exergy can be estimated by the equation (1) (Szargut et al., 1988).

$$B_{ch} = \Delta G_{Fo} + \sum_i N_i b_i \qquad (1)$$

where, B_{ch} is the chemical exergy of the compound (J/kg), ΔG_{F_0} is the standard Gibbs free energy of formation of the substance (J/kg), b_i is the chemical exergy of the i_{th} pure element of the substance (J/kg), N_i is the molar fraction of the i_{th} pure element of the compound. The exergy factor (E_xF) describes the cumulative exergy consumption of materials used. It is obtained from the cumulative exergy consumption method, it can use the standard values from some references (Ecoinvent, 2007; Talens Peiró et al., 2007). Therefore, the exergy of material resources can be calculated by equation (2) as follow.

$$B_{m_i} = A_i \times E_x F_i \qquad (2)$$

where, B_{mi} is the exergy consumption or cumulative exergy consumption (CExC) of material i (MJ), A_i is amount of material i (kg), and E_xF_i is the exergy factor of material i (MJ/kg).

The exergy consumption of energy resources which supplied to the system throughout its life cycle have to convert in exergy units, an exergy conversion coefficient of energy resources is needed. Normally, the exergy of fuels is calculated by multiplying between the low heating value and the coefficient as shown in Table 1, exergy of the electricity is equal to 1.00 (Gleich et al., 2006).

Table 1. The exergy coefficient of energy resources.

Energy sources	Exergy coefficient
Natural gas	1.04
Fuel oil	1.07
Diesel	1.07

Source: Gleich et al., 2006.

In this study, various transportation modes were used such as oceanic transportation and road transportation. It is assumed that all of the materials are transported by diesel vehicles and transported by fully-loaded vehicles on arrival and no-load on departure. In order to calculate the exergy consumption of the road transportation, the characterization factors for different types of vehicles have to be determined. The characterization factor (CF^{trans}) can be calculated by the relation between fuel consumption and the fuel used as the following equation (3).

$$CF_i^{trans} = \frac{FC_i \times B_i^{Fuel}}{Max.load_i} \qquad (3)$$

where, CF^{trans} is the characterization factor of the transportation mode i (MJ/tkm), FC_i is the fuel consumption of transport mode I (Liter/tkm), B_i^{Fuel} is the exergy content of fuel used (MJ/liter) which is calculated by multiplying the lower heating value and the energy to exergy ratio (β), $Max.load_i$ is the maximum load of truck capacity (ton,t). The characterization factor of various transportation modes were calculated by using data of fuel consumption from the literature (Sampattagul, 2008) the factors are listed in Table 2.

Table 2. Characterization factor of various transportation modes.

Transportation modes	Characterization factors; CF^{trans} (MJ/tkm)		References
	Full-loaded	No-loaded	
Oceanic transportation	0.1339	-	Ecoinvent
Truck, 11 ton	1.3752	1.1237	Self-calculation
Truck, 16 ton	1.6291	1.2254	Self-calculation
Truck, 32 ton	1.0157	0.7978	Self-calculation
Truck tank car, 16 ton	1.1580	1.0065	Self-calculation
Van truck, 7 ton	2.0677	1.6076	Self-calculation

The exergy consumption of transportation materials can be calculated by using the equation (4) as follow.

$$B_i^{trans} = M_i \times D_i \times CF^{trans} \qquad (4)$$

where, B_i^{trans} is the exergy consumption of transportation material i (MJ), M_i is mass of transported material i (ton), D_i is the distance in transportation of material i (km).

2.4 Exergetic efficiency analysis

In order to analyze exergy consumption of the renewable electricity system, the exergy analysis approach has to be applied. Exergy accounting offers a convenient way to unify measurement of various types of resources to evaluate the quality of the resources the process (Yang et al., 2009). Szargut et al. applied the concept of life cycle assessment to exergy analysis to account for the sum of the primary exergy consumed by the process which can identify the exergy loss and detect system improvements (Talens Peiró et al., 2007). Exergetic efficiency is defined as the proportion between useful exergy (exergy of product) and the consumption of exergy by the system (Szargut, 2005), can be calculated by the equation (5)

$$\eta = \frac{B^{useful,product}}{B^{in}} \quad (5)$$

where, $B^{useful,product}$ is the useful exergy or exergy of product (MJ), B^{in} is the total exergy consumption of the defined system (MJ). In this study, exergy inputs from solar radiation and kinetic energy from wind were classified as free energy and were not accounted.

2.5 Renewability assessment

In order to evaluate the environmental performance of the system, renewability indicator (λ) was applied for evaluating energy conversion of the system in a life cycle perspective. The concept of renewability indicator is defined by the equation (6)

$$\lambda = \frac{\sum_i (B_P)_i}{\sum_j (B_{NR})_j} \quad (6)$$

where, B_P accounts for the exergy of products and byproducts (MJ), B_{NR} is the total of non-renewable exergy consumption in the systems. The numerical value of λ can vary between zero to infinity. The results of the environmental evaluation of this indicator can be interpreted as

- Systems with $0<\lambda<1$ are considered non-renewable and environmentally unfavorable. Because the exergy content of products and byproducts is less than the total exergy consumed in the production chain.
- If $\lambda=1$, the system is reversible with non-renewable.
- If $\lambda>1$, the system is environmentally favorable and, additionally, increasing λ implies that the system is more environmentally friendly.
- If $\lambda \to \infty$, the system is reversible with renewable inputs.

3. Results and discussion

3.1 Inventory analysis

Table 3 shows the results in exergy consumption for all inputs of solar and wind power generation in the construction phase and operational phase to generate the electricity of 1 kWh or 3.6 MJ.

For solar power generation, the results illustrate the major contribution of exergy consumption in the construction phase (6.84 MJ/kWh), which is mainly from solar panel (4.02 MJ/kWh) followed by concrete (1.80 MJ/kWh), Steel (0.52 MJ/kWh) and batteries (0.46 MJ/kWh).

In the life time of solar power generation, batteries were replaced due to the limited life time. In addition, tap water was used to clean up the surface of solar panels.

For wind power generation, the results are similar to solar power generation; the major exergy consumption is contributed by materials during construction (2.43 MJ/kWh). Even though silicon was used in small quantities it shows significant exergy consumption in the system, because silicon has a highly cumulative exergy consumption which occurs mainly during the production process. The results emphasize that renewable power generation systems consumed most of the exergy in the life cycle chain.

3.2 Exergetic efficiency

The aim of exergy analysis is to account for all resource (materials and energy) inputs to exergy unit. This means that exergetic efficiency can measure the resource efficiency of the system. Exergetic efficiency is the proportion between exergy output of electricity and the exergy input in order to produce 1 kWh of electricity. Table 5 illustrates the efficiency of solar, and wind power, comparing the results with coal power generation.

Wind power produces the highest exergetic efficiency with a coefficient of 1.47 which implies that the system produces more exergy than it consumes, whereas solar and coal power generation exhibit an efficiency of less than 1.

According to Gong and Wall propose in Life Cycle Exergy Analysis (LCEA) approach, the condition for sustainability of the system is $E_{production} \geq E_{in} + E_{indirect}$ (Gong and Wall, 2001). From LCEA perspective, the results imply that wind power generation is a sustainable system, whereas solar and coal power generation are considered as unsustainable systems.

3.3 Renewability

In order to evaluate the renewability of the system, exergy of non-renewable exergy ***(B_{NR})*** supplied to the system have to be separated from the total exergy inputs as shown in Table 4. Wind and solar power generation systems consumed non-renewable exergy with 23% and 9% of the total exergy inputs, respectively. This result exhibits a smaller proportion than coal power generation (29%) due to this approach; exergy inputs from solar radiation and kinetic energy supplied by wind turbine were classified as free energy and were not accounted.

Table 3. Exergy consumption for solar and wind power generation per 1 kWh of electricity.

Phases	Inventory			CExC		Exergy consumption (MJ)
	Inputs	Quantity	Unit	Quantity	Unit	
Solar						
Construction	Solar panel	2.80E-03	kg	1,436.05	MJ/kg	4.02
	Concrete	6.07E-02	kg	29.65	MJ/kg	1.80
	Steel	3.10E-03	kg	166.65	MJ/kg	0.52
	Batteries	2.30E-03	kg	199.47	MJ/kg	0.46
	Inverter	7.30E-04	kg	64.65	MJ/kg	0.05
					Sub-total	**6.84**
Operation	Batteries (replacement)	2.30E-03	kg	199.47	MJ/kg	0.46
	Tap water	2.80E+00	L	0.16	MJ/kg	0.45
	Distilled water	1.17E-03	L	0.05	MJ/kg	0.00
					Sub-total	**0.90**
					Total	**7.74**
Wind						
Construction	Cement	3.02E-04	kg	73.45	MJ/kg	0.02
	Steel	4.23E-03	kg	166.65	MJ/kg	0.71
	Rock	1.57E-02	kg	0.001	MJ/kg	1.57E-05
	Gravel	1.51E-02	kg	4.52	MJ/kg	0.07
	Silicon	7.86E-04	kg	1696.26	MJ/kg	1.33
	GRP	5.02E-04	kg	591.45	MJ/kg	0.30
					Sub-total	**2.43**
Operation	Lubricant oil	3.45E-05	kg	215.35	MJ/kg	7.43E-03
					Sub-total	**7.43E-03**
					Total	**2.43**

Table 4. Exergy consumption inputs and non-renewable exergy consumption of solar, wind and coal power generations in Thailand

Phases	Exergy consumption (MJ)					
	Wind		Solar		Coal	
	B_{in}	B_{NR}	B_{in}	B_{NR}	B_{in}	B_{NR}
Construction	2.425	0.365	6.842	0.365	0.378	0.020
Transportation	0.020	0.018	0.182	0.151	0.005	0.004
Operation	0.007	0.177	0.904	0.177	47.621	14.249
Total	2.453	0.560	7.928	0.693	48.004	14.273

According to the results from Table 5, the renewability analysis indicates that solar and wind power electricity generation systems are environmentally favorable ($\lambda>1$), wind power shows the highest renewability of 6.43 followed by solar power of 5.20.

On the other hand, a coal powered system produces a λ factor of less than 1 which implies that the system is non-renewable and environmentally unfavorable (Velásquez et al., 2013). Moreover, renewability can measure the degree of using non-renewable resource to generate 1 kWh of electricity.

From the results, wind power consumed less non-renewable resources than solar power, so the renewability of wind power is slightly higher which implies that wind power is a more renewable system.

3.4 End of life

In LCA study, environmental impacts have been caused during the life cycle of the process, especially at the end of life phase. The various approaches for end of life for materials, such as landfill, incineration or recycling cause different environmental damage. Generally, with solar and wind power generation, most of the materials can be recycled. For solar power generation, firstly, the PV module and BOS (balance of system) are dismantled separately, and then the PV module is sent to the recycling factory.

It is found that glass and aluminum of the PV module is about 74% and 10% recyclable respectively. In addition, structural steel is also about 90% recyclable (Zhong et al., 2011).Currently, recyclable technology is able to recover 100% of aluminum, 90% of glass and silicon (Desideri et al., 2012).

Table 5. Comparison of exergetic efficiency and renewability with different power generation systems.

Energy sources	Efficiency (η)	Renewability (λ)
Solar	0.45	5.19
Wind	1.47	6.43
Coal	0.07	0.25

At the end of life phase of wind turbines, after disassembly many parts are sent to be recycled It is found that 90% of steel, copper, aluminum and lead can be recovered (Zhong et al., 2011; Davidsson, 2011). All non-recycled materials are buried in landfills or incinerated.

Recycled materials can be substituted for primary materials in production processes. Recycling processes produce benefits for the environment, not only by decreasing energy requirements but also reducing CO_2 emissions. It was found that, in the manufacturing of PV plants, using 40% recycled steel, reduced energy requirements by about 33% and decreased CO_2 by about 43% (Krauter and Ruther, 2004)

4. Conclusion

Life cycle assessment is an effective tool to evaluate environmental impact and sustainability of technology. Exergy concept applied with life cycle thinking, contributes to the thermodynamically environmental profile of the system. Exergy-based indicators provide data that reflects the sustainability and level of renewability. Renewable power generation systems consume more exergy in the construction phase than at any other time.

Exergetic efficiency can interpreted as the sustainability of the system. Wind power exhibits the most sustainability compared to solar and coal power generation. The results of renewability are not only classified as renewable or non-renewable systems but also indicate the renewable level of the system. From the evaluation, wind power has the highest renewability followed by solar power. Additionally, the results of this study provide data for the government to make decisions for implementing renewable power generation policies for the future.

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