Fuzzy logic based environmental indicator for sustainability assessment of renewable energy system using life cycle assessment

AUTHOR(S)

G Liu, A Baniyounes, M Rasul, Aman Maung Than Oo, M Khan

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Gang Liu[*], A. Baniyounes, M.G. Rasul, M.T.O. Amanullah and M.M.K. Khan

Central Queensland University, Power & Energy Research Group, Faculty of Sciences,Engineering and Health, Queensland 4702, Australia

Abstract

The use of renewable energy system (RES) is increasing rapidly. However, it is still difficult to measure the environmental impact of renewable energy system. This study aims to develop a general environmental indicator which is able to reflect all the aspects of environmental impacts of a RES. The life cycle assessment (LCA) and fuzzy logic is used to develop an environmental indicator to assess all the environmental impacts. The five important environmental indicators are selected based on LCA standard: Abiotic Depletion Potential, Land Use, Climate Change, Photochemical Ozone Creation Potential and Acidification Potential. Fuzzy inference system is used to convert the original values of these indicators into fuzzy data and aggregate them into the general indicator. The computed fuzzy value of the general indicator is then defuzzified into a crisp number as the final indicator value of environmental impacts.

1. Introduction

Nowadays, renewable energy technologies like solar and wind are widely used for power generation in many countries, because of their advantages of no fossil fuel resource consumption and zero greenhouse gases (GHG) emission. However, looking into the whole life cycle of renewable energy systems, energy consumption and emissions emitted in the phases of elements manufacture, transportation, construction and decommissioning are difficult to assess comprehensively. Therefore, it is necessary to develop a general indicator to assess the comprehensive impacts of renewable energy system on the environment.

With the rapid development of life cycle assessment (LCA) method and the wide application of ISO 14000, there are an increasing number of literatures about LCA of renewable energies. Sherwani et. al. [1] reviewed the life cycle assessment of solar electricity generation systems based on three main types of solar PV (amorphous, mono-crystalline and poly-crystalline) in different countries. Tremeac and Meunier [2] also used LCA method for comparing two wind turbine systems: a 4.5 MW system and a 250 W system. In their study, a four-step methodology of LCA is built and 14 midpoint categories are divided into four damage categories: climate change, resources used, ecosystem quality decrease and human

* Corresponding author. Tel.: +61 -7-49232840;
E-mail address: g.liu@cqu.edu.au.

health. However, it is difficult to find life cycle assessment for hybrid renewable energy system. Nevertheless, there is no a general indicator which is capable to comprehensively reflect all the aspects of environmental impacts on RESs.

The study aims to assess the environmental impacts of a RES including PV and wind modules by LCA method. The impacts cover five categories: Abiotic Depletion Potential, Land Use, Climate Change, Photochemical Ozone Creation Potential, and Acidification Potential [3]. All of these indicators are normalized, and then are aggregated into a general environmental indicator by fuzzy logic. Through developing a set of fuzzy rules, the numerical outputs as the final results of the general sustainability are transferred into a crisp number by the defuzzification process.

2. Life Cycle Assessment

Life cycle assessment (LCA) is defined as the 'compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle'. Thus, LCA is also seen as a technique for assessing various aspects associated with sustainable development of a product and its potential impact throughout the whole life of a product, process or project [1]. The most important application of LCA is [4]:

- Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the aim to priorities improvements on products or processes.
- Comparison between products for internal or internal communications.

The environmental impacts related to the environmental burdens cover all the types of impacts upon the environment, including extraction of various types of resources consumption, emission of hazardous substances and land use.

For the purposes of product development and improvement, strategic planning, public policy making and marketing decision-making, a life cycle assessment framework is generally built as shown in Figure 1. In the life cycle assessment framework, the first procedure is to define the goal and scope of the assessment. Then it is inventory analysis and impact assessment. After that, it is the interpretation of the assessment results to the applications.

In life cycle assessment, the environmental impact of a system (product or project) is the sum of its individual indicator of impacts in categories affecting natural resources, human health and the ecosystems. The environmental impacts can be assessed by environmental burden which is given by Equation 1.

$$EB = \sum_i Factor_i \times m_i \tag{1}$$

Where EB is environmental burden in Environmental Load Units (ELU), $Factor_i$ (ELU/kg) is the valuation weighting factor for the i-th resource, while m_i (kg) is the quantity of the i-th resource used.
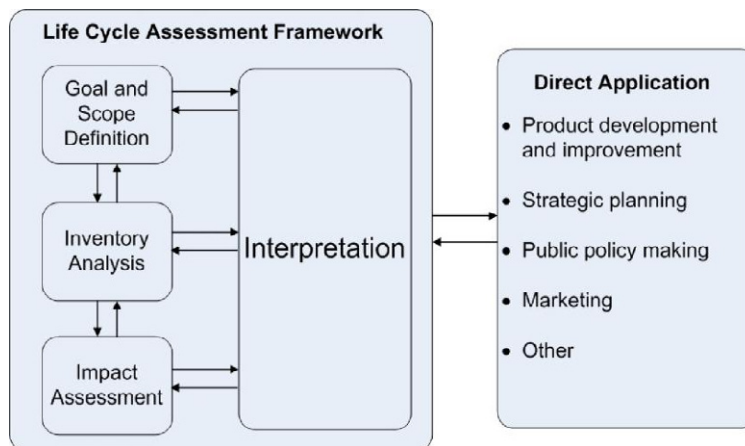

Fig. 1: Phases and applications of an LCA [5]

The fuzzy inference system is used as the role of interpretation in this study. The flow chart of the indicator development procedure is shown in Figure 2. By unifying and normalizing the LCA results of a RES, the values of basic indictors (BIs) are determined. The BIs are fuzzified into fuzzy numbers corresponding to sustainability judgments. Then a rule base is

built to calculate the fuzzy results of the top layer of the indicator. The final step is to defuzzify the indicator results into crisp numbers so that the users are able to evaluate RES easily.
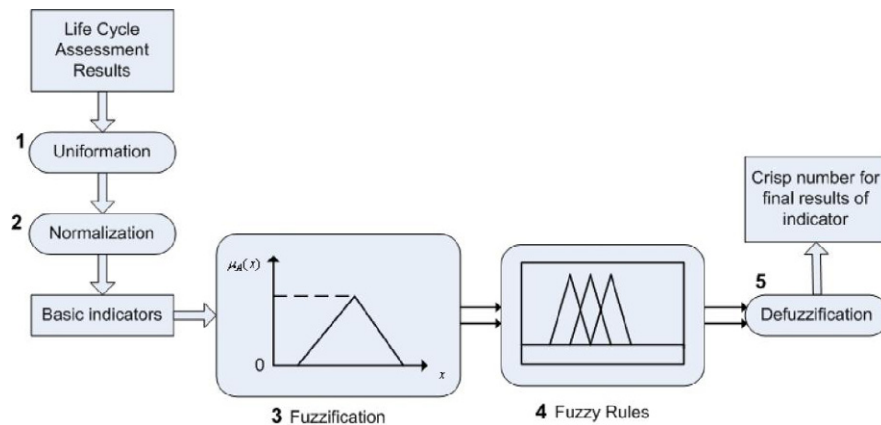

Fig. 2: Flow chart of sustainability indicator development

3. Fuzzy Logic Based Environmental Indicator

3.1. Indicators selection

According to the life cycle analysis, five important types of environmental impacts are considered in the development of environmental indicator. The resources consumed and the relative gases or wastes emitted during the whole life cycle of a RES, including the materials exploit, components manufacture, installation and the scraping of components, are considered in the sustainability assessment. Abiotic depletion potential (ADP) is a characterization factor for product based on extraction rate and global reserves. Any types of resource consumption can be converted into impact in the category of ADP [6]. Land use (LAND) is calculated by the aggregation of inventory data by multiplying the occupation time by the land area used. The characterization factor is equal to 1 for all types of land-used [5]. Global warming potential (GWP) is a measure of how much heat a greenhouse gas could trap in the air. Photochemical Ozone Creation Potential (POCP) is considered as a damage vegetation and material in the troposphere. High concentrations of ozone are toxic to animals and humans. Acidification Potential (AP) is used to measure the negative impacts of acid depositions on the environment. The combustion of fossil fuel for electricity generation is one of the main sources for emissions of acidifying substances.

3.2. BIs normalization

In generally, there are three types of BIs: smaller is better (Figure 3), larger is better (Figure 4) and nominal is better (Figure 5). In equations included in the figures, t_c, u_c, T_c and U_c are the least and most desirable values for the BIs, which would be dependent on local energy policy or the local usage level of renewable energy, or dependent on the worth and the best systems' level when making a decision among a number of options. The x axis z_c is the original value of BIs and y axis x_c is the normalized value. In this study, all the indicators are negative, and therefore, the normalization that smaller is better is used.
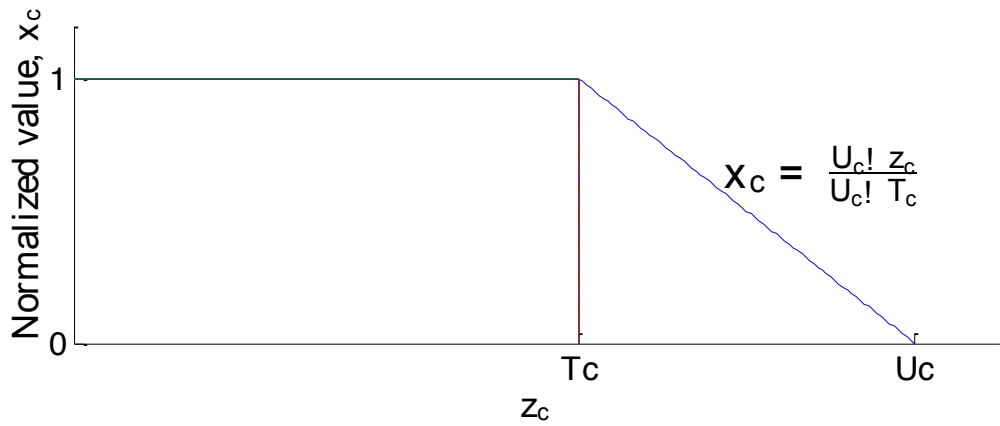
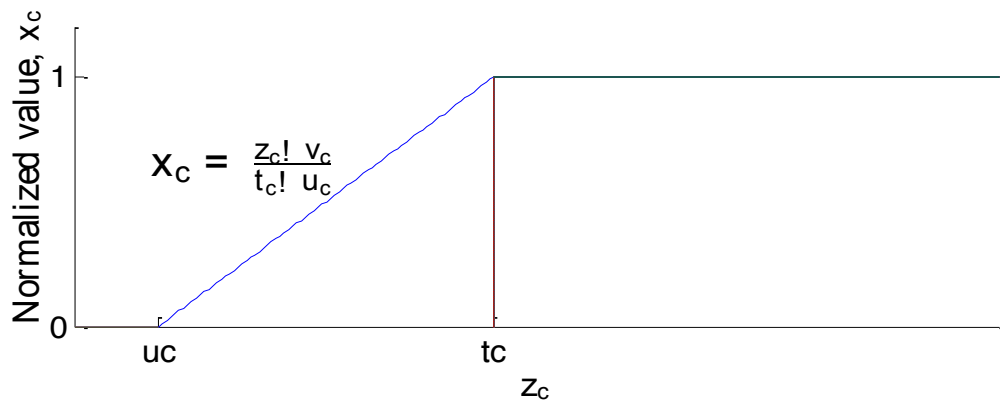Fig. 3: Normalization by linear interpolation: smaller is better)

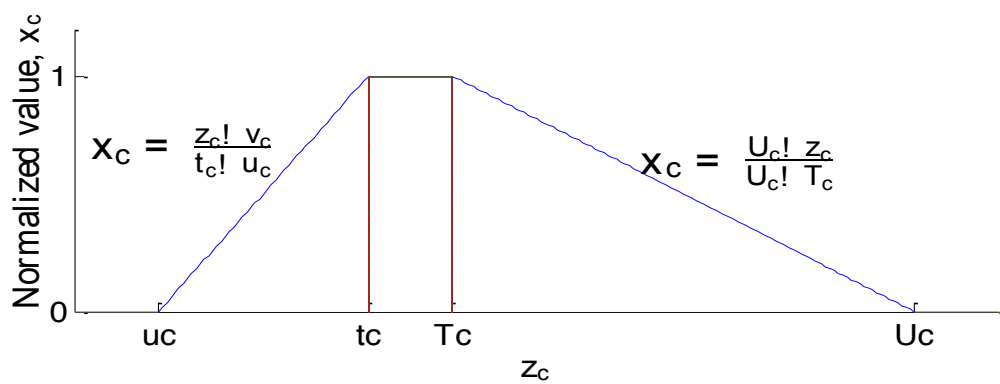Fig. 4: Normalization by linear interpolation: larger is better

Fig. 5: Normalization by linear interpolation: nominal is better

3.3. Fuzziffication of indicators

After normalization, the values of all the BIs are on the interval [0, 1]. Then, the triangle fuzzy numbers are used to fuzzify the BIs: 0 (0, 0, 0.4) for low sustainability, $0.\underset{\sim}{5}$ (0.1, 0.5, 0.9) for fair sustainability, and $\underset{\sim}{1}$ (0.6, 1, 1) for high sustainability as shown in Figure 6.
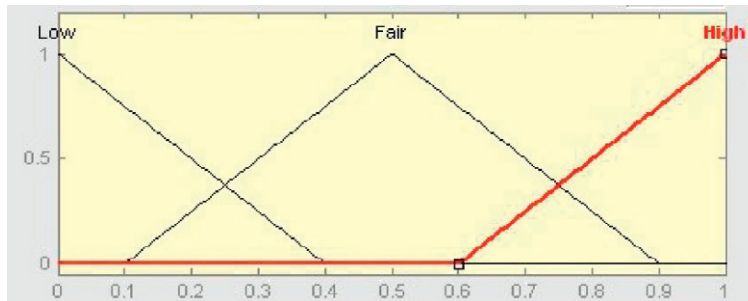

Fig. 6: Triangle fuzzy number of the inputs of the indicator

3.4. Fuzzy decision-making

The fuzzy rules are given as below the logic sentences [7]. All the fuzzy rules are weights equal in this study. The inference engine is constructed based on mamdani fuzzy system (Figure 7).

Rule 1: IF condition C^1 THEN restriction R^1
Rule 2: IF condition C^2 THEN restriction R^2
…
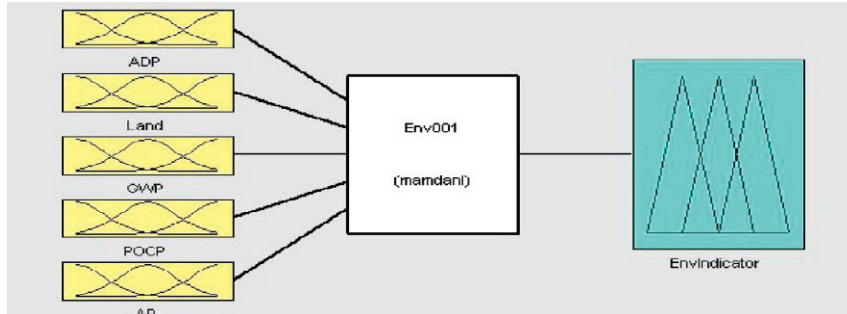Rule n: IF condition C^n THEN restriction R^n

Fig. 7: Rule base of the environmental indicator

3.5. Defuzzification

Defuzzification is to convert a fuzzy quantity (fuzzy number) to a precise quantity (crisp number), which is the positive procedure of fuzzification that is the conversion of a precise quantity to a fuzzy quantity [8]. In other words, defuzzification is to determine the best nonfuzzy score value (BNS) for the corresponding fuzzy number. There are generally three methods to compute the BNS value: mean of maximal (MOM), centre of area (COA), and λ- cut [9]. In this paper, the COA method is used from Ref. [10] to defuzzify the fuzzy numbers. The method is given by the mathematic expression [8], as follow:

$$z^* = \frac{\int \mu_{\underset{\sim}{C}}(z)z\,dz}{\int \mu_{\underset{\sim}{C}}(z)\,dz} \tag{2}$$

Then,

$$z^* = \frac{l}{3} + \frac{m}{3} + \frac{u}{3} \tag{3}$$

Where, the parameters l, m and u are respectively the left, medium and right point of the fuzzy number $z(l,m,u)$; z is the horizontal ordinate of the fuzzy number and z^* is the crisp number corresponding to z.

4. Case study and verification of the indicator

A case of a hybrid RES including a PV and wind component is presented in this section. The system is running under the subtropical climate conditions of Australia. The BIs values of the system are given directly in this case study. The values of ADP, LAND, GWP, POCP and AP are given respectively: 0.181, 0.147, 0.214, 0.255 and 0.72. For such a system, the values of the former four BIs are very low (lower than 0.255), and the value of AP is relatively higher. It is therefore, predicted that the environmental assessment of this system would be not very strong. As shown in Figure 8, by using the environmental indicator developed in this paper, the score of the environmental assessment indicator is obtained as 0.361. This value is different to the arithmetic mean value (0.333) of the five BIs.

In order to verify the fuzzy environmental indicator and the arithmetic mean value, a comparison between these two values is worked out through calculating 20 hypothetic cases. As can be seen from Figure 9, the horizontal axis represents the arithmetic mean value and the vertical axis represents the fuzzy indicator results. The linear regression between the indicator and mean value can be represented by a linear function based on the least square method: y = 0.629x + 0.192. There is a good linear correlation between them, where the correlation coefficient is 0.894 (and R^2=0.799). This illustrates that the results of fuzzy indicator have some difference to the arithmetic mean value and therefore are rational.
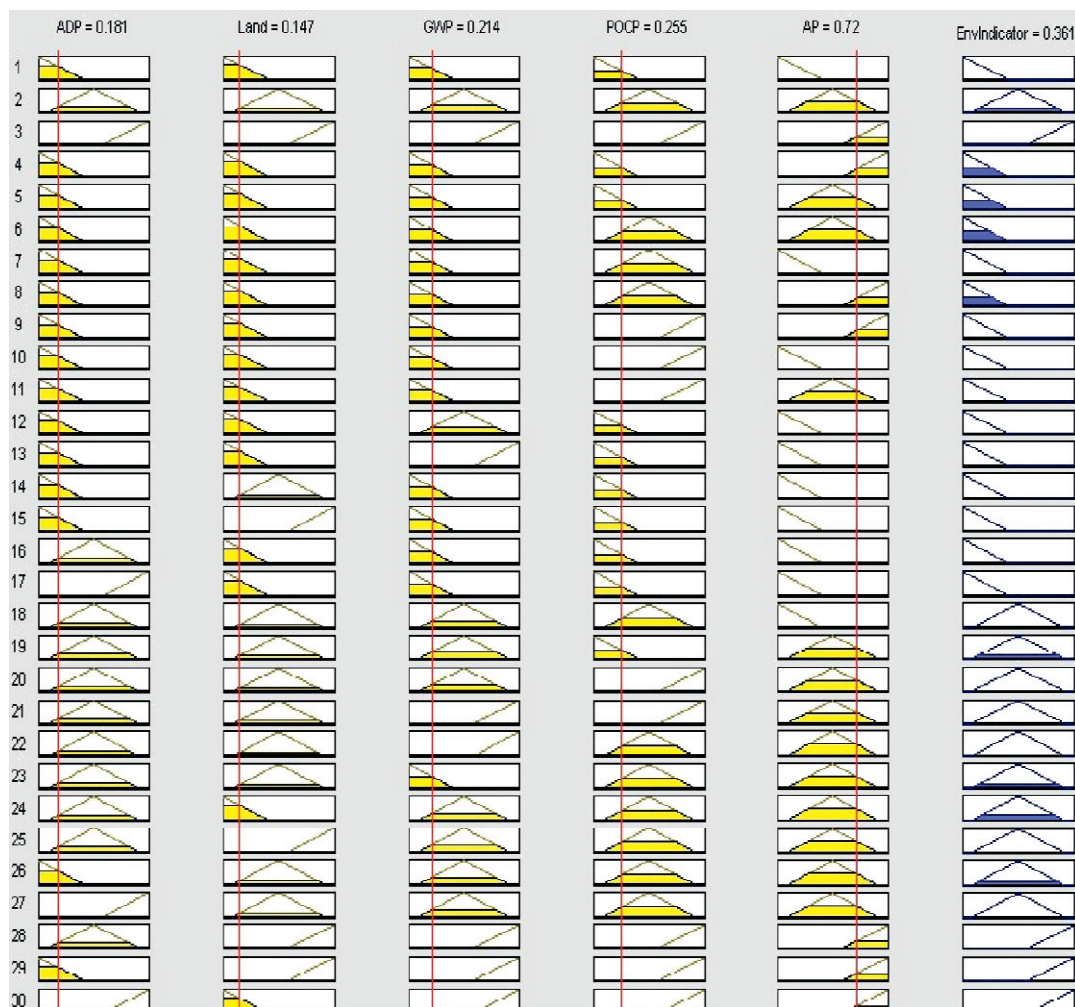

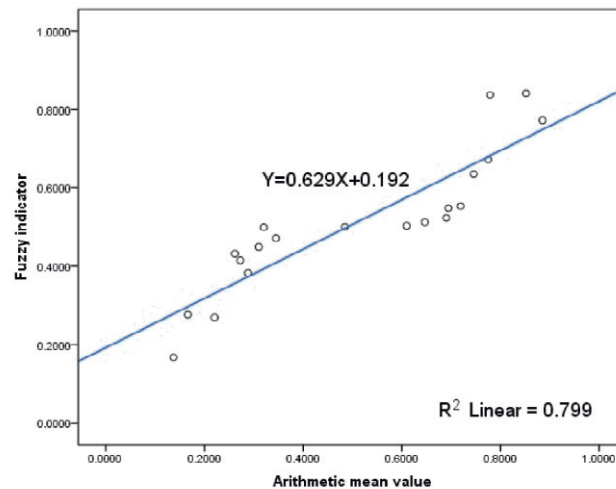Fig. 8: Rule viewer of the environmental indicator

Fig. 9: Rule viewer of the environmental indicator

5. Conclusion

This paper develops a general environmental indicator based on fuzzy inference system. Based on the life cycle assessment, five basic indicators are selected. By carrying out the procedures of normalization of BIs, fuzzification of BIs, development of fuzzy rules, and defuzzification of the final results, the general indicator is modelled. A case of an Australian RES is presented to explain the application of this indicator. In addition, a range of 20 hypothetic cases are used for the indicator's verification through comparing the results of the indicator and the arithmetic mean values. It is found that the general environmental indicator is rational and has a good linear correlation to arithmetic mean value.

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