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Intuitionistic fuzzy multi-criteria decision making framework based on life cycle environmental, economic and social impacts: The case of U.S. wind energy

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ABSTRACT

Intuitionistic Fuzzy Set theory can be used in conjunction with environmentally extended input–output based life cycle assessment (EE-IO-LCA) models to help decision makers to address the inherent vagueness and uncertainties in certain sustainable energy planning problems. In this regard, the EE-IO-LCA model can be combined with an intuitionistic fuzzy set theory for a multi-criteria decision making (MCDM) application with a set of environmental and socio-economic indicators. To achieve this goal, this study proposes the use of the Technique for Order of Preference by Similarity to Ideal Solution method to select the best wind energy alternative for a double layer MCDM problem, which requires expert judgments to simultaneously apply appropriate weighting to each life cycle phase and sustainability indicator to be considered. The novelty of this research is to propose a generic 9-step fuzzy MCDM method to solve sustainable energy decision-making problems using a combination of three different techniques: (1) an intuitionistic fuzzy entropy method to identify the individual importance of phases and criteria; (2) an IFWGA operator to establish a sub-decision matrix with the weights applied to all relevant attributes; and (3) an IFWAA operator to build a super-decision matrix with the weights applied to all of the life-cycle phases considered. This proposed method is then applied as a case study for sustainable energy planning, specifically for the selection of V80 and V90 onshore and offshore wind turbines to be installed in the United States. It is strongly believed that this methodology will provide a vital guidance for LCA practitioners in the future for selecting the best possible energy alternative under an uncertain decision-making scenario.

Keywords: Multi-criteria decision making; Intuitionistic fuzzy sets; Aggregation operator; TOPSIS; Life cycle sustainability assessment; Wind energy

1. Introduction

1.1. Wind energy and life cycle assessment

The environmental, economic, and social problems associated with the US energy industry create tremendous challenges and opportunities, requiring a holistic sustainability assessment of different energy policies for decision-making problems and other practical applications associated with the US energy sector (Anadon et al., 2009). The US energy industry will inevitably require a technological revolution to address its many current challenges, including issues related to energy security, environmental sustainability, and economic

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competitiveness (Anadon et al., 2011). In the US, there is currently an unprecedented interest in wind energy technologies as a very promising sustainable energy alternative. According to the US Department of Energy (DOE)'s futuristic scenario, 20% of the US power grid mix will be obtained from onshore and offshore wind power plants by 2030. To achieve this goal, The US government will need to supply 300,000 MW (megawatts) of additional wind generation capacity (US Department of Energy, 2008). Inevitably, the growing share of wind energy in the US electrical power grid will require a greater understanding of the environmental, economic, and social (a.k.a. the triple-bottom-line, or TBL) impacts of wind energy projects. To analyze the total social, economic, and environmental impacts of wind energy technologies, a thorough life cycle assessment (LCA) is used to quantify the total cradle-to-grave environmental impacts of a predetermined functional unit of energy, accounting for impacts from various life cycle phases such as raw material extraction, production, construction, use, and final disposal (Pehnt et al., 2008; Martinez et al., 2009; Weinzettel et al., 2009; Gujba et al., 2010; Santoyo-Castelazo et al., 2011).

Process-based LCA (P-LCA) is the most commonly used method in current LCA literature, having been used extensively for various environmental analyses of wind energy and other applications (Lenzen and Munksgaard, 2002), but the P-LCA methodology is subject to "truncation errors" due to narrowly defined system boundaries (Onat et al., 2014a,b; Cellura et al., 2012; Kucukvar et al., 2015). In P-LCA models, mostly onsite impacts are considered without a full coverage of all upstream supply chain contributions (Kucukvar and Samadi, 2015; Lenzen, 2000; Onat et al., 2015a). To address these limitations, Environmentally-Extended Economic Input–Output based LCA (EE-IO-LCA) approaches have been proposed to quantify the environmental burdens of the systems being analyzed by tracing their entire supply chain and accounting for the corresponding (Cellura et al., 2011; Kucukvar and Tatari, 2011; Egilmez et al., 2013, 2014; Kucukvar et al., in press). Several studies have used the P-LCA method, the EE-IO-LCA method, and/or a combination of both methods in LCA analyses of wind energy alternatives (Park et al., 2015; Wiedmann et al., 2011). For instance, Jungbluth et al. (2014) used the P-LCA method to analyze the environmental impacts of four different onshore wind turbines, each with different capacities ranging from 30 to 800 kW, and one offshore wind turbine with a capacity of 2 MW. Lenzen and Wachsmann (2004) focused on a particular wind turbine located in Brazil and Germany and estimated the effects of geographic factors on its energy consumption and carbon dioxide (CO_2) emissions. Ardente et al. (2008) developed a P-LCA model to evaluate the energy and environmental impacts of a wind farm consisting of 11 wind turbines, each with an individual capacity of 660 kW. Atilgan and Azapagic (2015) investigated the life cycle environmental impacts of electricity generation from fossil fuel power plants in Turkey, including 16 lignite power plants, eight hard coal power plants, and 187 gas power plants. In another study, Martinez et al. (2009) developed P-LCA model for a 2-MW offshore wind turbine installed in Spain. Weinzettel et al. (2009) utilized the LCA methodology for a floating wind turbine, and the results were compared with those of conventional offshore wind turbines and of electricity from a natural combined gas cycle. In a recent study, Noori et al. (2015a) developed an EE-IO-LCA model to compare the environmental impacts of V80 and V90 onshore and offshore wind turbines installed in the US.

Although LCA literature is abundant with studies addressing the life-cycle impacts of wind energy technologies, only a handful of works concentrated on the socio-economic implications of wind energy in addition to the environment (Noori et al., 2015b; Slattery et al., 2011). Triple bottom line (TBL) impacts, which cover all three dimensions of sustainability, are therefore a critical concept for policy-makers to quantify trade-offs between different dimensions of sustainability (Jeswani et al., 2010). The TBL concept focuses on the three main dimensions of sustainable development (environment, economy, and society) (Elkington, 1997; Wiedmann et al., 2009) and has also been integrated into EE-IO-LCA analyses to capture all direct and indirect environmental and socio-economic impacts. For instance, Foran et al. (2005a,b) developed a TBL model of the industrial sectors of Australia's entire economy, including environmental, economic, and social metrics for 135 sectors. Researchers from the University of Sydney constructed the TBL-EIO model and created the BottomLine[3] software for the economies of Australia, the UK, and Japan (Wiedmann and Lenzen, 2009). Several studies have also used the TBL-EIO methodology for sustainability analysis of supply chains (Foran et al., 2005a,b), companies (Wiedmann et al., 2009), buildings (Onat et al., 2014a), electric vehicles (Onat et al., 2014c; Onat, 2015a), energy (Malik et al., in print), pavement alternatives (Kucukvar et al., 2014a,b), and construction sectors (Kucukvar and Tatari, 2013; Kucukvar et al., 2014c). In a recent work, Noori et al. (2015b) constructed a hybrid LCA model by combining a TBL analysis with the EE-IO-LCA method to compare the ecological and socio-economic sustainability performance of V80 and V90 onshore and offshore wind turbines installed in the US.

1.2. *Multi-criteria decision making*

In current literature, the multi-criteria decision-making (MCDM) method is used to select the most feasible energy alternative based on different environmental, economic and social indicators of sustainability. The MCDM literature for energy-related decision making problems mainly focuses on ranking renewable energy alternatives, determining optimal energy resource allocations, and planning various projects (Ardente et al., 2004). A comprehensive review of studies on MCDM approaches for energy planning showed that the Analytic Hierarchy Process (AHP), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), the Elimination and Choice Translating Reality (ELECTRE) method, the weighted sum method, the weighted product method, compromise programming, and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are among the most widely used MCDM methodologies in the literature (Greening and Bernow, 2006; Kucukvar et al., 2014b; Løken, 2007; Pohekar and Ramachandran, 2004; Wang et al., 2009a,b; Onat et al., 2016a), and these MCDM techniques have been extensively applied for ranking the best energy alternatives. For instance, Wang et al. (2009a,b) focused on the benefits of MCDM analyses in sustainable energy decision-making and presented a comprehensive review on commonly-used MCDM approaches and indicators. San Cristóbal (2011) applied a combination of compromised ranking and the AHP method to the selection of renewable energy projects in Spain. Furthermore, MCDM methods are frequently used to compare different alternatives for electricity and heat supply, assess the feasibility of wind turbines for an island in Italy (Cavallaro and Ciraolo, 2005), and select the best wind farm

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