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Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis

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HIGHLIGHTS

- We rank 13 electricity generation technologies based on sustainability.
- We use 10 indicators in a weighted sum multi-attribute utility approach.
- Weights are calculated based on a survey of 62 academics from the field.
- Large hydroelectric projects are ranked as the most sustainable.
- Decision makers can use the results to promote a more sustainable energy industry.

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ABSTRACT

Solving the issue of environmental degradation due to the expansion of the World's energy demand requires a balanced approach. The aim of this paper is to comprehensively rank a large number of electricity generation technologies based on their compatibility with the sustainable development of the industry. The study is based on a set of 10 sustainability indicators which provide a life cycle analysis of the plants. The technologies are ranked using a weighted sum multi-attribute utility method. The indicator weights were established through a survey of 62 academics from the fields of energy and environmental science. Our results show that large hydroelectric projects are the most sustainable technology type, followed by small hydro, onshore wind and solar photovoltaic. We argue that political leaders should have a more structured and strategic approach in implementing sustainable energy policies and this type of research can provide arguments to support such decisions.

1. Introduction

Over the last decades, the world has become increasingly aware of the environment's limited ability to support the unrestrained development of humanity. Air, water and soil pollution as well as climate change are having a significant effect on human health and quality of life in some of the world's largest developing economies (Kan et al., 2012; Pandey et al., 2005). The fossil fuel intensive energy sector is a substantial contributor to worldwide environmental degradation, with energy related CO_2 emissions expected to produce a 3.6 °C increase in average temperature over the long term (IEA, 2012b).

Simply restricting the expansion of the energy sector would not be a viable approach to managing environmental conservation, considering that economic development – the main goal of governing authorities worldwide – is tightly connected to energy demand (Breeze, 2005). Thus, establishing a balance between economic growth, quality of life and the exploitation of natural resources was deemed necessary as far back as the 1980s.

In response to this need, the specially appointed World Commission on Environment and Development published a report where the concept of sustainable development is defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987). Measuring the sustainability of the energy sector has evolved around three main dimensions: environmental, economic and social. In their paper, Carrera and Mack (2010) refer to previous research in the fields of sustainability and risk management and state that sustainability concepts that focused primarily on ecology, with social and economic factors seen as secondary, are historically the oldest. These are called “single pillar” models (Voß et al., 2005). More recent research has utilized “multi-pillar” models, which assess the environmental, economic and social dimensions and sometimes bring up the necessity of using other components such as culture or institutions (Carrera and Mack, 2010; Genoud and Lesourd, 2009; Rogner, 2010).

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The aim of this paper is to comprehensively rank a large number of electricity generation technologies based on their compatibility with the sustainable development of the industry. Quantifying the level of sustainability is done through sets of evaluation variables which are generally called “sustainability indicators”. Some of the first attempts at creating such sets were made by the International Atomic Energy Agency and the United Nations Department of Economic and Social Affairs in 1995 and then later in 2001. The findings of this early research were refined through an ample project which involved several international organizations and the final results were published in 2005 under the name “Energy Indicators for Sustainable Development” (IAEA, UNDESA, IEA, Eurostat, EEA, 2005). This three-pillar framework now constitutes a significant reference point for research regarding the sustainability of the energy sector.

There is currently no standardized methodology that can be used to evaluate energy sector sustainability. Angelis-Dimakis et al. (2012) conclude that researchers generally have to customize their approach depending on their specific objectives. Several researchers have used the Energy Indicators for Sustainable Development to establish their own set of indicators (Angelis-Dimakis et al., 2012; Streimikiene and Šivickas, 2008), while others have used a new framework altogether (Carrera and Mack, 2010; DECC, 2012; Tsai, 2010). It should be noted that two types of sustainability assessments exist: those referring to a system (e.g. national energy sector of a certain country) (Sheinbaum-Pardo et al., 2012; Streimikiene and Šivickas, 2008; Tsai, 2010) and those referring to electricity generation technologies (e.g. wind, photovoltaic, nuclear) (Evans et al., 2009; Genoud and Lesourd, 2009; Wei et al., 2010). The current paper aims to provide an analysis of the second type.

Several evaluation approaches can be used for sustainability assessment (e.g. input–output analysis, emergy accounting), however life cycle analysis is considered to be the most comprehensive, as it generates an understanding of the effect that power plants of a certain type can have over their entire existence (Evans et al., 2009). The current paper will use the life cycle analysis approach to define the value of the various indicators where applicable (e.g. the technological factors and social acceptance are technology or fuel source specific regardless of the life cycle period).

Researchers can choose from several methodologies to quantitatively measure energy sustainability: system dynamics, energy return on investment, figure of merit etc. (Liu et al., 2013). Due to its effectiveness in supporting decisions which involve trade-offs between conflicting objectives, the most widely used approach is the multi-criteria decision analysis (MCDA) (Wang et al., 2009), which we have also used in the current study.

An assessment of past research on the topic of power technology sustainability, including the extensive literature review provided by Wang et al. (2009), has revealed some improvement opportunities.

First, much of the research observed assesses only a limited number of technologies (Doukas et al., 2007; Evans et al., 2009; Máca et al., 2012) or assesses several technologies, but uses a single sustainability dimension (European Commission, 2003; Wei et al., 2010). We aim to analyse 14 different technologies, thus assessing a virtually complete set of electricity generation alternatives (Breeze, 2005).

Second, the same indicators (e.g. efficiency, pollution) are classified in different dimensions across various studies (Evans et al., 2009; Genoud and Lesourd, 2009; Wang et al., 2009). This can be due to the strict adherence to the traditional three-pillar construct (economic, environmental, social). We propose a four dimensional approach that includes the “technological” component and use the assessment of Wang et al. (2009) to classify “ambiguous” indicators in a manner consistent with relevant past research.

Finally, most research on this topic that utilizes MCDA uses equal weights for the indicators in the ranking calculation (Wang et al., 2009). We use an adapted SWING weighting method based on the results obtained from interviewing 62 academics from the fields of energy and environmental science.

2. Methods

The research methodology employed in this study, summarized in Fig. 1, can be split into four main stages: selection of the electricity generation technologies to be assessed, selection and valuation of the sustainability indicators, weighting of the sustainability indicators and sustainability ranking of the electricity generation technologies. The following subsections address these four stages individually.

2.1. Set of electricity generation technologies to be assessed

The aim of this paper is to provide a sustainability ranking for a large number of power generation technologies. The encyclopaedic work of Breeze (2005) presents an exhaustive set of electricity

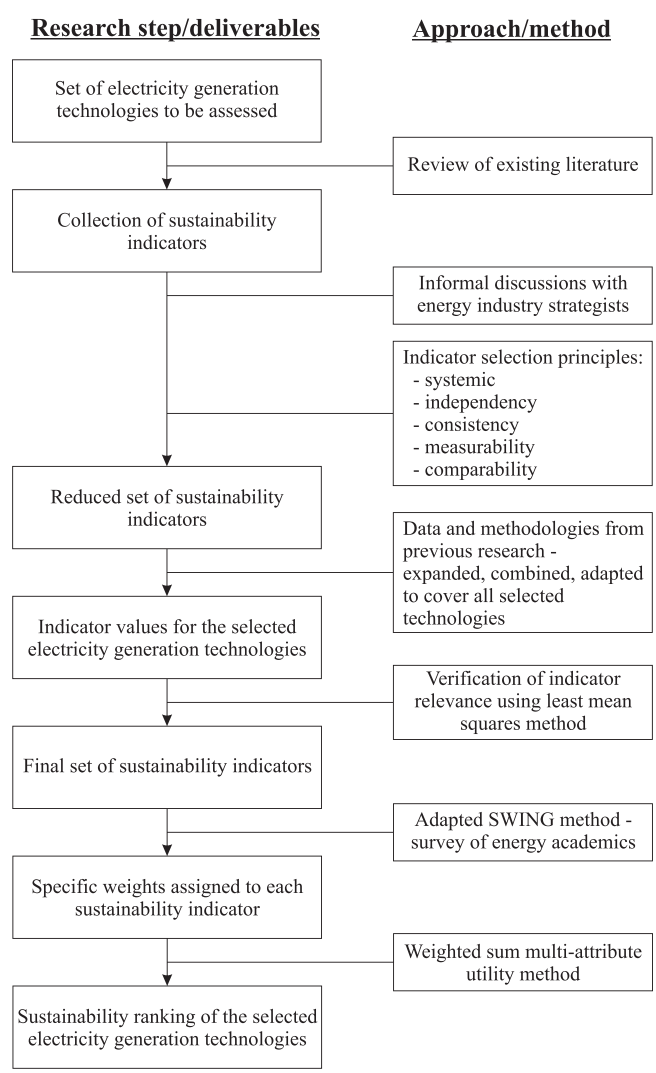

Fig. 1. Summary of research steps and methodology.