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Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England

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HIGHLIGHTS

- A holistic and comprehensive sustainability assessment model is proposed.
- Three solar photovoltaic systems are assessed for their sustainability performance.
- CdTe solar PV system performed the worst among the three systems.
- Polycrystalline solar PV system is the most sustainable choice in all categories.

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ABSTRACT

This paper proposes a comprehensive sustainability assessment model incorporating (a) life cycle approach and sustainability theory. In the model, sustainability is assessed from three categories: techno-economic, environmental and social. A total of thirteen indicators were included in the proposed model, with five evaluating the techno-economic performance, six evaluating the environmental performance, and two examining the social impact. The effectiveness of this model is then demonstrated through its application to a case study of solar photovoltaic in the North East region of England. Three types of the most commonly deployed solar photovoltaic electricity generation systems are included in the case study: monocrystalline (s-Si), polycrystalline (p-Si) and Cadmium telluride (CdTe) thin film.

The multi-silicon solar photovoltaic system is found to be the most sustainable option for its high performance in the techno-economic and environmental categories; the CdTe based system is the least-favoured option across all three categories; and the polycrystalline system has the best performance across all categories. Energy conversion efficiency appears to be one of the most influential factors for the solar photovoltaic system's sustainability performance. Despite being the least costly system among the three, the CdTe system appears to be the least financially viable option mainly due to its low energy-conversion efficiency.

This study estimates the environmental impact of selected technologies using the CML2001 method and then employs ReCiPe method to cross-validate the estimated results. Identical results were found for all indicators apart from eutrophication potential, due to the difference in impact quantification methods between CML and ReCiPe.

1. Introduction

The increasing demand-supply ratio of global oil reserves and climate change are driving the adoption of renewable energy as a desirable alternative to fossil fuels. However, due to uncertainties surrounding the energy technologies concerned and the complexity of the power system, a comprehensive assessment of all energy options is essential for exploring the sustainability performance of energy technologies and identifying their sustainability burdens [1], and thus assist decision-making and provide a solution to improve the sustainability of energy technologies [2–4].

The "three pillars" of sustainability, also known as "triple bottom line" refers to the three core components of societal development: environment, economy, and social values [5]. These values need to be equally represented in order to achieve sustainable growth [6–8]. However, observing from current practice, although terms such as "Integrated Assessment" and "Triple-bottom-line Assessment" are widely used in literature, there is little consensus regarding the use of the term Sustainability Assessment [9]. There

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is a vast amount of literature covering sustainability assessment of energy systems that only focuses on one or two of the three pillars of sustainability (e.g. [10,11]); or employing only a qualitative research technique, (e.g. [12]) which not only lacks in depth of scientific enquiry, but also leaves room for uncertainties and bias.

A life cycle approach (also known as life cycle thinking) encourages taking account of a product's impact at every stage of its life cycle. The integration of the life cycle approach and the triple bottom line method forms the life cycle sustainability assessment (LCSA); this method not only ensures that all aspects of sustainability are tuned and checked against each other, but also guarantees consideration of the impact of a given product throughout its lifespan. In the words of Kloepffer [13], the merit of a life cycle sustainability assessment method is "on feasibility and robustness even more than scientific brilliance and completeness."

Life cycle assessment (LCA) is the only internationally-standardised environmental impact assessment method, and it is underpinned by the life cycle approach [13]. It offers a complete review of sustainability impact throughout a product's entire life cycle, from "cradle-to-grave". LCA had soon become favoured by academics and industries since it was first developed in the 1960s, for its effectiveness in assisting in optimising environmental performance of a single product and its ability to enable a fair comparison between multiple products [14,15]. Over the past decade, LCA has become not only a powerful tool for scientific inquiries, but also the primary method for translating sustainability science into useful knowledge to support business and regulatory decision making.

The assessment method proposed by Youds [1] and Stamford and Azapagic [15] employs the life cycle sustainability assessment method and also uses the LCA method to account for energy technologies' environmental impact; it is by far the most comprehensive method for assessing the sustainability of energy technologies in the UK. Despite its comprehensiveness, however, the focus of this method remains at a national level, where regional characteristics are not taken into account. The significant impact of the geographical scale at which assessment is conducted is demonstrated through a number of studies in the 1990s [16]. As illustrated in Fig. 1, increased geographical scale of assessment may compromise the level of detail; on the other hand, downscaled assessment narrows the assessment scope [17]. Regional level is where social institution, ecological boundaries and economic phenomena overlap [18–20]; an assessment conducted on a regional scale is not only robust, it can also facilitate effective decision-making based on options that both use available natural resources and serve community priorities the best.

This study introduces a holistic and systematic regional life cycle sustainability assessment model which can be used to evaluate sustainability performance of electricity generation technologies. The practicality of this model is then demonstrated by applying to a case study of solar photovoltaic (PV) technology deployment in the North East region of England. To the author's knowledge, this is the first model of its kind. This paper also presents a novel indicator of circularity of energy technologies, and this indicator will be further explained in the following sections.

2. Method

In the model, electricity generated is regarded as a product, and sustainability performance of this product is examined throughout its entire life cycle using a group of indicators.

The design process of the model is displayed in Fig. 2. A survey of sustainability theory is first carried out to establish the theoretical framework of the assessment model; where the "triple-bottom-line" and life cycle approach are found to be the most suitable. In the second stage, the indicator selection, there are two distinctive main approaches to select indicators: the first one is the top-down approach, which means experts select and design the indicators; the other is the bottom-up approach, which features the participation of stakeholders in the framework design and indicator selection process [3]. In this model, both approaches are employed to ensure the robustness of assessing relevant sustainability issues. Over thirty sustainability assessment research articles and reports were reviewed in the literature survey, and stakeholders ranging from the energy industry to local city councils were consulted.

Selected indicators are divided into three impact categories in accordance to the three pillars of sustainability: techno-economic category, environmental category, and social category. The proposed model comprises of thirteen indicators in total, with five addressing the techno-economic impact, six addressing the environmental impact and two evaluating social impact.

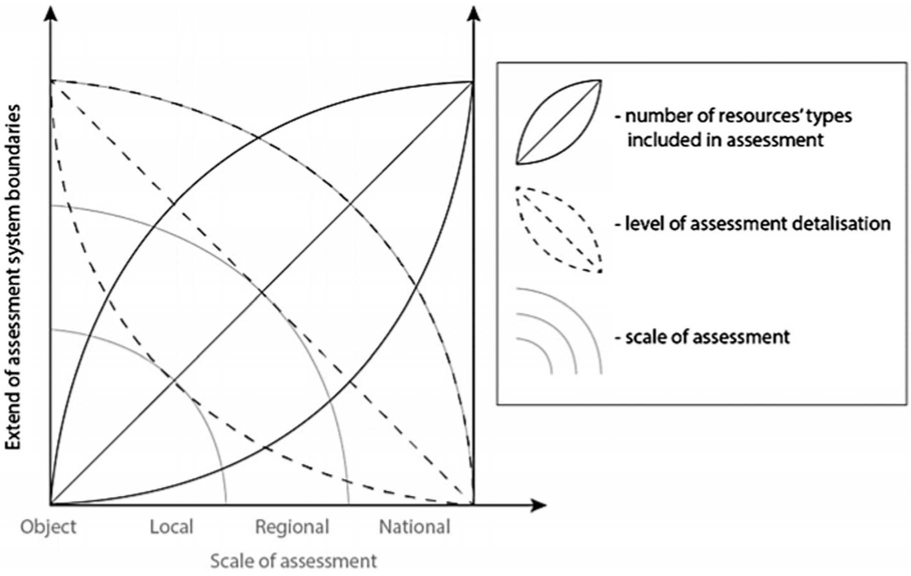

Fig. 1. Impact of sustainability assessment scale [21].

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