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Assessing the sustainability of renewable energy technologies using multi-criteria analysis: Suitability of approach for national-scale assessments and associated uncertainties

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ABSTRACT

Multi-criteria analyses (MCAs) are often applied to assess and compare the sustainability of different renewable energy technologies or energy plans with the aim to provide decision-support for choosing the most sustainable and suitable options either for a given location or more generically. MCAs are attractive given the multi-dimensional and complex nature of sustainability assessments, which typically involve a range of conflicting criteria featuring different forms of data and information. However, the input information on which the MCA is based is often associated with uncertainties. The aim of this study was to develop and apply a MCA for a national-scale sustainability assessment and ranking of eleven renewable energy technologies in Scotland and to critically investigate how the uncertainties in the applied input information influence the result. The developed MCA considers nine criteria comprising three technical, three environmental and three socio-economic criteria. Extensive literature reviews for each of the selected criteria were carried out and the information gathered was used with MCA to provide a ranking of the renewable energy alternatives. The reviewed criteria values were generally found to have wide ranges for each technology. To account for this uncertainty in the applied input information, each of the criteria values were defined by probability distributions and the MCA run using Monte Carlo simulation. Hereby a probabilistic ranking of the renewable energy technologies was provided. We show that the ranking provided by the MCA in our specific case is highly uncertain due to the uncertain input information. We conclude that it is important that future MCA studies address these uncertainties explicitly, when assessing the sustainability of different energy projects to obtain more robust results and ensure better informed decision-making.

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1. Introduction

Renewable energy markets and policy frameworks are evolving rapidly throughout the world in response to a number of global challenges and concerns, including climate change, increasing energy demand and energy security [1]. Governments and policy-makers are introducing legislation and support mechanisms to accelerate the development of the renewable energy sector, and many countries now have ambitious targets for renewable energy generation and addressing carbon emissions. For example, Scotland has set a target of generating the equivalent of 100% of Scottish demand for electricity and 11% of heat capacity from renewable sources by the end of 2020 [2].

To meet renewable energy and carbon emission targets in a sustainable fashion, it is important to understand and assess the full environmental footprint as well as the trade-offs between the benefits and dis-benefits associated with various renewable energy technologies. The selection of the most suitable renewable energy technology for a given area or location is typically faced with a range of conflicting environmental, socio-economic and technical criteria. For example, the benefits may include a reduction in greenhouse gas emissions and decreasing the reliance on non-renewable sources of energy, while the dis-benefits could be that the renewable technology is very costly, or has adverse impacts on landscapes or habitats. There is a need for approaches that can address these conflicts and trade-offs when assessing which renewable energy technology is most sustainable and appropriate at a given location.

A popular approach for investigating and assessing the full environmental impacts from a given product is life-cycle analysis (LCA). LCA attempts to assess the environmental impacts associated with all the stages of a product's life from-cradle-to-grave, i.e. from mining and processing of raw materials to manufacture, distribution, use, repair and maintenance, and disposal and/or recycling. LCA has been used widely for investigating and comparing the full environmental footprint of different energy generating systems, including renewables (e.g., [3–9]). However, LCA typically only considers known and quantifiable environmental impacts such as greenhouse gas emissions, while e.g. socio-economic implications of the product generally are not accounted for, although recent developments have attempted to complement the more traditional environmental LCA with social aspects (e.g., [10–12]). However, integration of the environmental, economic and social "dimensions" within an LCA framework is still to be developed.

When evaluating the sustainability of different renewable energy generation technologies, there is a range of important indicators and criteria that needs to be considered [13]. Multi-criteria analysis (MCA) is useful for problems in which there are a finite number of alternatives to be assessed on the basis of a range of conflicting criteria featuring different forms of data and information. MCA is becoming an increasingly popular method for addressing the multi-dimensional and complex nature of sustainability assessments. It has been widely applied for assessing and comparing the sustainability of different renewable energy technologies, plans and policies [14], both in specific areas or regions (e.g., [15–18]), but also for more generic assessments (e.g.,[19,20]).

The outcome of any MCA will generally depend on the selected criteria on which the different alternatives are assessed, the weights assigned to the criteria, and the specific method used for ranking the alternatives based on how well they perform given the criteria. Typically it is assumed that all criteria and their respective weights can be expressed as crisp values, in which case the ranking of the alternatives is straightforward. However, in real-world sustainability assessments of renewable energy alternatives, both the input data for the different alternatives and the weighting of the criteria will often be associated with significant uncertainties. For example, Evans et al. [13] found that the greenhouse gas emissions (in kg $CO_{2\text{-eq}}$/kW h) and the price of electricity generation (in USD/kW h), which are two of the most commonly applied criteria in MCAs of renewable energy developments, varied widely for each of the four renewable energy technologies considered in their study. Such uncertainty may significantly influence the outcome of a MCA and lead to a much less clear-cut ranking of the alternatives. However, many of the existing MCA studies of different renewable energy alternatives do not explicitly consider the uncertainties associated with input values and/or the weighting of criteria. In some studies uncertainty is acknowledged by e.g. carrying out a sensitivity analysis or scenario analysis of the criteria weighting (e.g., [19–21]) or by carrying out the MCA using multiple approaches (see e.g. review in [22]) as a way to check the robustness of the results. Other studies address the uncertainties in MCA by using fuzzy logic, where certain input values and/or the weights are defined as fuzzy variables (e.g., [23–25]). Fuzzy approaches have proven useful for handling the more qualitative information and subjective judgements going into a MCA, which are often expressed in linguistic terms such as "weak", "moderate", "strong" and "very strong" [26].

This study intends to critically appraise the MCA method for assessing, comparing and ranking different renewable energy technologies based on a range of uncertain sustainability indicators. The aim of this study is therefore twofold: first, to develop and apply a MCA to assess the sustainability and rank eleven renewable energy technologies at a national scale, using Scotland as an example; and second, to investigate how the uncertainties in the applied input information may influence the results of such a ranking exercise. The specific contributions of this work can be summarised as follows: (i) we develop and present a MCA for national-scale assessment of renewable energy technologies. The developed MCA is based on the widely used PROMETHEE method (Preference Ranking Organization Method of Enrichment Evaluation) [27] and considers nine commonly adopted sustainability criteria; (ii) we provide extensive literature reviews for each of these criteria to determine best estimates and assess the variability/range of the input criteria values, and we feed this information into the MCA to provide a ranking of the selected renewable energy alternatives; and (iii) because the applied input information is found to be very uncertain, we modify the PROMETHEE method to account for the uncertainty in the criteria values by using Monte Carlo simulation. We hereby provide a probabilistic ranking of the considered technologies and directly demonstrate how the variability in the input information affects the outcome of the MCA. We are of the opinion that uncertainty needs to be