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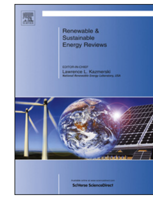

Optimal diversity of renewable energy alternatives under multiple criteria: An application to the UK

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ABSTRACT

We propose a multi-criteria analysis of alternative combinations of renewable energy technologies to meet a sustainable energy supply. It takes into account a range of criteria to reflect relevant environmental, social and economic considerations, capture the value of diversity, and reflect innovative potential and learning capacity. The combination of these factors allows for solutions in which there is more balance between economic, environmental and social dimensions, unlike in previous studies. Scenarios that might have been preferred on the basis of, for example, minimal costs or low CO_2 emissions, will have to be reconsidered because of negative effects in terms of land use or unemployment. The decision making philosophy in this case changes from that of optimization to multi-criteria satisficing. This article argues for consideration of the following dimensions of the energy system: costs, emissions, water use, land use and employment. Consideration of such dimensions will shift energy system into the direction of overall sustainability while making it more resilient in the long-term. The approach is applied to the case of the United Kingdom by making use of a MARKAL model, complementing its goal of cost-minimization with additional, social and environmental criteria. This gives rise to a number of suggestions for UK energy mix and policy.

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1. Introduction

There is widespread agreement that we need a diversity of sources and technologies to supply energy for human production and consumption. There is however no consensus about the specific energy mix. Indeed, it is unclear what would characterize an optimal mix which would take adequate account of prices, learning curves, pollutive emissions and scarce resource use, as well as

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relevant economic, geographical, climatic and environmental conditions of a given country or region. Here we present and apply a method for determining the long-term optimal mix of the energy technologies and the role renewables should play in it.

The main innovative element of our study is the addition of environmental and social criteria to the cost minimization goal of the MARKAL model for the assessment of national energy strategies. These criteria capture the value of diversity, reflecting the security of supply, employment, representing the social dimension and water use and land use, covering the environmental dimension. The combination of these factors allows for solutions in which there is more balance between economic, environmental and social dimensions and less dominance of a preferred alternative, as is common in previous studies focused on energy systems modeling using the MARKAL model. The method we propose here combines two elements, namely a MARKAL model and a multi-criteria decision aid (MCDA) approach. First, we generate cost and CO_2 emission indicators for UK energy system scenarios with the MARKAL model based on data from Strachan et al. [45]. Next, we perform a comparative multi-criteria analysis of individual energy options (wind, solar PV, hydro, gas, coal, nuclear and wood) using the Aggregated Preference Indices System (APIS) MCDA tool. The data for such an MCDA analysis is based on published sources and has been collected by Environment Europe Limited during the Oxford Summer and Winter Schools in Ecological Economics and an MCDA workshop in Ingolstadt. Next, we extend the MARKAL model output by additional measures, covering employment, a measure of diversity of the energy mix, land use and water use. Then, using additional social and environmental dimensions, we performed an MCDA analysis of MARKAL scenarios for the whole energy system. We pay particular attention to the analysis of trade-offs among different dimensions (e.g. diversity and CO_2 emissions). Moreover, by modeling explicit trade-offs among different criteria, we can learn about the implications of strategic decisions in question. An MCDA approach allows to explicitly analyze a more balanced set of aspects of energy system performance, which is not currently done within studies employing the MARKAL model

The remainder of this article is organized as follows. Section 2 provides an overview of earlier studies that have used MCDA to optimize the energy mix, as well as (the very few) studies that have specifically analyzed the importance of diversity. Section 3 presents the description of the MARKAL model and the initial set of energy system scenarios for the UK. Section 4 describes the Multi-Criteria Model for Sustainable Energy Options and presents the comparative results of the Multi-Criteria Analysis for individual energy options using the APIS framework. Section 5 explores the trade-off analysis in the context of MARKAL energy scenarios for the UK. Section 6 concludes.

2. Literature review

Several studies have applied multicriteria decision aid (MCDA) tools to planning and investment in energy alternatives. They include different types of MCDA methods, notably AHP [6,31], ASPID [1], MACBETH [4], ELECTRE ([13,26,40]), PROMETHEE [9,16,25] and NAIADE [5,12]. We briefly describe these studies below as we have learned from them how to design our own approach.

Siskos and Hubert [40], who dealt with the comparison of energy alternatives in the context of France from a social and public health point of view. Six major energy systems were compared: oil, coal, nuclear, two types of solar thermal and solar photovoltaic. The ELECTRE III MCDA method was used to compare these alternative options where the following set of criteria was employed: accidents, public risk, individual risk, collective risk, cost of kWh, work content, balance of payments, creation of jobs, available resources, securing supplies, and technical feasibility.

Georgopoulou et al. [13] employed ELECTRE III to study the choice among alternative energy policies for the Greek island of Crete. The researchers emphasize the multicriteria nature of the strategic problem at hand and criticize the dominant cost-benefit approaches. The criteria identified include: investment costs, operation and maintenance cost, safety in covering peak demand, operationality, stability of the network, cohesion to local activities, regional employment, air quality, noise, visual disamenity, depletion of finite energy resources, risk of climate change, ecosystems protection, land use, and implementation of EU environmental policy.

Afgan and Carvalho [1] use the ASPID (Analysis and Synthesis of Parameters under the Information Deficiency) MCDA method to compare the following technologies: coal, solar thermal, geothermal, biomass, nuclear, PV solar, wind, ocean, hydro, and gas using a set of five sustainability criteria: efficiency, installation cost, electricity cost, CO_2 emissions and area required.

Haralambopoulos and Polatidis [16] employ the PROMETHEE II MCDA tool to justify group decision making regarding the development of geothermal technology in the Greek island of Chios. The following five criteria were taken into account: conventional energy saved (toe/yr), return of investment (yearly earnings per initial investment) and number of jobs created, environmental pressures and entrepreneurial risk of investment.

Mavrotas et al. [26] apply a combination of the ELECTRE TRI approach with integer linear programming to select the best applications for wind energy development in Greece. As ELECTRE TRI is capable of assigning a group of objects to one of the predefined classes, such an interaction of the methods allows to generate different combinations of structural parameters of the problem as well as carry out a grouping of alternatives when no strict differentiation among alternatives is required.

Noble [31] assesses five development scenarios for Canadian energy system given a range of criteria: atmospheric emissions, resource efficiency, energy security, economic factors, public health and safety, etc. Following the Delphi method to extract expert opinions, an Analytical Hierarchy Process (AHP) method is applied to perform multicriteria evaluations. At the national level the assessment panel identified alternative A3, which emphasizes an increase in renewable energies, electricity diversification and improvements in fossil-fueled technologies as the preferred option for Canada's electricity future. Stakeholder and group preference analysis is carried out as well.

Cavallaro and Ciraolo [5] employ a multicriteria assessment using the NAIADE method to evaluate the feasibility of installing wind turbines on an Italian island of Salina. Four different scenarios are considered, varying in term of capacity and number of installations, using the following criteria: investment cost, operating and maintenance costs, energy production capacity, fuel savings, technological maturity, realization times, CO_2 emissions avoided, visual impact, acoustic noise, impact on ecosystems, and social acceptability.

Madlener and Stagl [25] propose a comprehensive methodology for the assessment of renewable energy technologies using a structured set of criteria. The set is composed of a range of indicators, representing a biophysical dimension: Resource inputs needed for production (land resources, water, material requirements, indirect energy requirements), potential environmental consequences (impacts on natural biota, habitats and wildlife, environmental risks, visual intrusion, impact on microclimate, impact on soil productivity, impact of resettlements), potential consequences of energy conversion and use (air pollution, organic emissions, generation of solid wastes, water pollution, pressure on