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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 land and water resources and other hazards), and socio-economic impacts (employment, occupational hazards, noise, impact on local poverty, household income disparity, democratic control over markets, safety of power supply, impact on balance of trade, long-term economic viability, local net value added, economic risk to ratepayers, impact on flexibility of supply). The authors suggest to use Promethee II as a MCDA tool for this type of problem.

Gamboa and Munda [12] explore the problem of the wind farm location in Catalonia, Spain using the NAIADA MCDA approach. The following criteria are taken into account: land owner's income, distribution of income, income of municipalities, number of jobs, visual impact, forest loss, noise annoyance, avoided CO_2 emissions, and installed capacity. Stakeholder analysis is performed to understand how stakeholder coalitions could be formed.

Burton and Hubacek [4] study the implementation of renewable energy schemes in the local borough of County of Yorkshire with the help of the MACBETH method. The following technologies are compared: solar PV, micro-hydro, micro-wind, biomass, large scale wind, landfill gas, large scale hydro, energy from waste. The criteria taken into account are: capital cost, operation and maintenance, generation capacity, lifespan, carbon emissions, noise, natural environment and social consequences.

Diakoulaki and Karangelis [9] apply the PROMETHEE method to compare several energy strategies for Greece using the following criteria: investment cost, production cost, guaranteed energy, available power during peak load, security of supply, CO_2 increase, SO_2 emissions, and NO_x emissions.

Chatzimouratidis and Pilavachi [6] evaluate 10 energy generation technologies: coal, oil, natural gas turbine, natural gas combined cycle, nuclear, hydro, wind, photovoltaic, biomass, and geothermal using the Analytical Hierarchy Process. The following criteria are taken into account: quality of life (accident fatalities, NMVOCs, CO_2-eq, NOx, SO_2, PM and land required) and socio-economic aspects (job creation, compensation rates, and social acceptance).

Other contributions using multi-criteria analyses are studies of national energy systems focusing on particular countries: namely, Finland [17], Indonesia [33], USA [15], Japan [18], Portugal [36], Bangladesh [34], and Turkey (Ertay et al., 2011).

Our approach differs from all the previous studies in that it uses a system-wide MARKAL model with energy system scenarios and application of Monte-Carlo-based multi-criteria decision aid, APIS, which is capable of dealing with uncertainty. In addition, our study explores trade-offs among various sustainability dimensions more explicitly by presenting them in two-criteria spaces. Finally, it offers an assessment of energy system scenarios under changing policy priorities, thereby addressing the system's complexity.

Table 1 summarizes and compares the various studies. Certain criteria come back in many studies, notably (avoided) noise, visual intrusion, CO_2 emissions, various types of other pollution, individual and public risks (economic, political, environmental), employment), security of supply, social acceptance, and costs of investment/installation and maintenance. Fig. 1 shows a taxonomy of various sustainability criteria for sustainable energy analysis: economic, social, resource impacts, environmental impacts, risks and technical feasibility. In an earlier study [43] we review the literature on MCDA applications for energy analysis (see the introduction) to assess which criteria they had in common. The corresponding scores for each individual criterion in Fig. 1 reflect the assessed frequency of occurrence of a criterion in the literature. This provides a basis for undertaking the present study.

The criteria selected include:

– The most frequently used economic criterion of investment costs (in 58% of the reviewed studies) as well as cost of electricity (16.7%).
– The most frequently used environmental impact criterion of CO_2 emissions (58.3%), and resource use indicators, namely water use (8.3%) and land use (33%); and
– the most frequently used social indicator of employment (50%) and Energy Return on Energy Investment (EROI) (8.3%).

In the selection of the criteria we have tried to keep a balance between different dimensions and to use all relevant information available to us. The criteria selected are summarized in Table 3.

3. The MARKAL model

In the taxonomy of sustainability criteria for energy system development (Fig. 1), the most frequently used economic criteria were capital costs (41.6% of studies analyzed); operation and maintenance costs (33%) and local GVA (25%); among the social-employment (50%) and visual impact (33%) were named most frequently; in the resource inputs group of criteria the most popular were land (33%) and material requirements (16.7%); in the emissions section-CO_2 (58.3%) and noise (41.6%); among the technical issues-installed capacity (25%); and among the risk factors the most frequently used criteria was security of supply (33%).

The MARKAL model is an optimization tool developed at the International Energy Agency [35] in the aftermath of the 1970-s energy crisis, with the aim to assess strategies of development and planning of the energy system. It is a technological choice model which operates in terms of costs and emissions associated with different technologies and it is usually run in the cost-minimization setting. The MARKAL model has been widely used to address the needs of strategic policy formulation related to a changing energy mix. It is interesting to note that in the original paper the MARKAL model was presented as a multicriteria optimization tool, with a focus on analyzing efficiency frontiers or the boundaries of non-dominated solutions.

The MARKAL model with its extensions is currently used in 79 institutions in 38 countries: it has been applied in Australia [29], the USA [28], the UK [23], the province of Ontario, Canada [3], China [7], the Netherlands [14], Latvia [39], Estonia [2], Switzerland [38], Vietnam [30]. Applications focused on particular technologies or policy instruments deal with, among others, green certificate market in the Nordic countries [47] and in Italy [8], photovoltaics [10], and vehicle mix in the passenger car sector in Japan [21].

The UK Government is currently trying to establish its long-term strategy to realize a radical reduction of CO_2 emissions, primarily those caused by the generation of energy and transport activities. This can be done by increasing the use of nuclear energy, natural gas and off-shore wind or through a balanced mixed of smaller-scale renewables, including on-shore wind, hydro, geothermal, solar and other sources. Characteristically, these paths could have surprisingly similar CO_2 generation trends.

The classification of energy technologies in the UK MARKAL model is as follows: fossil fuel, renewable and nuclear. Within fossil fuels coal, gas and oil are distinguished, and within renewable on- and offshore wind, hydro (small and large scale), solar PV, solar thermal, waste-to-energy and biofuels. We will present multi-criteria analysis of energy technologies using an MCDA tool and then discuss the implications for the national energy system, using UK as an example. For this purpose we use the output of a MARKAL model for the UK [45] and extend it with the newly calculated measure of diversity. Table 2 contains a brief description of the key emission reduction scenarios in the MARKAL study by Kannan. The CO_2 trajectories for these scenarios are depicted in Fig. 2.

Table 1
Past MCDA studies of energy planning and investment.

Authors and year	Application	MCDA Method	Criteria	Alternatives	Insights
Siskos and Hubert [40]	France	ELECTRE III	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	Oil, coal, nuclear, two types of solar thermal and solar photovoltaic	Four energy strategies identified, highlighting differences among preferences in various stakeholder interest groups: economic thinking (with nuclear and coal occupying top places in the ranking); long-term resource management (photovoltaic is preferred); electricity producer strategy (nuclear and coal); strategy of local policies (solar thermal chosen top priority).
Georgo-poulou et al. [13]	Crete, Greece	ELECTRE III	Investment costs, operation and maintenance cost, safety in covering peak demand, operational 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, implementation of EU environmental policy	Energy strategies: (1) NIMBY; (2) utility oriented; (3) energy demand oriented; (4) moderate and centralized RES development; (5) moderate and balanced RES development; (6) collaborative; (7) maximalistic; (8) innovative. policies	“Good” strategies are defined as those, which come up highly ranked in both descending and ascending distillation. Strategies (3) and (6) are considered “good actions”; (1) and (8) never fall in the area of “good actions”; (2), (4), (5) and (7) are inbetween.
Afgan and Carvalho [1]	MISSING	ASPID	Efficiency, installation cost electricity cost, CO_2 emissions and area required	Coal, solar thermal, geothermal, biomass, nuclear, PV solar, wind, ocean, hydro, and gas	Priority given to various criteria determine alternative assessment results. Hydro appears as most sustainable in the neutral, energy efficiency, and environmental priority scenarios; Gas – in the installation cost priority scenario and Nuclear – in the electricity cost and area priority scenario.
Haralambopoulos and Polatidis [16]	Chios, Greece	PROMETHEE II	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	Four geothermal energy development scenarios for an island	Four types of stakeholders: local authority, central government, potential investor and the NGO are ranking the alternatives in different ways, with strongly divergent interests of NGO and a group of local authority, central government and a potential investor. A compromise scenario is proposed.
Mavrotas et al. [26]	Greece	ELECTRE TRI +MILP	Internal Rate of Return (IRR) of the investment, the maturity of the certification procedure (MCP), and the quality of the application (AQ)	113 Wind energy development applications: 5 predefined categories from “very good” to “very bad”	62 applications qualified in the ELECTRE TRI stage for the MILP application. The optimal solution with the highest average multicriteria scores included 19 applications from 8 companies (the maximum share of a single company being 32%)
Noble [31]	Canada	AHP	Atmospheric emissions, resource efficiency, energy security, economic factors, public health and safety etc.	Energy policy scenarios: (1) status quo (hydro–predominant source); (2) significant increases in natural gas; (3) natural gas, clean coal and renewables; (4) clean coal dominates; (5) nuclear energy phased out by 2030.	57 panellists from Public sector, Federal Government, Provincial Government, Industry, Consultants, NGOs were surveyed and A3 scenario was highlighted as the best. Interestingly Federal Government was more in favor of renewable than NGOs.
Cavallaro and Ciraolo [5]	Salina, Italy	NAIADE	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, social acceptability	Wind energy installations: Plan A (one turbine 150 kWh); Plan B (five turbines 15 kWh each); Plan C (two turbines 150 kWh each); Plan D (PV plus five turbines of 15 kWh each)	As a result of MCDA application, Plan A was considered the best, D – the worst, with B and C in between. Position of the Plan C varies with sensitivity analysis.
Madlener and Stagl [25]	Germany	PROMETHEE II	24 environmental and economic criteria: 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	14 renewable energy technologies: Small, medium and large scale Hydro, Wood, Wind, and PV	The application of PROMETHEE II with equal weights provides the following order of preference (from highest to lowest): small hydro refurbishment; small hydro; large wood ST; small wood ST; small wind, medium wind, large hydro, large wind, small wood GST, PV amorph, small wood GT, PV multi, PV mono (please see the original paper for clarification).

			resettlements), potential consequences of energy conversion and use (air pollution, organic emissions, generation of solid wastes, water pollution, pressure on land and water resources and other hazards), and socio-economic impacts (employment, occupational hazards, noise, impact on local poverty, household income disparity, democratic control over markets, safety of power supply, impact on balance of trade, long-term economic viability, local net value added, economic risk to rate-payers, impact on flexibility of supply)		
Gamboa and Munda [12]	Catalonia, Spain	NAIADE	Land owner's income, distribution of income, income of municipalities, number of jobs, visual impact, forest loss, noise annoyance, avoided CO_2 emissions, and installed capacity	Seven alternative wind energy installations differing in the number of windmills and power capacity	Several installations were chosen on the basis of the large criteria set. The stakeholder analysis module of the NAIADE software allowed to study possible convergence of stakeholder issues and coalition formation
Burton and Hubacek [4]	Munici-pality in Yorkshire, UK	MACBETH	Capital cost, operation and maintenance, generation capacity, life-span, carbon emissions, noise, natural environment and social consequences	Solar PV, micro-hydro, micro-wind, biomass, large scale wind, landfill gas, large scale hydro, energy from waste	The study showed small scale renewable to be more favorable: in the order of decreasing preference the results were: Solar PV, Micro-hydro, Micro-wind, Biomass, Large-scale wind, Landfill gas, Large-scale hydro, and Energy from waste
Diakoulaki and Karangelis [9]	Greece	PROMETHEE and cost-benefit analysis	Investment cost, production cost, guaranteed energy (10), available power during peak load, security of supply, CO_2 increase, SO_2 emissions, and NO_x emissions	Energy strategies: Business as usual scenario (BAU); Public Power Corporation scenario (PPC); Climate Change Abatement scenario (CCA); Unsteady Conditions Scenario (UCS)	Climate Change Abatement scenario with the highest share of renewable is preferred option for Greece both on the basis of MCDA PROMETHEE and cost-benefit analysis.
Chatzimouratidis and Pilavachi [6]	N/A	AHP	Quality of life (accident fatalities, NMVOCs, CO_2-eq, NO_x, SO_2, PM and land required) and socio-economic aspects (job creation, compensation rates, social acceptance).	Coal, oil, natural gas turbine, natural gas combined cycle, nuclear, hydro, wind, photovoltaic, biomass, and geothermal	Given different preference levels given to quality of life versus socio-economic aspects, renewable energy technologies occupy five leading places out of 10 in the ranking
Häyhä et al. [17]	Finland	Weighted sum	Production cost, direct and indirect use of fossil fuels, environmental impact (CO2 emissions), and global environmental support (emergency cost).	Scenario 1: major increase in nuclear power of 13 TWh by 2025 and a total amount of 39 TWh by 2050; Scenario 2: considerable increase in use of renewable energy sources (wood biomass and wind power) reaching about 6 TWh of wind power by 2025 and 20 TWh by 2050; and Scenario 3: increasing both renewable energy and nuclear power, allowing for replacement of coal and gas power plants, wind reaching 18 TWh and nuclear power 26 TWh by 2050.	Scenario 1 raises several technological problems and environmental concerns due to nuclear power, mainly related to waste disposal, limits of uranium supply availability, nuclear security and proliferation, and strong dependence on governmental subsidies. Scenario 2 also raised environmental concerns, mainly related to sustainable exploitation of forest ecosystems to supply massive amounts of wood biomass and environmental sustainability of peat extraction and peat-based power plants.Scenario 3 represented a compromise between Scenarios 1 and 2 as it assumed that in 2050 the use of fossil fuels would be almost completely replaced by renewable energy while nuclear power would be less dominant than in Scenario 1.
Ertay et al. [11]	Turkey	MACBETH and fuzzy AHP	Feasibility, risk, reliability, time to prepare, time to implement, continuity and predictability of performance, local technical know how, pollutant emission, land requirements, need of waste disposal, compatibility with national energy policy objectives, political acceptance, social acceptance, employment effect, implementation cost,	Wind, Biomass, Solar, Geothermal, Hydropower	The ranking order of the alternatives has been obtained by using MACBETH as follows: When Technological criterion is considered, the ranking order of alternatives is Wind > Solar > Biomass > Geothermal > Hydropower. When Environmental criterion is considered, the ranking order of alternatives is the same as those of technological criterion. However, Wind energy alternative is more dominant to the others in this case. When Socio-political criterion is considered, the ranking order is Wind > Solar > Biomass > Hydropower > Geothermal. And finally when Economic criterion is considered, the ranking order becomes Hydropower > Wind > Solar > Biomass > Geothermal.

Table 1 (*continued*)

Authors and year	Application	MCDA Method	Criteria	Alternatives	Insights
			availability of funds and economic value (PW, IRR, B/C),		
Ribeiro et al. [36]	Portugal	Mixed Integer Linear Programming (MILP) model and Additive Value Function	Costs, national industry, energy dependency, employment, visual impact, noise, local income, diversity of mix, rate of dispatchable power, investment in transmission network, CO_2 emissions, land use and public health.	Scenarios: Base, Natural Gas, Coal, Hydro-Gas, Maximum Renewable	All the respondents would be willing to increase the costs of power generation if other issues than the economical ones were to be taken into account. This fact alone proves the utility of MCDA. The evaluated scenarios were ranked differently by respondents with different perspectives, what is not unexpected when using multicriteria evaluation scenarios, "Hydro-Gas", was not chosen to be the preferred by any of the eleven respondents.
Hong et al. [18]	Japan	Weighted sum	Levelised cost of electricity, energy security, greenhouse-gas emissions, land transformation, water consumption, heated water discharge, air pollution, radioactive waste, solid waste and safety issues.	Four national scenarios until 2030: nuclear free, 15% nuclear, 20% nuclear and 35% nuclear.	(i) The nuclear-free scenario has more negative impacts than the current condition, (ii) to meet the greenhouse-gas- emission guidelines, more than 35% nuclear power supply is essential, (iii) to minimize accident risk, or possible fatalities from electricity generation, fossil fuels should be avoided rather than nuclear power, (iv) despite restoration and compensation costs, a higher penetration of nuclear power will lead to cheaper levelised costs of energy, and (v) the less nuclear power is used, the lower will be the sustainability of the future Japanese energy system.
Purwanto et al. [33]	Indonesia	Multi-objective optimization model with two goal functions	Costs and CO_2 emissions	Four energy scenarios	Indonesia should develop all possible renewable energy sources for electricity but will still require importing coal to achieve the lowest cost system or importing natural gas to achieve the lowest CO_2 and multi-objective system.
Rahman et al. [34]	Bangladesh	Stochastic Multicriteria Acceptability Analysis (SMAA)	Technical dimension: capacity utilization factor, compatibility with future capacity expansion, compatibility with existing infrastructure, availability of local skills and resources, weather and climate condition dependence, annual resource availability duration; Economic dimension: capital cost, annual operation and maintenance costs, lifespan of the system, learning rate, current market share, dependence on fossil fuel; Social dimension: public and political acceptance, scope for local employment, public awareness and willingness, conflict with other applications; Environmental dimension: lifecycle GHG emissions, local environmental impact; Policy/regulation dimension: land requirement and acquisition; emphasis on use of local resources; opportunity for private participation; tax incentives, degree of local ownership, interference with other utilities.	Four scenarios: Business-as usual (BAU), Renewables (REN), Renewable-biomass only (REN-b), and Energy conservation and efficient technologies (ECET).	REN-b and REN scenarios were found to be preferable over other alternatives based on acceptability indices. These two alternatives also obtained good confidence factors (0.89 and 0.83 respectively) and are favored with uniformly distributed weights.

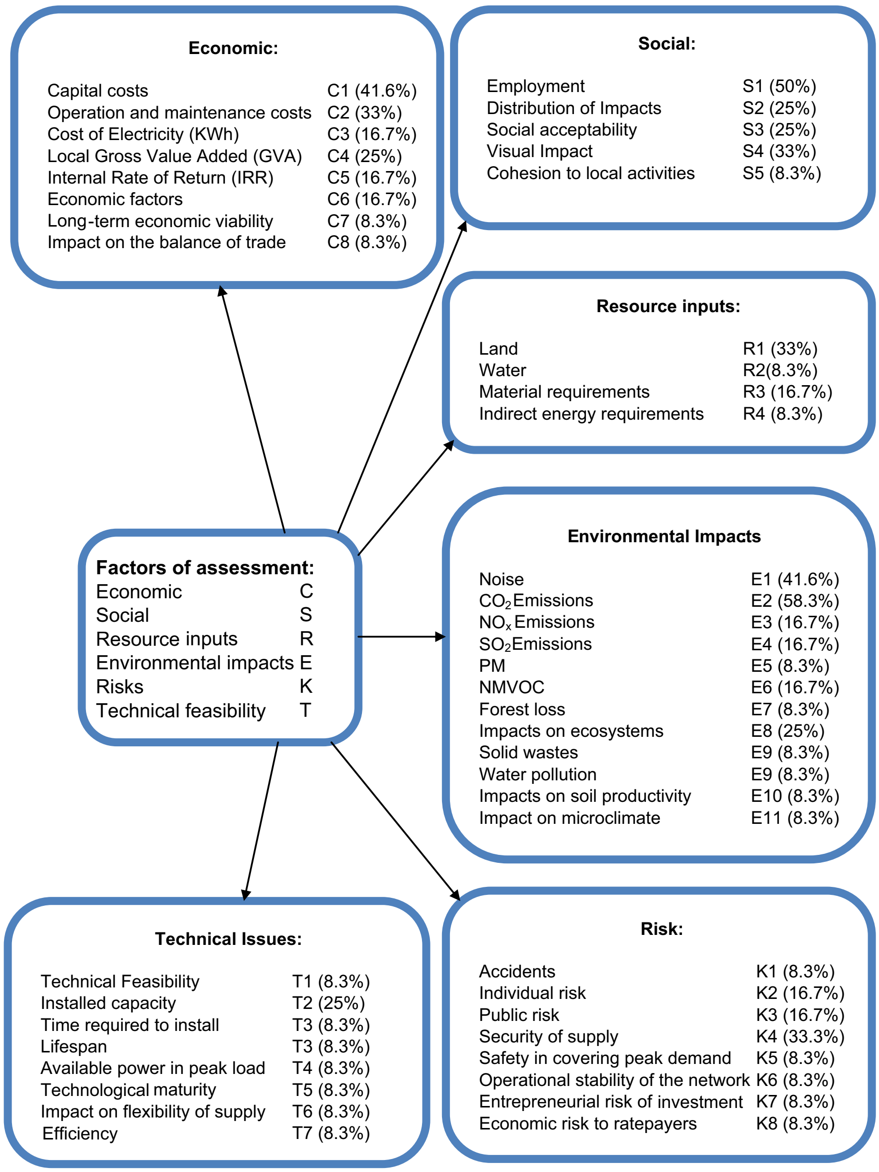

Fig. 1. Criteria used in the MCDA studies on sustainable energy (in brackets frequency of use).
Source: [43].

Based on Strachan et al. [45] and authors' calculations (Diversity 2050 column).

The UKERC team [45,46] has produced a wide range of UK energy system scenarios using the MARKAL model. These scenarios include (Table 2): Baseline (B) characterised by only the policies of Energy 2008 Bill and no CO_2 price; the Faint Hearted scenario (CFH), characterised by the 15% CO_2 reduction by 2020, extrapolated to −40% by 2050; Low Carbon scenario (CAM), characterised by the 26% CO_2 reduction by 2020 (CCC interim target equivalent), exponentially extrapolated to −80% by 2050 (118MtCO_2); the Early Action scenario (CEA) exhibiting a 32% CO_2 reduction by 2020 (CCC intended target equivalent), extrapolated to −80% by 2050 (118MtCO_2), the Least Cost Path scenario (CCP) characterised by the Same cumulative emissions as Early Action scenario (19.24GtCO_2), but a least-cost cumulative path and the Socially optimal Least Cost Path scenario (CCSP), exhibiting the same cumulative emissions as LC-EA (19.24GtCO_2), with a least-cost cumulative path, and social discount rate (3.5%).

4. The multi-criteria decision aid model of sustainable energy options

The main output of the MARKAL model consists of the data on investment costs, energy generation by technology and associated CO_2 emissions. The MARKAL model does not generate data for water use, land use or employment. We extend the UKERC study to include additional dimensions. This is done in the spirit of the taxonomy of criteria focusing on economic, social, resource inputs, emissions, risks, and technical feasibility dimensions, as shown in Fig. 1.

The relevance of a multi-dimensional approach can be illustrated by a historical example. The increased demand for offshore wind installation and the limited availability of ships capable of installing turbines led to a sharp increase in installation prices in the UK and extended waiting times. The rapid deployment of new technologies could also potentially lead to an increased demand for steel and aluminum, which illustrates the importance of the criteria reflecting use of resource inputs. Similarly, use of water or land, or emissions other than of CO_2, are relevant and

Table 2
Key MARKAL UK emission reduction scenarios.

Scenario	Scenario name	Key features	CO_2 reduction targets (2050 from 1990)	Cumulative emissions (GT CO_2, 2000–2050)	Costs 2050	Emissions 2050 (MT CO_2)	Diversity 2050
B	Baseline	Only policies as of 2008 Energy Bill; No CO_2 price	–	**30.03**	259.076	583	0.33
CFH	Faint hearted	15% CO_2 reduction by 2020, extrapolated to -40% by 2050 (355MtCO_2)	15% by 2020 and 40% by 2050	**25.67**	261.620	355	0.44
CLC	Low carbon-60	26% CO_2 reduction by 2020, extrapolated to -60% by 2050 (237MtCO_2)	26% by 2020 and 60% by 2050	**22.46**	267.048	237	0.62
CAM	Low carbon	26% CO_2 reduction by 2020 (CCC interim target equivalent), exponentially extrapolated to -80% by 2050 (118MtCO_2)	26% by 2020 and 80% by 2050	**20.39**	276.025	118	0.68
CEA	Early action	32% CO_2 reduction by 2020 (CCC intended target equivalent), extrapolated to -80% by 2050 (118MtCO_2)	32% by 2020 and 80% by 2050	**19.24**	275.516	118	0.67
CCP	Least-cost path	Same cumulative emissions as LC-EA (19.24GtCO_2), but a least-cost cumulative path	–	**19.24**	281.446	67	0.67
CCSP	Socially optimal least-cost path	Same cumulative emissions as LC-EA (19.24GtCO_2), with a least-cost cumulative path, and social discount rate (3.5%)	80% post 2050	**19.24**	226.780	179	0.64

Note: Based on Strachan et al. (2010) and authors' calculations (Diversity 2050 column).

could be a decisive factor when making a strategic judgement. Social effects, including those of employment in the new renewable energy sectors, and re-education of the staff of the plants to be decommissioned would also need to be taken into account.

The MCDA approach will allow us to consider key renewable and non-renewable options from the point of view of most relevant criteria (Table 3): Economic (Investment costs, Cost of electricity); Environmental (CO_2 Emissions, Water use, and Land use); Social (Employment) and Technical (Energy Return on Investment, EROI).

We apply the MCDA method APIS (Aggregated Preference Indices System), developed by Nikolai Hovanov [19]. It is based on the Bayesian model of uncertainty randomization. An extensive description of the method is contained in the recent publications: Shmelev [44], Hovanov et al. [20] and Afgan and Carvalho [1]. The APIS method is designed to compare complex objects, given a range of criteria describing their performance using an additive aggregated preference index and a measure of dominance reliability. This method is particularly suited for the analysis of energy options as it allows testing different priorities: economic, environmental, social and presents results accordingly. It has been chosen in this study for its ability to handle uncertainty in the weighting coefficients, for its clarity of presentation and for its capacity to model different policy priorities: cost minimization, CO_2 minimization or employment maximization. This method is relevant for addressing "problematique γ" [37], i.e. the class of problems focused on arranging all objects from a set into a ranking or a total preorder.

The weights in MCDA assessments are randomized by using a Monte-Carlo method, which can be interpreted as a kind of sensitivity analysis. The policy priorities that we defined imply relationships between weights, which translate into constraints in the weights optimization problem. An optimization problem was run to derive all those weights that satisfy the pre-set policy priority constraints. The MCDA results can then be presented as distributions of the performance scores taking into account uncertainty in weights coefficients rather than treating them as accurate point estimates.

The applications of the APIS tool to the multi-criteria decision problem of sustainable energy selection are shown in Figs. 3–8. First the standard steps of multi-criteria decision aid are undertaken, namely selection of alternatives and criteria and preparation of a decision matrix. The method allows setting up priorities, thereby setting the order of importance among the criteria. Then in a Monte-Carlo fashion the weights are randomized based on the information on priorities, this aspect makes the method more powerful than the application of individual weights alone. The results obtained under different priorities can be seen as reflecting different perspectives and viewpoints: that of a financier, that of an environmental NGO or a trade union. Consideration of each different priority contributes to a learning process, allows highlighting the trade-offs and helps to understand the complexity of the problem at hand.

The comparative analysis of various energy technologies helps to put the issue of technology selection in a multi-dimensional perspective, highlighting the importance of individual dimensions (social, economic and environmental) and the trade-offs between them. This is the first preparatory step for the full multicriteria analysis of energy scenarios. The results are presented as charts, indicating the performance scores (mid-points of the red bars on the horizontal axis) of each alternative energy option accompanied by the measures of uncertainty (distribution) of each performance score (red bars). Additional blue bars denote the probability of domination of one alternative over the other if there is an overlap between distributions of performance scores.

Table 3
Multicriteria decision matrix for sustainable energy options.
Source: Investment costs and Cost of Electricity: NREL [32]; CO_2 emissions: IPCC [22]; Water use: Meldrum et al. [27]; Land use: Hydro Quebec; Employment: Wei et al [48]; EROI: Lambert et al [24]. Estimates presented in this table are median values. Red indicates the worst and yellow – the best option for each criterion.

Criteria	Units	Energy Options						
		wind	solar	hydro	gas	nuclear	coal	wood
1) Investment costs	$m/MW (C)	5.39	24.04	7	1.25	5.99	3.22	4.4
2) Cost of electricity	c/KWh	7	31	7	5	8	7	17.3
3) Life cycle GHG emissions	g CO_2 eq/KWh	12	46	4	469	16	1001	225
4) Water use	l/kWh	0.0075	0.3	244	0.81	2.94	2.09	1.02
5) Land use	km^2/GWh	72	45	152	0.31	0.5	4	0.9
6) Employment	Person years/GWh	0.18	1.42	0.27	0.11	0.14	0.11	0.22
8) EROI	Dimensionless number (>1)	19.8	9	84.1	14	14	28	27

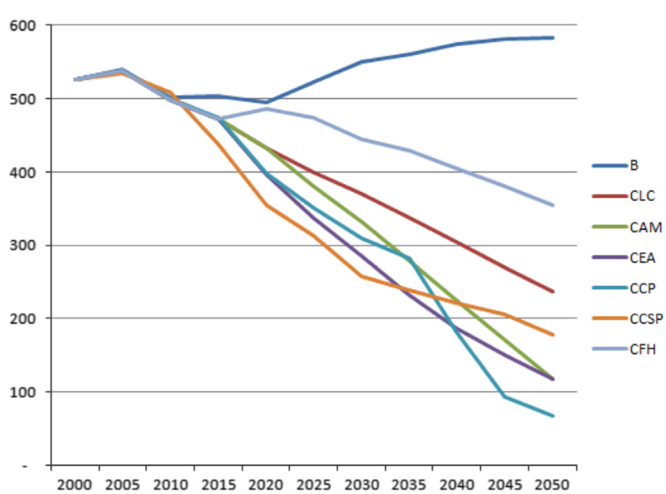

Fig. 2. Emission trajectories within major UKERC scenarios: B, CFH, CLC, CAM, CEA, CCP and CCSP presented in Table 2 and further analyzed in the this study.
Source: UKERC [46].

Under the investment costs minimization priority, as can be seen in Fig. 3, Gas has an overall performance score of around 0.78 and is a very competitive technology. It is followed by nuclear, coal, wood and wind with hydro and solar being less preferred if capacity factors are taken into account. Solar is least preferred under this priority.

Under a CO_2 minimization priority (Fig. 4), Nuclear appears the best (performance score of 0.77), closely followed by Wind, Hydro, and Solar. The worst performer on CO_2 emissions is Coal, with Gas, Hydro, Solar and Wood performing much closer to Wind and Nuclear, rather than Coal.

Under the Water use minimization priority (Fig. 5), the best performers are Nuclear and Gas, followed by Wind, Solar and Wood. The worst performer on Water use among the conventional technologies is Coal with Hydro being an obvious absolute 'leader', water being the main source of energy here. Full life cycle perspective has been taken into account as much as possible here, which means that emissions of the whole supply chain (related sectors) were taken into account.

Under Land use minimization priority (Fig. 6), the best performers are Gas and Nuclear, while the worst are Hydro, Solar, Wind, and Coal. This is largely determined by the direct land use in the case of wind and solar and indirect land use of supporting activities for Coal and Hydro.

Under the Employment priority setting (Fig. 7), Solar has a performance score of 0.68, creating the largest number of jobs per unit of energy produced, followed by Nuclear, Gas, and Wind.

Under the EROI priority setting (Fig. 8), Hydro is clearly the preferred option, reaching a performance score of 0.69, followed by Nuclear, Gas, Wood and Wind. The worst performers under EROI priority setting are Solar and Coal.

The results presented in this section show that the selection of the appropriate mix of various energy technologies is indeed a fine balance between realizing low Investment Cost (Gas), low CO_2 emissions (Nuclear and Wind), less water and land used (Gas and

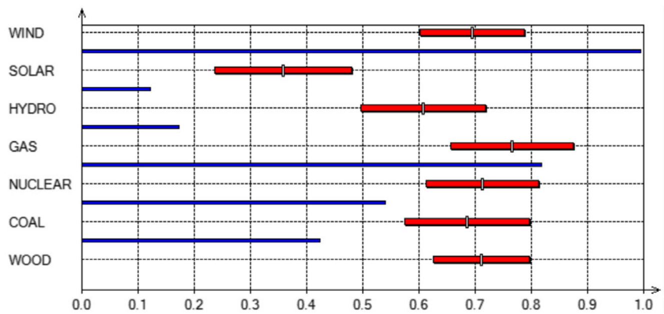

Fig. 3. Multi-criteria ranking of sustainable energy options with APIS: investment cost minimization priority.

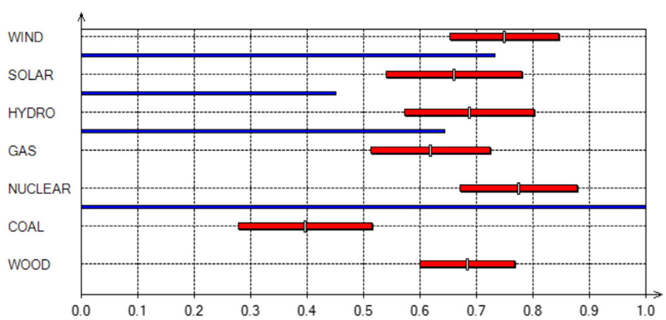

Fig. 4. Multi-criteria ranking of sustainable energy options with APIS: CO_2 minimization priority.

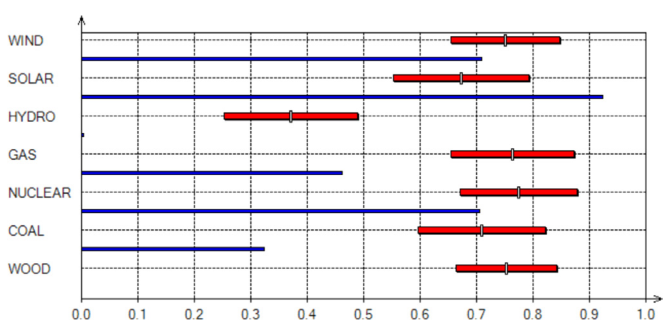

Fig. 5. Multi-criteria ranking of sustainable energy options with APIS: water use minimization priority.

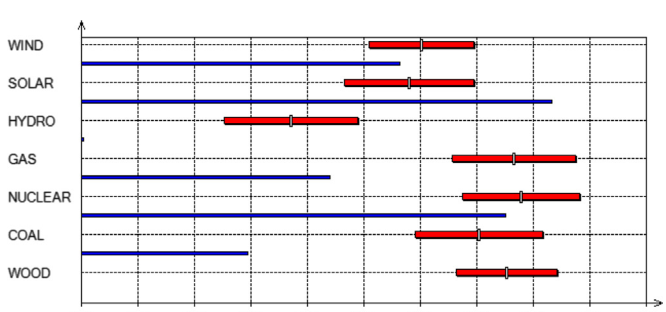

Fig. 6. Multi-criteria ranking of sustainable energy options with APIS: land use minimization priority.

Nuclear), more employment (Solar) and higher EROI factor (Hydro). If one adopts a weak sustainability point of view [42] and accepts more compensation among criteria, changing priorities creates different rankings of preferred sustainable energy options. To reach a decision in such a highly complex system it is necessary to find a societal consensus on the priorities and constraints (budgetary, resource, climatic etc.). Applied to the energy system

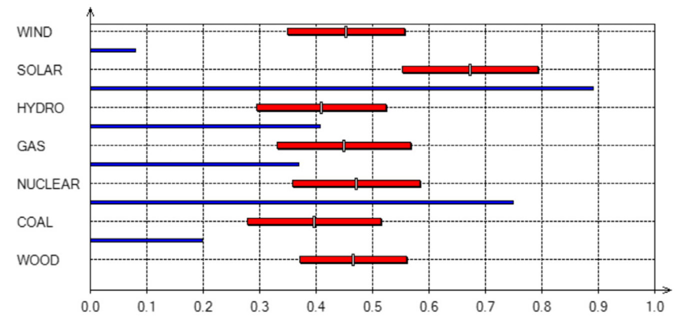

Fig. 7. Multi-criteria ranking of sustainable energy options with APIS: employment priority.

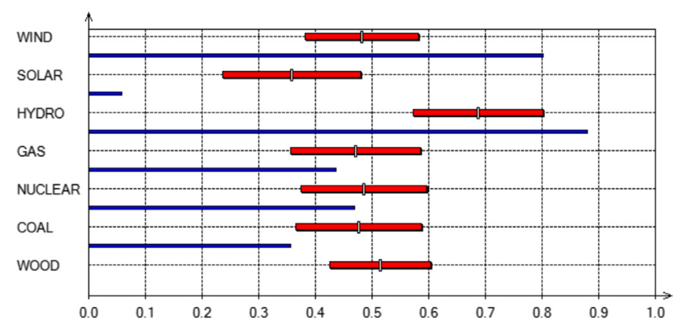

Fig. 8. Multi-criteria ranking of sustainable energy options with APIS: EROI priority.

as a whole, such an approach will determine, which energy scenarios will be more acceptable from the point of view of the whole spectrum of criteria (not just investment costs and CO_2), but also water use, land use, employment and EROI. In the next section, we will show – by using Investment cost, CO_2 emissions, Water use, Land use, Employment and technological diversity measures – the implications of using such a multi-criteria approach.

5. Trade-off analysis

Observing the trade-offs between various dimensions of the sustainable energy problem brings the analysis closer to the original formulation of the MARKAL model presented in Siskos and Hubert [40] and corresponds to the ideas expressed in Shmelev and Powell [41]. If we consider the trade-offs between CO_2 and diversity (Fig. 9). As can be seen in Fig. 9, there is a clear negative correlation or a trade-off between CO_2 emissions and diversity of the energy mix, which indicates that organization of the energy system with more diversity (thereby creating a more resilient system that keeps options open for the future) tends to produce less CO_2 emissions. The Baseline scenario (B), characterised by only the policies of Energy 2008 Bill and no CO_2 price, and the Faint Hearted scenario (CFH), characterised by the 15% CO_2 reduction by 2020, extrapolated to -40% by 2050 (Table 3) are exhibiting low levels of diversity of the energy mix. On the other hand, the Low Carbon scenario (CAM), the Early action scenario (CEA), and the Least Cost Path scenario (CCP) exhibit the highest levels of diversity of the energy mix.

Similar trade-offs apply when one considers relationships between Employment and CO_2, Employment and Water use, etc. (Figs 10–12). In the case of the Employment/CO_2 nexus (Fig. 10), CCP offering the lowest CO_2 emission levels in 2050 is also characterised by the highest employment levels in 2050. CFH, on the other hand, produces the lowest employment levels in 2050, while offering a very limited emissions reduction. CCSP, being the

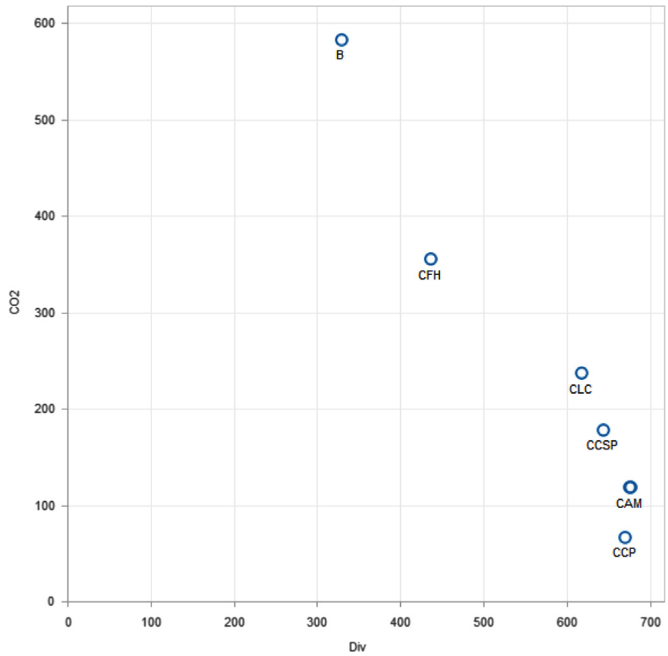

Fig. 9. CO_2 versus diversity trade-off: UK MARKAL scenarios B, CFH, CLC, CAM, CEA, CCP, and CCSP, described in Table 2.

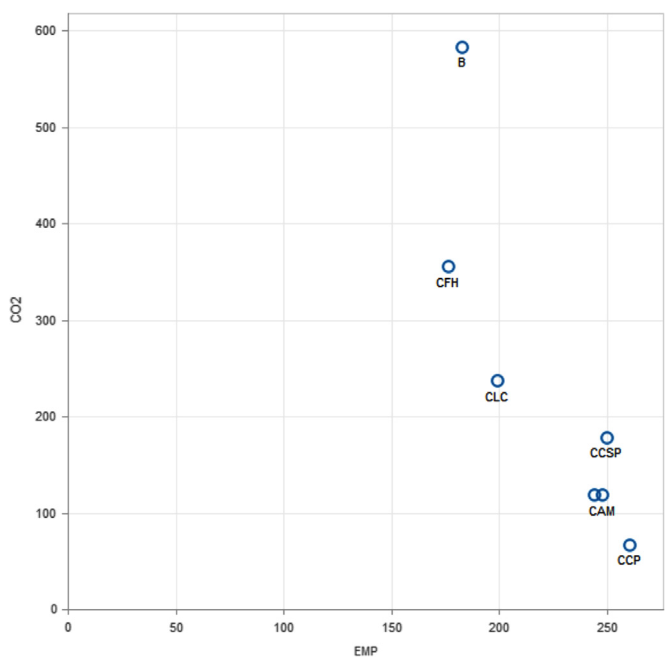

Fig. 10. CO_2 and employment trade-off: UK MARKAL scenarios B, CFH, CLC, CAM, CEA, CCP, and CCSP, described in Table 2.

cheapest option, is only fifth best in terms of employment performance.

Such a bicriterial analysis, i.e. focusing on trade-offs between two criteria, is a good starting point to analyze trade-offs between more than three criteria. A more encompassing application of MCDA tools (which will be done in this article using APIS) is, however, necessary to illustrate the exact position of each scenario in relation to each other under different priorities. It should be mentioned that a clear domination of one particular scenario on all criteria is rarely the case, as will be seen from the applications below. The preferred option should be chosen through a consensual process (e.g., an open dialog) among relevant stakeholders

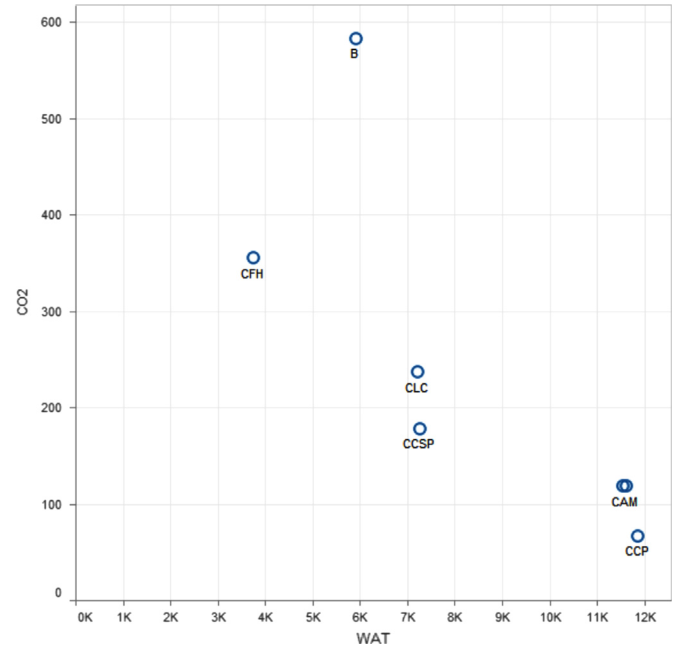

Fig. 11. CO_2 and water use trade-off: UK MARKAL scenarios B, CFH, CLC, CAM, CEA, CCP, and CCSP described in Table 2.

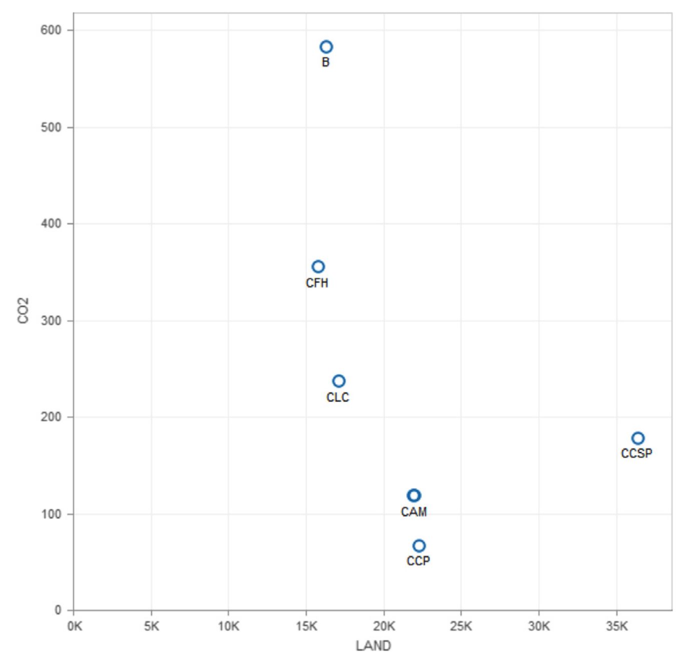

Fig. 12. CO_2 and land use trade-off: UK MARKAL scenarios B, CFH, CLC, CAM, CEA, CCP, and CCSP described in Table 2.

(of citizens, experts or politicians) involving consideration of various criteria.

In this study we were able to extend the standard output of the MARKAL model (Costs and CO_2 data) with additional variables, taking into account the energy mix in each individual scenario in 2050. We then applied the APIS tool to produce comparative multi-criteria analysis of the MARKAL scenarios (Table 3). This was done for different priorities (Cost minimization, CO_2 minimization, Employment maximization, Water use and Land use minimization). The resulting preference scores are shown in Figs. 13–17).

In the final part of our paper we present the MCDA analysis of the the MARKAL model scenarios extended by additional

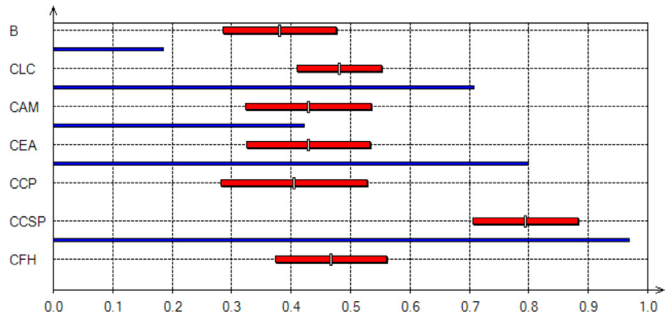

Fig. 13. MCDA analysis results of the UK energy scenarios, APIS, 2050: investment cost minimization priority.

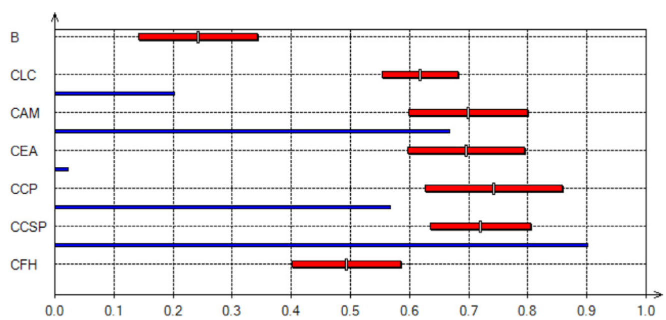

Fig. 14. MCDA analysis results of the UK energy scenarios, APIS, 2050: CO_2 minimization priority.

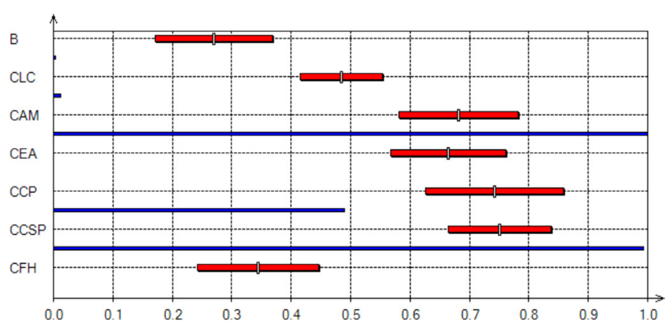

Fig. 15. MCDA analysis results of the UK energy scenarios, APIS, 2050: employment maximization priority.

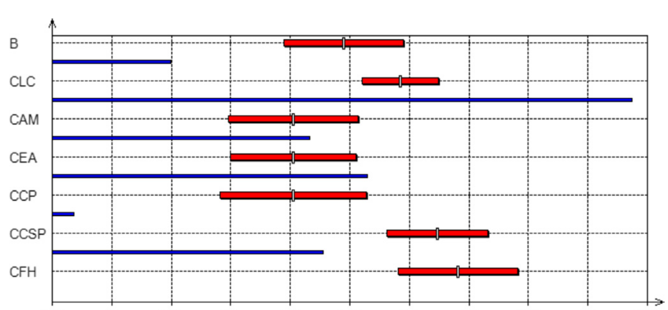

Fig. 16. MCDA analysis results of the UK energy scenarios, APIS, 2050: water use minimization priority.

dimensions with the help of the APIS tool. Under the Cost minimization priority (Fig. 13), the CCSP scenario is by far the preferred option, with a score of 0.79. Scenarios B, CAM, CEA and CCP (scores between 0.38 and 0.43) are the worst-performing under this priority. Scenarios CLC and CFH perform better than the previously mentioned lot, but significantly worse than CCSP.

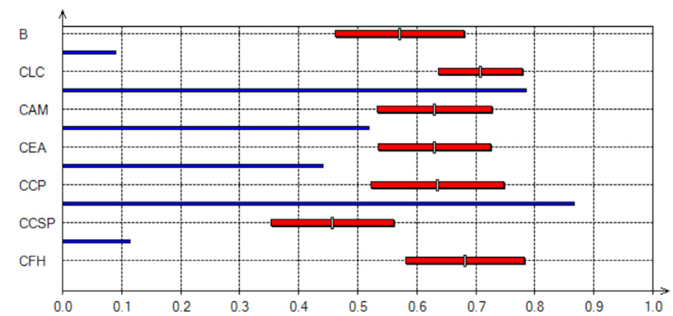

Fig. 17. MCDA analysis results of the UK energy scenarios, APIS, 2050: land use minimization priority.

In the the CO_2 emissions minimization priority case (Fig. 14), the CCP scenario becomes the leading one, closely followed by CAM, CEA and CCSP. The worst-performing scenarios under this priority setting are B (score of 0.24), CFH (0.49) and CLC (0.62).

Under Employment maximization priority (Fig. 15), the CCSP and CCP scenarios become the leading ones reaching the score of 0.75 and 0.74 respectively. It is followed by scenarios CAM (0.68) and CEA (0.67), the worst performers being B (0.27), CFH (0.34) and CLC (0.48).

The CFH scenario is better overall under the Water use minimization priority (0.68) and is followed by CLC (0.58), B (0.49), CCP (0.4), CAM (0.4) and CEA (0.4) (Fig. 16).

Considering Land use minimization priority (Fig. 17), the CLC scenario is better overall (0.71), followed by CFH (0.68), CCP (0.63), CAM (0.63), CEA (0.63), B (0.57), and CCSP (0.46).

If we look at the extreme cases, we see that the CCSP scenario involves high land requirements; CCP, CAM and CEA scenarios involve higher water use; and B, CFH, and CLC scenarios involve lower employment compared with other options in 2050.

6. Conclusions

At a time when global CO_2 concentrations have surpassed the level of 400 ppmv, the subject of a sustainable energy transition is of utmost importance. We have presented a Multicriteria Decision Aid study to inform such a transition, highlighting trade-offs among social, economic and environmental criteria. To generate data for all criteria, we used the energy system model MARKAL, which provides investment costs and CO_2 emissions for UK energy system decarbonization scenarios. Data for additional relevant dimensions like employment, water use and land use were obtained using lifecycle coefficients from published sources.

Our approach differed from the previous works by a synthetic strategy of application of the multi-criteria approach to individual energy options on one hand and whole energy system scenarios generated by the MARKAL model on the other. First, we have examined energy technologies: wind, solar PV, hydro, gas, coal, nuclear and wood from the point of view of investment costs, cost of electricity, employment, CO_2 emissions, water use and land use. The selection of criteria was informed by a review of MCA studies of energy options. We then applied the Multi-Criteria Decision Aid tool APIS to compare various energy options under different priorities: investment cost minimization priority, CO_2 emissions minimization priority, water use minimization priority, land use minimization priority, employment maximization priority and Energy Return on Energy Investment (EROI) maximization priority.

The application of MCDA to individual energy options revealed that Gas is the preferred option under the investment cost minimization priority; Nuclear is preferred under the CO_2 as well as water and land use minimization priorities; Solar is preferred under employment maximization priority; and Hydro is the preferred option under EROI maximization priority.

In this study the MARKAL generated scenarios were extended by indices of water use, land use and employment as these are not taken into account in the MARKAL model. We calculated these indices by multiplying outputs of the MARKAL model by relevant coefficients obtained through a comparative analysis of sustainable energy options to arrive at the aggregate measures of employment, water use and land use for the whole UK energy system. Next, we applied the APIS tool to compare the MARKAL energy system scenarios in 2050.

Summarising the results for the UK energy system scenarios, the Socially optimal least cost (CCSP) scenario involves high land requirements; Least-cost path (CCP), Low carbon (CAM) and Early action (CEA) scenarios imply higher water use; and Baseline (B), Faint hearted (CFH), and Low carbon-60 (CLC) scenarios exhibit lower employment compared with other options in 2050. The multi-criteria analysis illustrated the existing trade-offs among investment costs, employment, CO_2 emissions, water use and land use for individual energy options and strategies for the whole UK energy system.

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