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ANALYSIS

Multi-criteria analysis of nuclear power in the global energy system: Assessing trade-offs between simultaneously attainable economic, environmental and social goals

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ABSTRACT

To investigate the complex relationships among the energy-related challenges faced by humanity, we marry a large-scale energy systems model, MESSAGE, with a multi-criteria model analysis tool. Such an approach is applicable to other modelling frameworks and can significantly improve the analysis of multiple goals. We focus our study on nuclear power — a technology viewed differently by different stakeholders. We find that nuclear power plays an important role in global climate change mitigation efforts where energy security and affordability goals take precedence, but that the total amount of nuclear in the system is highly dependent on stakeholders' preferences. We also find synergies among climate mitigation and energy security goals, and also between these two goals and the reduced need for underground carbon storage.

1. Introduction

Humanity faces a complex array of energy-related challenges, for which there are no universal solutions. World population is rising; many people still lack access to modern energy forms and many, too, cannot pay high energy prices [1]. At the same time there is evidence that the dangerous effects of climate change can be avoided only by reducing greenhouse gas (GHG) emissions, to which the energy sector is one of the main contributors [2]. This means that consumption of energy services needs to be reduced or that there should be a switch to cleaner technologies to produce energy services, which could make energy more expensive. Many of the low-emitting energy technologies are not yet widely available on the commercial market, and their future potential is unknown. They thus present a technological risk. One such technology, carbon capture and storage (CCS), has been shown to have a special importance in future low-carbon systems due to its versatility which allows its potential use in many sectors and with many fuels [3,4]. Yet it is unclear if CCS will ever be widely used, as the technology has not yet been proven at full scale; the siting of storage repositories has also generated public opposition [5]. On top of these concerns, energy security is a priority on the policy agendas of individual countries and regions; this mainly manifests itself as a concern about dependence on imported fossil fuels or the reliance on too-small a number of energy sources [6]. Technology risks stemming from CCS and energy security concerns should be assessed in any scenario that aims at the reduction of GHG emissions and it should also be recognised that trade-offs may be required among goals. It is also obvious that different stakeholders attach a different level of importance to solving these economic, social and environmental challenges. They also do not they agree on what level of achievement of these challenges would be considered adequate. At the same time if different targets are considered jointly rather than seen as separate goals or constraints, important synergies among them can emerge; such synergies have been shown, for example, by [7] and [8]. Therefore, interactive multi-criteria tools can be useful for analysing possible trade-offs and synergies among energy sources and technologies.

Our research aims to add to the field of scenario literature in two unique ways. First, we focus specifically on nuclear energy, which allows us to address many of the nuclear-specific issues that have not been covered in previous scenario analyses using global

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energy—economy and integrated assessment models. Furthermore, we make a key methodological advance in the multi-criteria analysis (MCA) field by applying a new tool called Multiple-Criteria Model Analysis (MCMA) which supports the interactive MCA of large-scale linear models. The aim of this paper is twofold. First, to reflect upon the results of the MCMA analysis of the MESSAGE model, which has been extended by a detailed representation of nuclear power, a technology with widely recognised benefits and risks; and second, to demonstrate the possibilities enabled by the advanced MCMA technology. The case study reported here involves seven criteria representing different economic, social, and environmental goals.

2. Background

2.1. Integrated analysis of energy sector

Analysis of energy sector development involves selection of energy conversion technologies and requires consideration of several goals and constraints. The goals (often referred to as criteria, indicators, objectives, etc.) represent diverse aspects of decisions or choices, such as costs, emission of different pollution types, waste generation, different risks, etc. The constraints include: i) the demand for various energy carriers; ii) characteristics of introduction, extension, and phasing-out of technologies; iii) shares of specific technologies (e.g., base and peak); iv) availability of primary energy resources; and v) legal and social constraints on certain technologies. An integrated analysis of this sort requires a corresponding mathematical model, such as the International Institute for Applied Systems Analysis's (IIASA) integrated assessment modelling (IAM) framework, MESSAGE.

This paper focuses on the role of nuclear power technologies in the energy sector, in particular, their impact on minimising the costs of achieving climate change goals. To investigate the possible contribution of nuclear energy, however, new criteria, variables, and constraints have necessarily been added to the model. A description of these criteria can be found in the next section. A full description of the MESSAGE model is outside the scope of this paper; interested readers are referred to [7,9—11] for more information on the topic. Section 3.1 highlights key elements of the model that are necessary for understanding how it was modified for our purposes. Below, we summarise key issues related to using nuclear power.

2.2. Nuclear power

Nuclear power is a well-established technology: more than 10% of the world's current electricity is supplied by nuclear power [12]. It also produces low life cycle emissions of carbon dioxide [13] and can thus contribute to mitigating climate change. Historically, nuclear power has been expanding, mainly due to growing demand and security concerns [14,15]; however, accumulating concerns about climate change have, in some circles, renewed interest in it as a potential substitute for higher emission energy sources. Although climate change mitigation is possible without the use of nuclear power [e.g. [7,16]], excluding nuclear power from the energy system will likely make mitigation more difficult and costly to achieve, as shown in a study by the International Energy Agency (IEA) [17] and several others [e.g. [18—20]]. Numerous studies focussing on cost-competitiveness [e.g. [21,22]] have also demonstrated that a strong carbon price signal is likely to make nuclear power significantly more attractive. Thus nuclear power can help to achieve climate targets and contribute to energy affordability.

In addition, nuclear power could enhance energy security, in terms of reducing fossil fuel imports, and also diversify the electricity supply. Both Japan and France, for example, have stated that energy security is one of their main motivations for utilising nuclear power [23,24]. Uranium prices have traditionally been quite stable; they constitute a small share of the cost of producing electricity via nuclear power, and the fuel for reactors can be easily stored for a long period at the powerplant itself because of its high energy density. This enables countries to secure themselves against supply disruptions at low additional cost.

Even though nuclear power can be a beneficial source of energy in many ways, it raises other specific concerns such as accidents and nuclear weapon proliferation risks. The latter emanates from the fuel cycles associated with Light Water Reactor (LWR) technology, the globally dominant reactor design. LWR fuel cycles involve uranium enrichment, a dual-use process that is needed to produce LWR fuel but can also produce weapons grade material.[1] Moreover, some neutrons released during the fission process that are used to generate heat for producing power are absorbed in uranium-238 atoms and lead to the creation of plutonium-239 which, when separated from the rest of the spent fuel, can also be used to produce nuclear weapons. Although having a civil nuclear program does not mean that a country will automatically pursue nuclear weapons, having enrichment or reprocessing facilities provides a state with the technology to manufacture the critical component of bomb material [25]. If nuclear power is to make a major contribution to mitigating climate change, technologies that can enable weapons development are likely to spread. Extended discussion on nuclear weapons proliferation in a climate mitigation context can be found in [20].

Another concern regarding nuclear power is the creation of radioactive waste. The normal operation of a 1 GW_{el} nuclear power plant produces about 22 tonnes of high-level radioactive waste (HLW) per year in the form of spent fuel [26]. This waste remains highly radioactive for thousands of years and must therefore be isolated from the biosphere or converted to forms with shorter half-lives. One way of doing this entails building underground repositories in which the fuel can be stored and then sealed. Another path is to reprocess the fuel that has been burned in reactors and separate out the long-lived isotopes, which can then be further used as fuel for other reactor types. However, some storage will be necessary even in this case. Both solutions to the waste problem have been difficult to implement because of a lack of public acceptance, high costs, and proliferation concerns [27].

The reasons outlined above, together with the possibility of accidental radiation release from a nuclear power plant, make nuclear energy a controversial option, entailing benefits and risks that are not easily monetised. Yet, many countries, particularly developing states, have openly declared a willingness to start a nuclear program or to increase their current capacity, despite concerns stemming from waste disposal and nuclear weapon proliferation issues, reactor safety, and high construction costs [14]. This makes nuclear power an interesting case study for multi-criteria analysis, as it allows for varying the prioritisation of different goals.

2.3. Previous studies

With the Global Energy Assessment (GEA), IIASA was involved in developing transformational energy pathways that simultaneously achieve a variety of energy sustainability goals [28]. In these analyses, it is clear that the contribution of nuclear power to the future energy supply is one of the key uncertainties: nuclear power could play an important role in attaining stringent climate targets; on the other hand, certain technological and socio-political concerns could prevent a nuclear renaissance. One of the positive effects of nuclear power, namely, low carbon emissions, is usually well represented in energy—economy models; however, risks such as radioactive waste, proliferation risk, and risk of severe accidents are not often dealt with in a

[1] Enrichment could be theoretically avoided using CANada Deuterium Uranium (CANDU) reactors. However, they entail a different proliferation risk due to difficulties in monitoring material flows. This reactor type is not included in our study.

sophisticated manner. For example, scenario studies commonly present only nuclear phase-out scenarios, e.g. [29]; that is, a blanket assumption is made that no new nuclear capacity will be available. Most recently, the Stanford Energy Modeling Forum Study 27 (EMF27) investigated the importance of individual mitigation options by comparing the responses of 18 energy—economy and integrated assessment models to two different climate targets and various technology portfolio combinations [3]. The role of nuclear power was investigated by comparing a phase-out scenario to a scenario in which nuclear is part of the portfolio. This study found that employment of nuclear power leads to mitigation cost reductions that can reach up to 30% of the carbon abatement cost [29].

As other energy-related goals besides affordability and climate mitigation have increased in importance, multi-criteria analysis methods have been explored to more fully understand the relations between different objectives and their achievability. These studies, however, are often limited to a national or power plant scale (e.g. [30—32]). A notable exception is the IIASA Energy — Multi Criteria Analysis (ENE-MCA) policy tool [33]. This tool explores an ensemble of over 600 possible futures generated through parametric single criteria optimisations, in which the parameters represent different levels of constraint for the other criteria. The results of the optimisations are treated as discrete alternatives. Of several thousands of optimisations, only roughly 600 resulted in Pareto-optimal alternatives (i.e., the majority of generated alternatives were dominated,[2] therefore not worth further analysis). ENE-MCA supports multiple criteria analysis of these alternatives, thus enabling the assessment of the co-benefits of simultaneously achieving goals related to climate, health, and energy security and the discovery of synergies between climate and energy security [8]. Yet that study only deals with the discrete alternatives generated through the parametric optimisation and thus fails to explore the entire space of Pareto-optimal solutions. To do the latter a multi-criteria model analysis (MCMA) is necessary: such an approach has been applied to the study reported in this paper.

3. Methodology

3.1. Adaptation of the MESSAGE model for the study

In its basic form, MESSAGE is a global systems engineering optimisation model with considerable flexibility for defining energy technologies, countries/regions, and time periods. In the integrated assessment framework version of MESSAGE used in this study (i.e., the model developed and maintained exclusively at IIASA, which embeds MESSAGE within a framework of other tools) the model considers 11 regions[3] and a 120-year timespan. Our version utilises a linear programming modelling framework that optimises the global energy system by minimising total discounted energy system costs over the entire model time horizon (1990—2110). A global 5%/yr discount rate is used. The model includes energy resources, energy extraction (fossils, renewables, nuclear), conversion (e.g., heat, power, refining), and end use sectors (industrial, transport, residential/commercial). The driving force in the MESSAGE model is energy demand, which is split into seven categories for each region: thermal, electricity and feedstock demand for industry; thermal and electricity for residential and commercial buildings; transport and non-commercial biomass. MESSAGE is most commonly used for energy system planning, energy policy analysis, and scenario development. It is linked to MAGICC, a reduced-complexity coupled global climate-carbon cycle model, in order to estimate the climate system impacts of the various greenhouse gas emission trajectories of the scenarios [34,35]. MESSAGE has been used extensively in the development of scenarios for the Intergovernmental Panel on Climate Change (IPCC) [36] and for the Global Energy Assessment (GEA) report, coordinated by IIASA [28]. More detailed information on IIASA's MESSAGE framework is available, including documentation of model setup and mathematical formulation [7,9,11].

Our analysis builds on the MESSAGE version used in the GEA report, specifically the GEA-Mix setup with its intermediate levels of future energy demand. Investment costs for electricity production technologies in this scenario are shown in Appendix B. For plants with carbon capture and storage (CCS), only the costs of CO_2 capture and compression equipment are included here; the costs of CO_2 transport and storage are considered in MESSAGE as O&M costs, and therefore are not included in the investment costs shown in Appendix B. The same goes for nuclear power; the costs of nuclear fuel enrichment and reprocessing are considered in MESSAGE, but they are not included in the investment costs. Furthermore, for all power plants, the costs of electricity transmission and distribution (T&D) are not part of the investment costs shown here, though of course they are considered elsewhere in MESSAGE. The conventional version of the model makes use of two nuclear technologies with different cost and availability profiles, both utilising light water reactors (LWRs) with a once-through cycle. For this study, the fast breeder (FBR) fuel cycle and mixed oxide (MOX) fuel option[4] have also been implemented (Fig. 1) using cost data from a recent Massachusetts Institute of Technology study [37]. The costs that we assumed for this implementation are shown in Appendix A.

To investigate the benefits and risks of nuclear power in an integrated, holistic framework, we combined MESSAGE with a novel MCMA tool. More specifically, we extended the MESSAGE model specification by adding variables and constraints representing nuclear power technologies as well as the definitions of criteria presented in Section 3.3. We used MESSAGE to generate the MPS-format file corresponding to the single-criterion optimisation linear programming problem, and then, instead of sending this MPS to the traditional optimiser, we provided it to the interactive MCMA tool. The tool uses the MCA method described below and the analysis of the set of Pareto solutions, each solution corresponding to the preferences specified interactively by the user.

3.2. Multi-criteria model analysis

Typically, energy systems and integrated assessment models used for scenario analysis involve several criteria. Traditionally, two approaches to analysis by such models are used. First, the analyst can focus on a single goal (most often, minimising systems cost) and can include other criteria as constraints. As already mentioned in Section 2.3, this approach leads to many runs of single-criterion parametric optimisations (each corresponding to a set of constraints on the other criteria), the results of which can later be used as discrete alternatives subject to multiple criteria analysis. The second approach is to apply the linear aggregation of criteria, in which each criterion is given a weight, and then attempt to modify the weights to represent changing preferences for trade-offs among criteria. Both approaches, however, have serious limitations (discussed, e.g., in [38]).

[2] One alternative is dominated by another, if the latter has a better value for at least one criterion, and equally good values of all other criteria. See Section 3.2 for a summary of multiple-criteria analysis features.

[3] Sub-Saharan Africa, Centrally Planned Asia and China, Central and Eastern Europe, Former Soviet Union, Latin America and the Caribbean, Middle East and North Africa, North America, Pacific OECD, Other Pacific Asia, South Asia, Western Europe.

[4] We have here implemented the MOX fuel cycle with only one reprocessing step. Although it is possible to reprocess MOX fuel several times, the economics are worsened with every processing. In addition, no good cost data are available for multi-cycle MOX fuel use, as this is not practiced today.

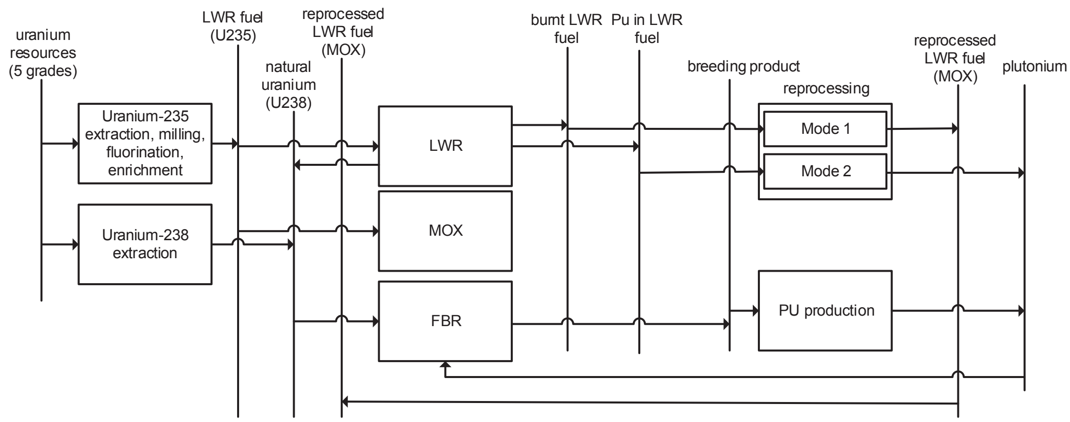

Fig. 1. Nuclear cycles in MESSAGE. FBR and MOX cycles were added for the purpose of this study. Lc and hc refer to low cost and high cost options of LWRs. The former is only available until 2040 and represents generation II reactors.

A comprehensive multiple-criteria analysis involves exploration of subsets of Pareto-optimal solutions,[5] also known as efficient or non-dominated solutions. The whole set of efficient solutions for non-trivial problems is typically huge[6] and complex; therefore, its analysis is impractical. Moreover, users are typically interested in analysis of those Pareto subsets that have desired trade-offs among criteria values. The latter observation justifies interactive MCA methods that provide users with effective controls to explore diverse Pareto subsets. One class of such methods is called the Reference Point[7] (RFP) method. The method used in this study, called the aspiration—reservation based approach, is an extension of the RFP method, and is described in detail in [39]. In this method the analyst interactively defines two points called Aspiration (A) and Reservation (R). The values defining the A—point are composed of the criteria values the user wants to (simultaneously) achieve, while the R—point contains the worst acceptable values. The pair of A/R—points is used for defining parameters of the so-called scalarising achievement function, maximisation of which provides a Pareto solution. Discussion of the method and its properties is beyond the scope of this paper; therefore we mention only that if the A—point is not attainable,[8] then the solution provided is the closest (in the sense of a distance measurement defined by the A/R—point) to the A—point; if the A—point is attainable, then the solution provided is uniformly better. Upon analysis of the solution obtained, the user decides which criterion or criteria he/she wants to improve (i.e., tighten the corresponding component of the R—point and optionally also set a more ambitious component of the A—point). Optionally, the user may set less ambitious values of the A/R—points of the criteria that should be compromised in order to achieve the desired improvement.[9]

The advantages that the method applied has over the MCA of discrete alternatives generated through parametric optimisation (as in [8]) can be summarised as follows. Firstly, the user specifies her/his preferences in a natural way using the A/R values. There are no restrictions for the A/R values (except the obvious one, namely, that the A has to be better than the R), and it is therefore easy to experiment with various combinations of the desired criteria values and to modify the values while learning their attainable combinations. Second, the method provides the Pareto set limited by the best and worst criteria values. These points are called the Utopia[10] and Nadir, respectively, and they imply for each criterion the range of values worth considering. Third, each optimisation run provides a Pareto solution. The method is therefore much more efficient than parametric optimisation, which provides a majority of dominated solutions in addition to many infeasible solutions.

3.3. *Criteria*

Depending on the purpose of the analysis, different sets of criteria are used; for example, in the analysis of future energy technologies in the NEEDS project [40] over 40 economic, environmental, and social criteria were defined. In the study described in this paper seven criteria were defined for exploring trade-offs between indicators representing different aspects of economic, social, and environmental concerns. The criteria, each to be minimised, are summarised in Table 1. Selection was based on their previous application in the literature as well as applicability to the MESSAGE model. The approach reported can easily be used with another criteria set, provided that each criterion can be represented by a corresponding variable of the underlying model.

Discounted system cost and cumulative GHG emissions are well established criteria in energy modelling and thus need no further elaboration. As the same does not hold for the other five criteria, we offer a short justification for each of them.

The total excavation needed for a repository was chosen to represent the radioactive waste issue connected to nuclear power production. HLW is produced in all three fuel cycles implemented in our version of MESSAGE, but in different amounts and with different characteristics. To bring all waste production under a common metric, the permanent storage capacity needed for storage of HLW in a granite repository based on data from [41] was used. Although recycling plutonium as MOX fuel removes about 1% of the material from the LWR spent fuel that would otherwise need to be stored, the resulting spent MOX fuel has a higher heat content, which makes it necessary to place the containers further apart and therefore increases the space needed for storage. The FBR cycle uses most of the plutonium in spent fuel, reducing the volume that needs to be stored. It is technically possible to extract also the remaining uranium-235 and uranium-238 from spent fuel for use in the production of new fuel, but we assume the cost to be

[5] A solution is Pareto-optimal if and only if there is no other solution with a better value of at least one criterion and at least equally good values of all other criteria.

[6] For models defined with continuous variables the Pareto set is composed of an infinite number of solutions having substantially different features.

[7] Here the *point* stands for a vector composed of criteria values.

[8] i.e., no solution has criteria values at least as good as the values defining the A—point.

[9] Note that due to the definition of the Pareto solution, improvement of a criterion value is possible only by worsening value of at least one other criterion.

[10] Because the Utopia point is not attainable in the properly specified multiple-criteria problem.

Table 1
Criteria used in this study.

Issue represented	Criterion	Short name	Unit
Affordability	Discounted cost of energy system including fuel cost	Cost	TUS$2005
Climate change mitigation	Cumulative GHG emissions	Emissions	$GtCO_2$-eq
Nuclear waste	Total excavation needed for HLW repository	Waste	Mm^3
Nuclear weapon proliferation (enrichment)	Cumulative production of uranium-235 enriched to 4%	U-235	kt of U-235
Nuclear weapon proliferation (reprocessing)	Cumulative production of plutonium	Pu	kt of Pu
Energy security	Cumulative global trade	Trade	ZJ
CCS failure risk	Carbon storage capacity required	C storage	Gt of CO_2

prohibitive compared to using new material during the current century. As a result, HLW produced by one GWyr of electricity from LWR, MOX, and FBR cycles would need 83—86 m^3 of storage space. These differences among cycles are too similar to facilitate a choice between technologies; thus the waste indicator in our model acts to limit nuclear power in total. This, however, can be changed if different technologies become available.

Proliferation risk stems from two sources, enrichment and reprocessing. In the current model we represent the proliferation risk from enrichment by the cumulative amount of uranium-235 enriched. Although this is fuel grade and not weapons grade uranium (meaning that uranium-235 content is ~4% instead of 90% or more), this criterion can be used as a proxy for the number of enrichment plants that would be needed, as well as their usage, and therefore also for the knowledge necessary to build and operate an enrichment facility.

Reprocessing poses a nuclear weapon proliferation risk due to the separation of plutonium. Although the reactor grade plutonium that we model is not ideal for military purposes due to the presence of even isotopes that cause a significant premature detonation risk, it could be used in the manufacture of weapons with considerable destructive force. In common with enriched uranium, the amount of plutonium produced in reprocessing can be seen as a proxy for the amount of reprocessing capacity and knowledge. Thus, although parts of the plutonium used as fuel undergo fission and thus disappear, we use the cumulative amount of plutonium separated via reprocessing as the criterion for proliferation risk.

There is no commonly accepted definition for energy security, and various criteria have been created to capture its different aspects. For an extended discussion see [42]. Import dependency is a widely used energy security indicator that mainly addresses the sovereignty aspect of energy security. In this study we use cumulative global primary energy trade volumes as a global proxy for national/regional import dependency. Although uranium is also traded globally, it is not included in the trade criterion because one nuclear power plant fuel load typically provides fuel for at least 2 years' and up to 10 years' worth can be stockpiled at relatively low cost [43].

Because of the key role that CCS can play in climate mitigation and uncertainties related to its large scale implementation [4], we chose the required carbon storage capacity as our measure of the risks involved. In addition, CCS and nuclear power are seen as competing mitigation options, as both could allow the generation of low-carbon base-load electricity [18].

It is also important to note that all our criteria are cumulative and therefore do not capture the time dynamics. The time period for aggregation is from 2010 till 2100 except for the cost indicator, which for technical reasons is aggregated from 1990 till 2110. However, this difference between time periods does not play a role in our analysis, as the variables for historic periods (1990—2010) are fixed.

Table 2
Nadir and Utopia values of criteria.

Criterion	Utopia	Nadir	Unit
Cost	47	66	TUS$2005
Emissions	1500	7600	$GtCO_2$-eq
Waste	0.13	25	km^3
U-235	1.6	150	kt of U-235
Pu	0	65	kt of Pu
Trade	2.9	21	ZJ
C storage	0	1600	Gt of CO_2

4. Results of multi-criteria analysis of the message model

Before the interactive analysis starts, the MCMA tool computes for each criterion its best (Utopia) and worst (Nadir) values. Then each user can define and run several analyses. Each analysis is composed of iterations. For each iteration the preferences are defined in two steps. First, whether the criterion is active or inactive is declared. Typically, all criteria are active, but in some iterations it is useful to deactivate some criteria. The latter implies that the criterion in question will not compete[11] with the active criteria. Second, for each active criterion the aspiration and reservation values are defined. For each set of preferences a corresponding Pareto solution is provided. Typically, an analysis is composed of several dozen iterations, and several analyses are conducted for a case study. This was also the case for the study reported in this paper. However, due to space limitations, we present below the results of only a small subset of iterations.

4.1. Utopia and Nadir values

The Utopia and Nadir values provide important information for each criterion; namely, the range of the criterion values for all Pareto solutions. Obviously, one should not expect a criterion value better than the Utopia; neither should one accept values worse than the Nadir. The Utopia point is easy to compute through a sequence of selfish optimisations (i.e., optimising each criterion one after the other while the other criteria are ignored). Exact computation of the Nadir is, however, resource-demanding, and the exact value is not important enough to justify excessive computational resources. Typically, therefore, approximations are used that can easily be updated during the analysis.

The Utopia and Nadir values for the problem under consideration are presented in Table 2. We point out two related issues. Firstly, the criteria value ranges are huge, considering the corresponding measure among diverse Pareto solutions. Second, at first glance one may be surprised at the non-zero values of almost all criteria. This can be explained by two factors. Firstly, the energy system must fulfil the given energy demand and technological constraints; this, in particular, explains the high cost even of the cost-minimising solution (i.e., without consideration of any other criterion). Third, replacing existing technologies requires time. For example, nuclear power is a significant part of the electricity supply today, and a decision to phase it out as soon as possible will in any case result in the production of some amount of nuclear waste and enriched uranium. The use of technologies that are not a significant part of today's portfolio such as CCS and FBRs, however, can be avoided if climate change mitigation is not a

[11] A similar effect can be achieved by setting the aspiration value close to the Nadir. However, declaring the criterion inactive is recommended because it is not only easier but also results in better properties of the underlying optimisation problem.

priority, and therefore the amount of carbon storage needed and plutonium produced can go to zero.

4.2. *Trade-offs and synergies between criteria*

The main purpose of MCMA is to examine trade-offs (how much one needs to compromise a criterion to improve another criterion) and synergies (improvements of more than one criterion) among criteria. Below we present selected results illustrating this point.

One of the fundamental trade-offs in the energy system is between the cost of the energy system and GHG emissions, given that, today, low-emitting technologies are often significantly more expensive than traditional fossil fuel-based energy. Table 3 shows the results of assigning different A/R values to the emission criterion representing climate change mitigation. The A/R values for the cost criterion are set at Utopia and Nadir, respectively; the other criteria are inactive. For such preferences, emissions are at their Nadir value when only the cost of the system is minimised. However, a small increase in importance of climate reduces emissions significantly without too much of an increase in cost — about a 20% reduction in emissions is achieved with only 0.4% added cost. This suggests that there is a significant amount of low hanging fruit in the energy system (i.e., low cost emission reduction opportunities). Setting more ambitious A/R levels aiming to achieve emission reductions roughly corresponding to 520 ppm CO_2-eq, corresponding in turn to about 450 ppm CO_2, requires significant increases in cost. In our case we used aspiration and reservation levels of 245 and 300 $GtCO_2$-eq for the 520 ppm CO_2-eq scenario (which we also call a stringent climate target) and 465 and 520 $GtCO_2$-eq for the 700 ppm CO_2-eq scenario (corresponding to 600 ppm CO_2, which we also call a moderate climate target) to allow the model some flexibility and also to meet the target emissions with a relatively high certainty. For example, meeting the 520 ppm CO_2-eq level increases the discounted cost of the whole energy system by about 8%.

The role of nuclear power becomes more important with more stringent climate targets such as 520 ppm CO_2-eq. This is in part caused by increased electrification in the system and the fact that there are a limited number of low-emitting electricity supply options. Both LWRs and FBRs are used with stringent climate targets, and therefore both enrichment and reprocessing are present. This is caused by large-scale nuclear expansion that drives up uranium prices to the level at which FBRs become profitable. Similarly, CCS increases in importance with more stringent climate targets. As a versatile mitigation option, it plays an important role in decarbonising both industry and the electricity sector. It is also important to note that the dependence on imported fuels is reduced by more stringent climate targets — a significant synergy. Most energy trade takes place in the form of fossil fuels, and as cutting emissions reduces fossil fuel use, the need for trade diminishes. Fig. 2 visualises these results.

To give an overview of the structure of the energy system and the effects of climate targets, we present in Fig. 3 the structure of the primary energy and electricity supply for different emission levels (averaged from 2060 to 2080). Without any climate target, most energy is provided by relatively cheap fossil fuels that have high emissions with small cost-competitive contributions by hydro and wind resources, and also biomass. Moving toward more stringent targets reduces the share of fossil fuels in both primary energy and the electricity supply. The total amount of primary energy is reduced by climate targets because of a switch to more efficiently produced energy carriers, mainly electricity in the heating and transport sectors. This can also be seen in the increasing electricity demand. Nuclear power, especially FBRs, is not economically competitive without a climate target but contributes almost a quarter of electricity in the case of stringent climate targets.

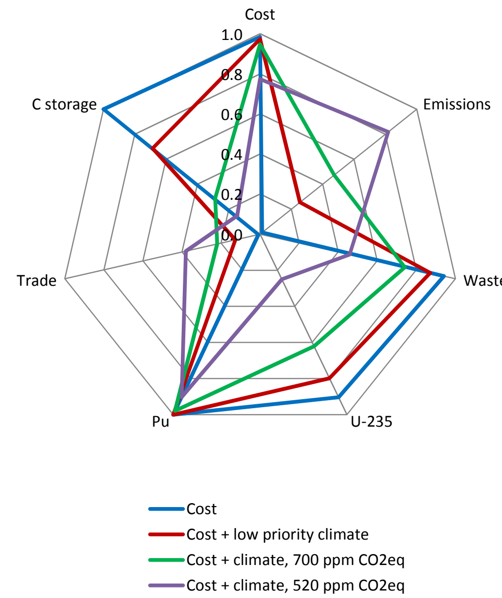

Fig. 2. Selected results from varying the importance on cost and climate criteria. The range between Utopia and Nadir values has been normalised, and Utopia and Nadir values have been assigned 1 and 0 accordingly.

Synergies between energy security goals and climate mitigation goals such as reduced trade volume and emissions have been identified [8] and can also be shown in our multi-criteria setting. We added a trade criterion to the cost and climate criteria with an aspiration level of 7 ZJ and reservation of 11 ZJ corresponding to a sustained trade level of 2010 on average for the rest of the century with aspiration set 2 ZJ lower and reservation 2 ZJ higher. The scenarios in this paper were chosen after careful deliberation between all co-authors and various other individuals who are considered experts in each of the different criteria areas (e.g., energy security). Based on these discussions and previous literature (e.g., [8]), the scenarios are believed to be realistic. Our aim is to demonstrate the method and to illustrate the interplay among criteria. We do not attempt any justification of preferences because these are subjective and differ amongst both analysts and policymakers.

Table 3
Selected results from varying the importance on cost and climate criteria.

Criterion/Scenario	Cost prioritisation	Cost prioritisation, low priority climate	Cost prioritisation, 700 ppm CO_2eq	Cost prioritisation, 520 ppm CO_2eq	Unit
Cost	47.3	47.5	47.9	50.9	TUS$2005
Emissions	7630	6160	4910	2750	$GtCO_2$-eq
Waste	1.59	3.27	6.14	13.2	Mm^3
U-235	15.9	30.9	53.9	109	kt of U-235
Pu	0	0	1.39	6.65	kt of Pu
Trade	20.5	18.4	16.7	14.3	ZJ
C storage	0.1	498	1110	1430	Gt of CO_2

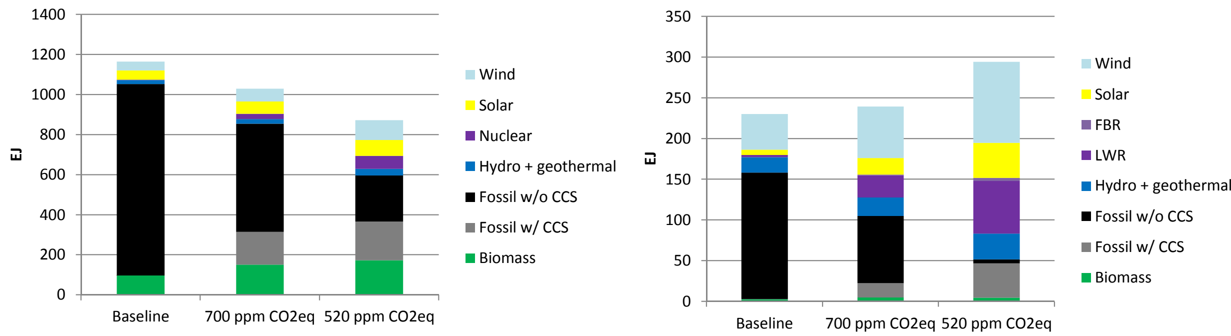

Fig. 3. The composition of primary energy (left) and electricity supply (right) for different emissions levels (average of 2060–2080).

Table 4
The effect of activating different criteria close to 700 ppm CO_2-eq level.

Criterion/Scenario	700 ppm CO_2eq	700 ppm CO_2eq + trade	700 ppm CO_2eq + U-235	700 ppm CO_2eq + U-235 + trade	700 ppm CO_2eq + U-235 + trade + Pu	Unit
Cost	48.0	48.4	48.1	48.5	48.5	TUS$2005
Emissions	4760	4800	4760	4820	4820	$GtCO_2$-eq
Waste	6.6	8.7	2.1	3.3	2.1	Mm^3
U-235	57.8	71.0	8.8	13.3	13.4	kt of U-235
Pu	1.4	4.7	7.6	13.6	4.0	kt of Pu
Trade	16.7	7.9	18.1	8.0	8.1	ZJ
C storage	1180	900	1350	940	930	Gt of CO_2

To further investigate the role of nuclear power, we increased the significance of the criterion for enriched uranium and set the aspiration and reservation levels to 1.6 kilotonnes (kt), which is rounded to 2 kt and 46 kt. A cumulative quantity of 46 kt of 4% enriched uranium-235 could be produced if half of the current enrichment capacity is operated for the rest of the century on average. Currently only a little over 30% of the existing capacity is used [44]; thus our scenario entails a considerable increase in enrichment activity.

Finally, in order to also address concerns about nuclear weapons proliferation stemming from reprocessing, we added the criterion for plutonium production by setting the aspiration level to 0 and reservation to 15 kt, corresponding roughly to 8 EJ of electricity production from FBRs over 50 years. For comparison, LWRs today provide roughly 9 EJ of electricity [45]. The results of these different preferences are presented below.

As can be seen in Table 4 most of the cost increase in the case of the moderate climate target comes from setting preferences on the amount of trade. This is due to the fact that a significant amount of fossil fuels can still be used with moderate targets. As trade consists mainly of fossil fuels, by activating the trade criterion we exclude cheaper fossil fuel options for some regions. This, in turn, enhances nuclear power, as can be seen from the increased amount of waste, enriched uranium, and plutonium produced. It is also interesting to note that although the overall deployment of nuclear power is increased, it is decreased in some regions that have large fossil fuel reserves. These regions are unable to export as much as they used to without taking into account trade preferences and, as a result, use more fossil fuel domestically, thereby lessening the need for nuclear power. Adding preferences that limit fossil fuels, especially gas that has the lowest emissions of all the fossil fuels, also forces other low-emitting technologies into the electricity system, enhancing not only nuclear but also wind and solar power. Limiting the availability of fossil fuels also reduces the need for carbon storage. Therefore, policies promoting energy security can also lessen the technology risk stemming from uncertainties around large-scale implementation of CCS.

Setting preference levels on the amount of enriched uranium enhances trade and also the use of FBRs, but the effect on FBRs is much more pronounced when both the trade and enrichment criteria are activated. Yet the amount of plutonium can be reduced at low extra cost if concerns about reprocessing are taken into account. This is partially due to the fact that FBRs are used during the second half of the century, during which discounting makes costs less significant in the model's objective function. These results are also visualised in Fig. 4.[12]

The abatement cost (i.e., the difference between the scenario in which carbon emissions is not an active criterion and the climate scenario at 700 ppm CO_2-eq level) is 0.7 TUS$2005 (cumulative, discounted). This cost is increased by almost 60% by our trade preferences alone. Adding preferences about the amount of enrichment has only a small effect on cost, raising it by about 10%. Combining trade as well as enrichment preferences with reprocessing increases the abatement cost by almost 80%.

Having the same preferences regarding the amount of trade as in the less stringent climate case results in lower extra cost when the climate target is stringent, as shown in Table 5. In the more stringent case, most fossil fuel sources will be phased out anyway, and trade will thus consist mainly of biofuels, which lowers the total volume. Although nuclear power is still enhanced by trade limitations, the effect is much smaller. Setting preferences regarding the amount of enrichment has a similar effect on cost as preferences have on trade in the case of a stringent climate target; this is in contrast to a more moderate target, where the effect of enrichment is much weaker than that of trade. Another interesting difference is that it is enough to only include enrichment among active criteria to significantly enhance the use of FBRs instead of both trade and enrichment. This is because trade, which consists mainly of fossil fuels, is already limited by the climate constraint. Similarly, as the use of fossil fuels is already limited by emission preferences, the amount of carbon storage used is affected less by trade and enrichment preferences. These results are visualised in Fig. 5. In common with more moderate climate targets, lowering the

[12] Figs. 4 and 5 do not include the cost and emissions criteria. Their values do not vary significantly between the results presented in these figures; therefore omitting them improve the readability of the figures.

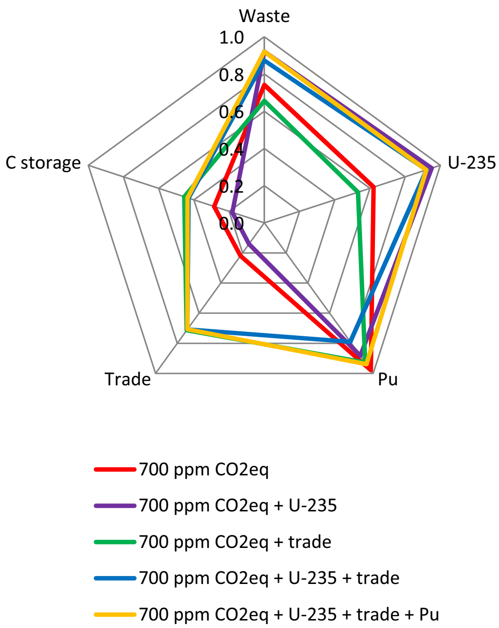

Fig. 4. Effect of different prioritisations of criteria at 700 ppm CO_2-eq level. The range between Utopia and Nadir values has been normalised, and Utopia and Nadir values have been assigned 1 and 0 accordingly.

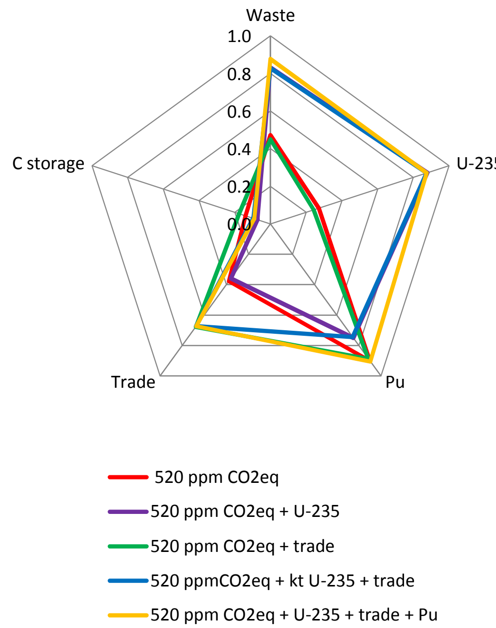

Fig. 5. Effect of different prioritisations of criteria at 520 ppm CO_2-eq level. The range between Utopia and Nadir values has been normalised, and Utopia and Nadir values have been assigned 1 and 0 accordingly.

production of plutonium can be accomplished without significant changes in other criteria values.

The abatement cost is about five times higher for the 520 ppm CO_2-eq target compared to the 700 ppm CO_2-eq target, reaching 3.8 TUS$2005. If preferences are put on trade and enrichment, then each results in a similar rise in cost that is much smaller than it is at moderate targets, amounting in effect to a 3—4% increase. Combining the two and adding reprocessing concerns by activating the Pu criterion raises the cost by 8%. These numbers are comparable to various other studies that have estimated the cost of phasing out nuclear [21,29]. It is important to keep in mind, however, that most of the previous studies investigate the cost of a total phase-out of nuclear power, whereas in our study nuclear power is merely limited. Moreover the abatement cost increase in our study is thus smaller than in the previous studies.

5. Discussion

5.1. Overview of the results

Investigating different prioritisations of climate indicates that much can be done to reduce emissions at almost no additional cost. Analysing in more detail what enables these emission reductions can provide valuable guidance for short-term policies. In the long term, however, substantial changes in the energy system are needed to significantly mitigate climate change.

Our results suggest that nuclear power can play an important role in climate change mitigation if energy security and affordability goals take precedence. This is especially pronounced when climate targets are stringent. However, including concerns about possible proliferation reduces the attractiveness of nuclear power considerably. The optimal amount of nuclear power in the system will strongly depend on decision makers' preferences, which may be different from those in the scenarios presented in this paper.

In addition to the need for climate policies, the future of FBR reactors depends strongly on the possibility of making reprocessing proliferation-resistant and therefore assigning less significance to this criterion. Even though FBRs may reduce the cost of achieving stringent climate targets, this cost is, in our opinion, relatively small and can thus easily be traded for reduced risk when concerns about proliferation are taken into account. However, one should bear in mind that as FBRs are used only in the second half of the century, their cost effect is dampened by discounting.

Focussing on stringent climate targets helps not only to fulfil energy security goals in our model but also to reduce the risk stemming from constructing carbon storage facilities. This outcome is due to reduced use of fossil fuels, resulting in synergies that diminish not only the majority of carbon needing to be stored, but also trade. Focussing on policies that limit the use of fossil fuels can thus have many important co-benefits.

Table 5
The effect of activating different criteria close to 520 ppm CO_2-eq level.

Criterion/Scenario	520 ppm CO_2eq	520 ppm CO_2eq + trade	520 ppm CO_2eq + U-235	520 ppmCO_2eq + kt U-235 + trade	520 ppm CO_2eq + U-235 + trade + t Pu	Unit
Cost	51.1	51.3	51.3	51.4	51.5	TUS$2005
Emissions	2670	2680	2680	2690	2690	$GtCO_2$-eq
Waste	13.3	13.8	4.3	4.4	3.2	Mm^3
U-235	109.9	114.1	19.5	20.1	20.2	kt of U-235
Pu	6.5	7.4	16.3	16.6	6.2	kt of Pu
Trade	13.9	8.6	14.2	8.7	8.7	ZJ
C storage	1420	1360	1530	1490	1500	Gt of CO_2

5.2. MCMA tool

The MCMA tool also offers an effective way for users without mathematical skills to conduct interactive multiple-criteria analysis. This is made possible by the interactive specification of preferences for each criterion in terms of pairs of values, namely Aspiration (A) and Reservation (R). This is an intuitive, robust, and effective approach to integrated analysis of models. We briefly justify these attributes below. The method is intuitive because the (A, R) pair is composed of the values that the user wants to achieve and to avoid, respectively. These values are specified in the units in which the criteria are defined; therefore the meaning of the (A, R) pairs is obvious to anyone who understands the meaning of the underlying variables, as is the interpretation of the range of criteria values defined by the Utopia and Nadir values.

The approach is robust because the (A, R) values can be specified freely: they need to conform to obvious requirements (i.e., to belong to the range defined by the Utopia and Nadir values). The MCMA always (i.e., for any specifications of [A, R] pairs) computes a Pareto-efficient solution. In particular, if the R value is too optimistic (i.e., cannot be achieved for all criteria simultaneously) then the computed Pareto solution is the closest to the goal specified by the R values.[13] We point out that a parametric optimisation with constraints specified by such R values would report that the problem is infeasible. If the A is too pessimistic (i.e., better values can be achieved for all criteria), then the computed Pareto solution is uniformly better.[14] The parametric optimisation for such cases returns dominated solutions.

The approach is effective because, for each specification of preferences, it provides a corresponding Pareto-efficient solution composed of attainable goals for the corresponding criteria. Obviously, for each problem one can specify an infinite number of attainable goals; only a small subset of them (still composed of infinite number of solutions) is Pareto-efficient, and thus worth analysing. An effective analysis will ensure that a manageable number of Pareto solutions are generated that are the best match to the preferences of the model users. Such preferences are defined by a sequence of the (A, R) pairs defined based on consideration of solutions obtained previously. In other words, the MCMA supports an effective learning process that aims to find realistic (i.e., attainable) reservation levels, and the corresponding aspiration level, the latter expressing implied relative priorities for improving criteria values above the reservation levels.

To conclude, the MCMA tool provides a significant improvement in multi-criteria model analysis compared with the traditional methods of parametric optimisation or criteria aggregation into a composite goal function.

5.3. Criteria

As with any other selection of criteria, our choices in this study have their limitations. Although discounted systems cost is widely used in energy—economy models as a criterion for energy affordability, it produces effects that must be discussed. Discount rates larger than zero tend to value the current generation's utility higher than that of future generations and they also put little weight on investments made in the long term (in 50 years or less depending on the applied discount rate). In our model, discounting the energy system cost also creates differences in dynamics among cost and other criteria that are not discounted. The costs (for meeting a given level of service demand) that occur toward the end of the modelling period count less than the costs at its beginning, whereas, for example, every tonne of enriched uranium produced counts the same no matter when it was produced.

The MESSAGE model calculates the cumulative carbon-equivalent emissions and this serves as the criterion representing global climate change. The effect of emissions on atmospheric carbon dioxide concentrations and subsequently on radiative forcing and temperature change is uncertain due to a number of important feedback loops in the Earth's carbon, ocean, and atmospheric cycles. These uncertainties are exemplified by the climate sensitivity parameter, for which different probability distributions exist [2]. Furthermore, the timing of emissions also has an effect. If all the carbon were to be emitted in one year, the resulting peak temperature would be significantly higher than if the same amount of carbon were emitted at a uniform rate over decades. Moreover, the build-up of CO_2 in the atmosphere is a cumulative problem with a certain amount of inertia in it. Emissions earlier in the century therefore matter more than emissions in later decades. By using cumulative emissions as our indicator, we fail to account for some climate system dynamics and complexities. Yet cumulative CO_2 emissions have proven to correlate well with future temperature rises; cumulative GHG emissions, although not quite so suitable, can also be used in energy system models [46].

The volume of nuclear waste per GWyr of electricity also depends on selected technologies. With better burnup, more energy in the same volume of fuel can be utilised and the volume of waste per GWyr of electricity therefore reduced. As our model does not include projections for improvements in technology, our results may overestimate the amount of waste produced in the future. Furthermore, nuclear waste is not only characterised by volume but also by radiotoxicity. The storage time can be reduced significantly, from 100,000 years to about 1,000, via reprocessing and removal of long-lived isotopes. This change is not currently reflected in our modelling, but we think its omission is justified, as even 1000 years is far beyond any current policy horizon.

Although proliferation is a serious concern with nuclear power, quantification on a regional or global scale is not easy. Most criteria that have been developed rely on characteristics associated with a national scale, and in general the decision to acquire nuclear weapons is viewed as a choice left up to individual regimes [25]. Using these indicators in our model may lead to situations in which all necessary conditions are present on a regional scale but not on a national scale, which we do not model. The amount of enriched uranium and plutonium can be used as simplified criteria but have several problems. Most importantly the location where the uranium is enriched or the spent fuel is reprocessed leads to different reactions on the part of the international community. France has been enriching uranium for decades without reprisals, but Iran's enrichment capability has incurred multiple rounds of international sanctions. In the current MESSAGE setup, enrichment is modelled as taking place at the global scale instead of regionally. This is meant to represent the current enrichment paradigm, where international oversight and safeguards prevail no matter where the enrichment occurs in the locational sense. The risk of proliferation is also lower when uranium is enriched or spent fuel is reprocessed in a few large plants instead of many small ones. With large plants, material flows can be monitored more easily, and also fewer people and countries will possess the reprocessing know-how. These aspects are, however, difficult to capture in a global scale model, even one like MESSAGE that is regionally disaggregated.

There is no universally agreed-upon definition of energy security or how to measure it. One of the most commonly used definitions that have been applied in the scenario literature focuses on import dependency (i.e., the sovereignty dimension). In particular, dependence on imported gas and oil is often referred to as a problem [42]. However, other considerable energy-security aspects can be relevant but are not captured by the trade criterion. For example, the criterion does not reflect the diversity of regional energy supply. A region can have no

[13] This interpretation is similar to the goal programming approach. However, the latter requires a specification of the distance measure (which in turn requires advanced mathematical skills) while the MCMA uses a scalarising achievement function parametrised by the (A, R) pairs specified by the users.

[14] In such cases the goal programming provides solution equal to the A point, which is not efficient.

imports but rely on a single energy source and therefore be vulnerable to price or technological changes. Nor does the criterion distinguish between imports from different regions. Therefore, if all imports come from one region, then it is possible that actual regional vulnerability is high even if the volume of imports is low. Similarly, the trade criterion does not take into account the robustness of the system, that is, how well the system can deal with extreme natural events or failures of energy infrastructure.

6. Conclusions

Global energy studies require comprehensive analysis of several criteria that are partly in conflict, partly synergetic. Interactive multi-criteria tools can thus help in the analysis of possible trade-offs and synergies among energy sources and technologies. Nuclear energy is a prime candidate for such an analysis and, given the diverging views on this technological option from the vantage point of different stakeholders, requires analysis in a holistic context. In this study we combined the MESSAGE model with a novel Multi-Criteria Model Analysis (MCMA) tool utilising an aspiration-reservation methodology of MCA. The main aim of this paper was to investigate the applicability of this approach to large-scale energy models. To assess the role of nuclear power we implemented seven criteria: energy affordability, climate change mitigation, energy security, CCS failure risk, proliferation risk due to enrichment and reprocessing, and radioactive waste creation.

The following conclusions can be drawn from our analysis:

- About a 20% reduction in cumulative GHG emissions compared to our baseline between 2010 and 2100 can be achieved by increasing the discounted energy system cost by 0.4%. However, to reach the 520 ppm CO_2-eq target with relatively high certainty (which implies cumulative GHG reductions of 64%), the cost for the energy system would increase by about 8%.
- Climate targets are needed to make nuclear power competitive at the modelled cost level. More stringent climate targets make nuclear power more competitive if waste and proliferation criteria have low priority.
- Nuclear power plays an important role in climate change mitigation if energy security and affordability goals take precedence.
- The optimal amount of nuclear power in the energy system depends strongly on the stakeholders' preferences.
- There is a significant synergy between climate mitigation and energy security goals related to reduced import dependency, as most energy trade consists of high-emission fossil fuels.
- Focussing on both climate-mitigation and energy-security goals lessens the need for CCS and therefore also of technology risk arising from the availability of underground carbon storage. This is because the majority of current energy trade consists of fossil fuels; limiting it or limiting emissions will thus reduce the use of fossil fuels and also the need for imports, and also storage of carbon.
- Taking into account the proliferation risk stemming from enrichment in combination with climate targets limits the total amount of nuclear power but enhances the use of FBRs. Assigning importance to limiting reprocessing as well, however, allows nuclear power to be reduced without significant changes in other criteria values.

We find that our method significantly improves the analysis of attainability of multiple simultaneous goals in large-scale energy-systems models. The approach is more intuitive and requires minimal mathematical skills on the part of the user. Our method also avoids infeasible or dominated solutions that are caused by the stringent constraints applied in parametric optimisation. The main difficulty of our approach is finding and implementing suitable indicators in a large-scale energy model; further developments are needed in this area.

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Appendix A. Cost components of light water reactor (LWR), fast breeder reactor (FBR) and mixed oxide (MOX) fuel nuclear cycles.

Process	Unit
Yellow cake conversion	10 $/kgHM
Enrichment	160 $/SWU
Fabrication of UOX fuel for LWR	250 $/kgHM
Fabrication of MOX fuel for LWR	2400 $/kgHM
Fabrication of breeder FR fuel	2400 $/kgHM
Reprocessing of spent UOX	1600 $/kgiHM
Reprocessing of breeder Fuel	3200 $/kgiHM
Geological disposal of spent UOX	396 $/kgIHM
Geological disposal of spent MOX	2640 $/kgIHM
Interim storage for UOX	200 $/kgiHM
Interim storage for MOX	200 $/kgiHM
Disposal of HLW from breeder	172 $/kgIHM

Appendix B. Power plant investment costs (in USD2005/kW). Min-max indicates the range across the eleven MESSAGE regions.

Technology	2005		2050		2100	
	min	max	min	max	min	max
Bio-hydrogen	1389	1716	1191	1203	1039	1039
Bio-hydrogen with CCS	1419	1752	1272	1334	1073	1073
Bio-liquids	1178	2025	945	1420	873	1227
Bio-liquids with CCS	1670	2194	1497	1670	1263	1343
Biomass powerplant	1354	1864	1315	1575	1263	1494
Biomass powerplant with CCS	2184	2698	2323	2420	2188	2188
Coal powerplant with CCS	2401	2966	2245	2276	2076	2076
Coal to hydrogen	802	991	657	668	596	596
Coal to hydrogen with CCS	823	1016	706	713	616	616
Coal to liquids	809	1372	912	1291	904	1241
Coal to liquids with CCS	822	1391	926	1308	918	1258
Fast breeder reactor	N/A	N/A	6068	6068	3673	5673
Gas to hydrogen	404	499	331	337	300	300
Gas to hydrogen with CCS	526	649	451	455	393	393
Gas to liquids	425	525	479	494	475	475
Gas to liquids with CCS	461	570	520	536	515	515
Geothermal powerplant	3008	3457	2933	2954	2835	2835
Hydropower plant	1758	3175	2177	3175	2267	3175
IGCC	1372	1695	1277	1280	1189	1189
IGCC with CCS	1986	2453	1889	1928	1731	1731
NGCC	424	565	421	426	401	401
NGCC with CCS	966	1194	928	948	854	854
Solar CSP powerplant w/o storage	3972	5665	2269	2871	2338	2481
Solar CSP powerplant w/storage	8465	12,207	4361	5522	4410	4670
Solar PV power	3157	3551	1243	1535	1065	1065
Standard coal powerplant	471	2213	922	1672	1000	1552
Standard gas powerplant	254	573	253	573	241	573
Standard nuclear powerplant	3575	6175	4953	4953	4643	4643
Wind powerplant	1523	1661	867	959	781	781

Unit: USD2005/kW.

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