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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.