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Endogenizing the probability of nuclear exit in an optimal power-generation mix model

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ABSTRACT

A major accident at a nuclear power reactor can lower public acceptance of this energy source and may result in a nuclear exit. This paper proposes an optimal power-generation planning model that deals explicitly with the costs involved in changing the power-generation mix due to a nuclear exit. The model introduces the probability of a major accident leading to a nuclear exit at a future time period as an endogenous variable, which is determined depending on the amount of nuclear power being generated during the preceding period. The proposed model is formulated as a stochastic programming problem that aims to minimize the expected value of overall power-generation costs computed with a weighted probability of every future state, branched according to a possible nuclear exit at each time period. An application of the model quantitatively implies that less nuclear dependency is optimal for a higher assumed frequency of a major accident per generated unit of electrical energy from nuclear—not only for the cost of direct damage from the accident, but largely because of the increased cost of overall power generation due to the subsequent nuclear exit. To put it differently, lowering the frequency of a major nuclear accident per reactor·year brings benefits exceeding the conventionally perceived effect of reducing an accident's direct damage. Lowering the major accident frequency to one per 10^6 reactor·years would free the optimal planning of future electricity supply from influence of an accident causing nuclear exit, if the geographical scale of the exit were limited to one-twentieth of the entire world.

1. Introduction

Nuclear power generation is acknowledged to be cost-effective and to involve lower life-cycle emissions of greenhouse gases than mainstream thermal power generation options. A literature survey has shown that the life-cycle emissions of greenhouse gases per unit of generated electrical energy from nuclear power generation are estimated to be lower than those from conventional coal-fired power generation by two orders of magnitude [1]. A specific evaluation study on the life-cycle emissions of carbon dioxide (CO_2) of Japanese light-water and fast breeder reactors concluded that the expansion of nuclear power generation is effective to reduce CO_2 emissions in the power sector [2]. Accordingly, some expect future increases of nuclear power generation in the effort to cope with the global need to mitigate the depletion of fossil fuel resources and the progress of climate change [3]. Nevertheless, the probability of a major accident occurring at a nuclear power reactor can never be completely nil.

A major nuclear accident with radioactive contamination causes two types of economic and environmental losses: the first is direct damage to those residing near the reactor, including health impacts and relocation costs, which are generally regarded as the impact of a nuclear disaster; the second type of loss involves the increase in the overall cost of the power supply, together with the cost of intensified emission of CO_2, due to the increased operation of fossil-fired power plants when operation of the nuclear reactor is suspended, even if temporarily, after the accident. Such nuclear suspensions can be prolonged, and may even evolve into a phase-out or permanent exit, depending on the tenor of public opinion. In fact, the 2011 Fukushima Daiichi nuclear

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accident inflicted the second type of loss on Japan as seriously as the first.[1] Moreover its effect has crossed international borders. For instance, as a result of the Fukushima accident, the German government decided to accelerate its abandonment of nuclear power generation [6].

There is a wide range of views regarding how much a major nuclear accident intensifies social pressure in favor of nuclear phase-out or exit. Siegrist et al. showed that the impact of the Fukushima accident on public opinion was limited [7]; Hayashi and Hughes indicated a similar result and argued that a fundamental shift in global nuclear generation policy resulting from the accident is quite unlikely [8]. A statistical analysis by Csereklyei regarding the impacts of the past two serious accidents at Three Mile Island in 1979 and Chernobyl in 1986 on the downward trend of nuclear plant installation revealed that the impact of the former accident was limited only to the United States while the latter accident had a global influence [9]. Joskow and Parsons, who formerly stated that "another significant accident at an existing nuclear plant anywhere in the world could have very negative consequences for any hope of a nuclear renaissance" [10], have claimed that the Fukushima accident would contribute to a reduction in the future nuclear expansion trend; however, this contribution has turned out to be very modest at the global level [11]. Pedraza expressed an extreme view that "if a new nuclear accident occur [sic] in the future in any nuclear power plant, then the use of nuclear energy for the generation of electricity will be excluded from the energy mix of all countries" after the Fukushima accident [12].

While it is uncertain how another major accident in the future would influence the use of nuclear energy in the power sector, the possibility of causing the above-mentioned second type of loss cannot be excluded. Were a nuclear phase-out or exit to occur after nuclear dependency has developed, our society would suffer a surge in electricity costs and increased CO_2 emissions; this is not favorable from a view point of sustainable development, especially if those impacts occur on a large scale. Given the public-goods characteristics of electricity and CO_2, it is important to examine the impact of the second type of loss potentially caused by another major accident on the desirable future evolution of the power-generation mix from a precautionary point of view. This examination would also help elucidate the effect of lowering the frequency of accidents per unit of generated energy by enhancing the safety of nuclear reactors to alleviate not only the first but also the second type of loss.

With this background in mind, this paper proposes a mathematical programming model with which to derive the optimal intertemporal path to a power-generation mix taking both types of losses into account, and presents an application of the model under tentative assumptions. Existing studies have evaluated each type of loss independently, as shown in the following review section. However, to the best of our knowledge, no study has attempted to demonstrate a cost-optimal power-generation model that considers an integration of the two.

The proposed model deals stochastically with a sudden nuclear exit in response to a major nuclear accident that potentially occurs at any time in the future. The probability of an accidental nuclear exit at each time period is introduced as an endogenous variable associated with nuclear power generation in the preceding period. It derives the future power-generation mix so as to minimize the discounted sum of the expected value of overall power-generation costs, calculated by weighting with the endogenized probability of a nuclear exit at each time period.

The remainder of the paper is structured as follows. Section 2 reviews past studies regarding power-generation planning that took the impacts of major nuclear accidents into account, and clarifies the difference between them and the present study. Section 3 introduces the formulation of the optimal power-generation mix model that endogenizes the probability of a nuclear exit proposed in this study. In Section 4, the assumptions and results of the first demonstration of the model are described. The results computed with the proposed model will be contrasted with those of a conventional model that does not consider a nuclear exit. Section 5 presents a selected sensitivity analysis that assumes variations of the crucial parameter settings. Finally, Section 6 summarizes the outcome and concludes by addressing the limitations of the study.

2. Brief literature review

The EC (European Commission) estimated the costs of direct damages caused by a major nuclear accident and associated radioactive contamination as a part of its ExternE project, aimed at assessing the external costs of energy [13]. It calculated the expected value of the nuclear accident-associated external cost per generated unit of electrical energy as the product of the estimated damage cost and the frequency of an accident per unit of generated nuclear energy.

Since the ExternE project was conducted as a pioneering work, many have attempted to assess the external cost of nuclear power generation and nuclear accidents. Recent examples include the following: Sheldon et al. evaluated the life-cycle environmental externalities of hydro and nuclear power plants including potential accidents in terms of replacement energy inputs [14]; Sovacool et al. assessed the property damage and human fatalities caused by accidents in each of 11 energy systems including nuclear power generation based on a statistical analysis of past accident cases [15]; Silva et al. estimated the cost per severe nuclear accident applying the methodology of probabilistic risk assessment [16]; and Rabl and Rabl showed that the cost of a major nuclear accident could be one order of magnitude greater than the estimates of the ExternE project as the accident-oriented displaced population might be very large depending on the nuclear reactor site [17]. Hughes has attempted to deal with the rather indirect impacts of an accident [18]. He provided a framework with which to evaluate the impact of various events and their durations on the resilience and adaptation of energy systems, though he has as yet presented no quantitative evaluation of a nuclear accident.

Some energy modeling studies have assessed the cost-optimal energy supply system structure taking the above external costs into account. A typical example is a study by Rafaj and Kypreos [19], which added the external costs of accidents, air pollution, climate change, and other burdens to the ordinary private costs of various power-generation options in their MARKAL-type global energy system model to derive the power generation mix that minimizes the sum of private and external costs. Similar studies include the following: de-Llano Paz et al. took into account the external costs in an electricity best-mix model based on the portfolio theory considering the variability of technology costs [20]; Kosugi et al. internalized the monetary values of several environmental loads calculated based on a Japanese life-cycle impact assessment as the

[1] The accident at the Fukushima Daiichi nuclear plant triggered the suspension of almost all nuclear power stations for several years in Japan, leading to an increase in the overall electric-power supply cost. The cumulative cost increase over the four years up to the end of 2014 fiscal year was estimated to be 12.7 trillion JPY (Japanese yen), approximately 110 billion USD (United States dollars), according to the Agency for Natural Resources and Energy [4].

As for the direct damage cost due to the accident, admitting the great difficulty of its estimation, compensation for damages paid by the Tokyo Electric Power Company to victims evacuated from their homes in the area surrounding the nuclear plant may give a reference value. As of 27 November 2015, the cumulative total amount of compensation was 5.73 trillion JPY, equivalent to approximately 50 billion USD [5].