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Original Article

INTEGRATED SOCIETAL RISK ASSESSMENT FRAMEWORK FOR NUCLEAR POWER AND RENEWABLE ENERGY SOURCES

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A B S T R A C T

Recently, the estimation of the social cost of energy sources has been emphasized as various novel energy options become feasible in addition to conventional ones. In particular, the social cost of introducing measures to protect power-distribution systems from power-source instability and the cost of accident-risk response for various power sources must be investigated. To account for these risk factors, an integrated societal risk assessment framework, based on power-uncertainty analysis and accident-consequence analysis, is proposed. In this study, we applied the proposed framework to nuclear power plants, solar photovoltaic systems, and wind-turbine generators. The required capacity of gas-turbine power plants to be used as backup power facilities to compensate for fluctuations in the power output from the main power source was estimated based on the performance indicators of each power source. The average individual health risk per terawatt-hours (TWh) of electricity produced by each power source was quantitatively estimated by assessing accident frequency and the consequences of specific accident scenarios based on the probabilistic risk assessment methodology. This study is expected to provide insight into integrated societal risk analysis, and can be used to estimate the social cost of various power sources.

1. Introduction

After the Fukushima Daiichi nuclear power plant (NPP) accident, the Japanese government published a report in which the unit electricity generation costs of various power sources are estimated [1]. This report suggests that the unit value of nuclear power generation will be 8.9 yen/kWh (11.4 U.S. cents/kWh), including the social cost of 1.6 yen/kWh (2.0 U.S. cents/kWh), by the year 2020. Regarding renewable energy, by the year 2020, the unit value of onshore wind power is estimated to reach 9.3–17.3 yen/kWh (11.9–22.2 U.S. cents/kWh) and that of residential solar power generation is estimated to reach 12.0–13.9 yen/kWh (15.4–17.8 U.S. cents/kWh); whereas the social cost of wind-turbine generators (WTGs) and solar

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photovoltaic (PV) systems is estimated to be 0 yen/kWh. The additional expenditure of providing measures to protect the power-distribution network from power-source instability and that of accident-risk response for renewable energy sources were not considered; however, these social costs must be considered for proper electricity generation cost estimation.

In general, solar PV systems and WTGs are considered to be intermittent energy sources, whose power output is not continuously available because of certain external factors that are outside direct control. The effective use of such intermittent energy sources in an electric power grid for utility purposes usually relies on the use of backup power to compensate for the irregular fluctuations in output from the intermittent sources. When one considers the external cost of additional backup power installations to compensate for the deficiencies in the energy supplied by various sources, the electricity generation cost can increase, depending on the performance or reliability of each source.

In terms of the cost of accident-risk response, concerns have been raised regarding the potential public risks of not only NPPs but also WTGs and solar PV systems. The primary concern regarding NPPs is that radioactive fission products may be released into the environment and may pose a radiation hazard to the adjacent public in the case of a severe accident scenario [2]. Although renewable energy sources generally appear to generate no potential hazards, several studies have highlighted the potential risk of an accidental fire in a PV array theoretically releasing toxic substances into the environment, and turbine blades can be thrown to nearby sites in the case of blade-failure accidents in WTGs, endangering anyone living near the wind farms [3,4].

To account for these risks in the estimation of the social cost of various power sources, an integrated societal risk assessment framework for NPPs, WTGs, and solar PV systems, based on power-uncertainty analysis and accident-consequence analysis, is proposed in this paper. For the power-uncertainty analysis, the deficiencies in power output caused by the inadequate performance of a given power source are assumed to be compensated for through the immediate use of gas-turbine power plants. For the accident-consequence analysis, various possible accident scenarios were considered, including a hypothetical NPP accident, a fire-related incident within a solar PV system, and the whole-blade failure of a utility-scale wind turbine. This study is expected to provide insights into integrated societal risk analysis and will be used as the basis for estimating the social costs of various energy sources.

2. Proposed framework

2.1. Power-uncertainty analysis

This study looks at a hybrid energy system consisting of a main power source, in combination with auxiliary gas-turbine power plants as the backup power source, to supply electricity when the main power source does not generate sufficient energy to satisfy the load demand, or is not available during outage periods. The required annual production of the hybrid energy system can be calculated as the sum of the actual annual power output of each power source and the required annual power output from the gas:

$$W_r = \mu_i C_{p,i} W_i + W_g \tag{1}$$

where W_r is the required annual energy production of the hybrid energy system, W_g is the required annual power output from the gas turbines, and μ_i, $C_{p,i,}$ and W_i represent the availability factor (AF), capacity factor (CF), and rated annual energy output of the main power source, respectively. To ensure a reliable supply from this system, the annual production of the hybrid energy system must be equal to the rated annual power output of the main power source, and thus the annual power production required of the gas turbines that must be installed can be derived as follows:

$$W_r = W_i \tag{2}$$

$$W_g = (1 - \mu_i C_{p,i}) W_i \tag{3}$$

Using Eq. (3), the electricity generation cost can then be derived as the sum of the yearly electricity generation cost of the main power source and the yearly electricity generation cost of the required gas turbines, divided by the annual rated power production of the energy source

$$c_i = \frac{c_{e,i} W_i + c_g W_g}{W_i} = c_{e,i} + c_g \frac{W_g}{W_i} = c_{e,i} + c_g (1 - \mu_i C_{p,i}) \tag{4}$$

where c_i is the electricity generation cost of the main power source, $c_{e,i}$ is the conventional electricity generation cost estimates of the main power source, and c_g is the electricity generation cost of the gas turbines. Therefore, the performance indicators, such as CF and AF, of the main power source must be analyzed to estimate the external cost for additional gas-turbine installation, based on Eq. (4). The CF is defined as the net actual generation (NAAG) that is produced by a generating unit in a given period as a fraction of the net maximum generation (NMG) [5].

$$\mathrm{CF} = \left(\frac{\mathrm{NAAG}}{\mathrm{NMG}} \right) \times 100\% \tag{5}$$

where the NAAG is the energy that is generated by a unit in a given period and the NMG is the energy that could be produced by the unit in the given period if it were to operate continuously at maximum capacity. The AF is defined as the fraction of a given operating period in which a generating unit is available without any outages [5]:

$$\mathrm{AF} = \left(1 - \frac{\mathrm{POH} + \mathrm{UOH}}{\mathrm{PH}} \right) \times 100\% \tag{6}$$

where the planned outage hours (POHs) are the number of hours for which a unit is in a standard or extended planned outage state. The unplanned outage hours (UOHs) are the number of hours a unit is in a Class 0, Class 1, Class 2, or Class 3 or in maintenance outage states, whereas the period hours (PHs) are the number of hours a unit is in the active state.

2.2. Accident-consequence analysis

In this study, to quantitatively assess the consequences of various accident scenarios, the public health risk was