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Socioeconomic costs of replacing nuclear power with fossil and renewable energy in Taiwan

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ABSTRACT

Economic analysis is essential for developing sustainable energy, especially low-carbon nuclear and renewable energy. Therefore, this study attempted to provide a comprehensive evaluation on the social costs of nuclear, coal, gas, solar photovoltaic and wind energy in life cycle aspect, and compared these results with the European and Japanese estimates for verification. The atmospheric dispersion simulation results show that a cumulative effective dose of radionuclides equal to the radionuclides released during the first 19 days of the Fukushima Daiichi disaster would exceed the regulatory limit of 1 mSv/year for part of the residents living near the sites. The results of meta-analysis of life cycle social costs show nuclear power has the lowest private costs among all energy. Regarding external costs, only wind energy is competitive with nuclear in most cases. Moreover, replacing Nuke No.1–3 with coal and gas would cause an estimated 460 and 255 premature deaths annually, respectively, totaling 715 life losses per year in Taiwan. In sum, with decreasing land carrying capacity by population growth, the environmental and social-economic feasibility of energy development need further assessment with respect to the international protocols for sustainable development goals and climate change mitigation targets.

1. Introduction

Many studies have discussed whether nuclear power is a viable economic option for fulfilling the urgent need of climate change mitigation [1–3]. Several studies have claimed that nuclear power would not only help to mitigate climate change, but would also help to prevent air-pollution-related health costs [4,5]. Despite that fact, presumably due to “nimby” effect, most people are opposed to any type of generation. Anti-nuclear petitions are common in Taiwan, particularly after the Fukushima accident since, like Japan, Taiwan is located in the Pacific Rim where earthquakes frequently occur. Construction of the Lungmen nuclear power plant (a.k.a. Nuke No.4) began in 1999 under much disputation. After Taiwan's first party alternation in 2000, the anti-nuclear ruling party announced to stop the project and lead to code a “nuclear-free homeland” target in the Environment Basic Law in 2002. In Taiwan, two nuclear power plants, Jinshan (Nuke No.1) and Kuosheng (Nuke No.2), are currently operating within 30-km radius of the most populous Taipei Metropolitan center. Moreover, the reactor at Lungmen is located only 40-km away from homes of 5 million residents in capital city. In 2015, under the pressure of anti-nuclear public opinion, the government announced that Nuke No.4 would be put in safe storage for 3 years until 2017, and its operation would need referendum agreement. In 2014, three operating nuclear power plant generated 40,801 GWh, accounting for 18.61% of total annual electricity generation of 219,200 GWh. The “gradually reduce nuclear” policy would be implemented by decommissioning the currently operating Jinshan, Kuosheng, and Maanshan nuclear power plants, *i.e.*, Nuke No.1~3 at their 40 years of design lifetime and it will not be postponed. That is, six nuclear reactors would stop generating electricity after 17 May 2025. Facing nearly 40,000 GWh/year of electricity gap in the future, more power generation from coal, natural gas, or renewable energy are necessary to meet the energy demand for social and economic

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development.

Nuclear radiation contamination is perceived as persistent environment pollutant like the "century poison" dioxin, which also cause mutation on offspring for generations. Compared to externalities, the severity of an accident has a greater effect on public opinion. Therefore, it is important to reveal not only the externalities associated with energy production at normal operation phase but the probability and consequence of energy accidents to stand for a sustainable energy policy and to elevate public agreement. A nuclear accident like that in Fukushima Daiichi station, Japan, after an earthquake-induced tsunami on March 12, 2011 could release large amounts of radioactive materials, which could be more serious than the Chernobyl accident in 1986, causing substantial damages to the society and environment. However, few studies detailed the methodology for quantifying potential impacts associated with radiation exposure due to nuclear accidents. Itsubo & Kubo used the chemical dispersion model CMAQ to simulate dry and wet depositions and atmospheric concentrations of cesium-137 (^{137}Ce) and Iodine-131 (^{131}I) during March 12–29, 2011 [6]. The grid-level estimates of the losses of disability-adjusted life year (DALY) for excess cancers associated with acute inhalation exposure to ^{131}I and ^{137}Ce were calculated for the first 18 days after the Fukushima Daiichi accident.

Life cycle impact assessment (LCIA) is currently the best method of quantifying externalities arising from human activities, especially for the carbon footprint and greenhouse gases (GHG) emission. The European Commission and the US Department of Energy jointly performed the ExternE project to assess the external costs of electricity generation in a life cycle aspect. The ExternE results are often used for comparison in various studies of the external costs of energy. Moreover, the Atomic Energy Commission of Japan (JAEC) claimed that the cost of nuclear power generation should include the additional costs of accident risk [7]. The ExternE results show that, assuming a core melt probability of 5E-5 per reactor year, the costs of a nuclear accident are relatively low ($0.15/MWh) [8]. This risk values are broken down into the valuation of health effects, food bans, and evacuation and relocation of local residents based on the estimates for the Chernobyl accident. Compared with accidents involving other energy sources, nuclear accidents have relatively low fatalities but have the highest economic costs (41% of all property losses due to major energy accidents worldwide) [9].

A major goal of the "National Vision for the Golden Decade" project launched in 2011 is to achieve sustainable development by creating a low-carbon society and restoring natural environment have become the basis of public movement in Taiwan. The "Renewable Energy Development Act" promulgated in June 2009 put feed-in tariffs (FIT) as economic incentive in practice. On July 1, 2015, Taiwan promulgated the "Greenhouse Gas Emission Reduction and Management Act", stipulated a GHG reduction target to reduce emissions to lower than 50% of the 2005 level by 2050, that is 35 years later. Achieving this goal would require a rollback from 269 million $mtCO_2e$ in 2005 to 134.5 $mtCO_2e$, the emission level in year 1991. Moreover, in response to the Lima call for climate action in 2014, Taiwan has submitted its intended nationally determined contributions (INDC) to reduce GHG emissions by 20% compared to the 2005 level or to be lower than the 2000 level (227 $mtCO_2e$) by 2030 in August 2015. Co-benefit analyses of the energy sector indicate that air pollutants and GHG can be significantly reduced by clean energy development and energy conservation [10,11]. However, the social-economic effects, including private and external costs, of nuclear electricity have seldom been quantified and compared with other energy sources.

The aim of this study was to quantify and compare the monetary values of social costs for the most commonly used energy sources in the world, specifically, the cost of nuclear energy. The lifecycle emission factors of GHG and four criteria air pollutants (CAPs), PM_{10}, SOx, NOx, and CO for nuclear, solar photovoltaic (PV) and wind energy were drawn from literatures and used to estimate the emissions of fuel cycle from cradle to grave. After deriving empirical emissions factors for the domestic coal and gas plants at operation phase, this study used the atmospheric dispersion model (AERMOD) to simulate atmospheric concentrations of CAPs from fossil-fired power plants and radionuclides from a nuclear accident. Moreover, a surrogate radionuclide release rate derived from estimates for the Fukushima Daiichi accident were entered in the AERMOD to simulate the radiation exposure level of the residents around the power plant. Excess cancer cases associated with radiation exposure were estimated and health costs for cancer treatment were monetized considering a world average probability of nuclear disaster. Furthermore, the estimation results of external costs were incorporated with geographic information system (GIS) software ArcGIS to generate grid maps of population-weighted external costs. Additionally, private and external costs of energy calculated in this study were compared those reported in other studies. Finally, the analytical results were discussed for the policy implications on future energy development.

2. Methodology

2.1. Research framework

The social-economic costs of energy include both private costs and external costs. The former includes capital cost, operation and maintenance costs, and fuel cost. These costs can represent as levelized cost of electricity. The levelized cost (C_{Lev}) of coal, natural gas, and nuclear is calculated as

$$C_{Lev} = \frac{C_{cap} + C_{run}}{E} \times \frac{r}{1 - (1 + r)^{-n}} \quad (1)$$

where C_{cap} denotes capital cost (US$ kW^{-1}); C_{run} represents running cost (US$ kW^{-1}); E is per unit electricity generation by source (kWh kW^{-1}), which was 6300 for coal, 6000 for natural gas, and 7800 for nuclear; r denotes private discount rate, which is set to 5%; and n represents lifetime of electricity facilities (yr), which is set to 30 years in average.

For renewable energy, the Taiwan government has already calculated a levelized cost for each energy type as fixed feed-in tariffs (FIT) to be paid by the state-owned power wholesaler Taiwan Power Company (Taipower) over a 20-year period after it is connected to their electricity grid. For PV in 2014, the average FIT rates is $0.16/kWh. For onshore wind, the FIT is $0.272/kWh for 1 $kW_{capacity}$ to <10 $kW_{capacity}$ and $0.088/kWh for ≧10 $kW_{capacity}$.

For nuclear power, according to the Taipower official statistics, the unit running costs for nuclear power in 2012 was $24/MWh, including fees for depreciation (8%), fuel (22%), operation & maintenance (46%), and so-called "backend fund" for nuclear waste disposal (24%) [12]. Adding the running cost of $24/MWh and the average capital costs of $11.7/MWh for Nuke No.1~4 derived the internal cost estimate of $35.7/MWh.

The external costs of electricity generation include the health impacts via inhalation of life cycle emissions of air pollutants and the social cost of carbon in this study. Another cost specified for nuclear power is the accidental release of large amounts of radiation, which is a major public concern. Because the health impacts from air pollution, climate change, and a nuclear accident have very different time horizons, this study avoided discrimination on the valuation of life for current and future generations by applying a social discount rate of zero in estimates of external costs.

Fig. 1 illustrates the methodology applied to quantify the