



South Korean energy scenarios show how nuclear power can reduce future energy and environmental costs



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HIGHLIGHTS

- Nuclear power has a key role to play in mitigating greenhouse-gas emissions.
- The Greenpeace scenario has higher total external cost than the nuclear scenarios.
- The nuclear-centred scenarios offer the most sustainable option for South Korea.
- The similar conclusions are likely to apply to other Asian countries.

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ABSTRACT

South Korea is an important case study for understanding the future role of nuclear power in countries with on-going economic growth, and limited renewable energy resources. We compared quantitatively the sustainability of two 'future-mapping' exercises (the 'Governmental' scenario, which relies on fossil fuels, and the Greenpeace scenario, which emphasises renewable energy and excludes nuclear power). The comparison was based on a range of environmental and technological perspectives, and contrasted against two additional nuclear scenarios that instead envisage a dominant role for nuclear energy. Sustainability metrics included energy costs, external costs (greenhouse-gas emissions, air pollutants, land transformation, water consumption and discharge, and safety) and additional costs. The nuclear-centred scenarios yielded the lowest total cost per unit of final energy consumption by 2050 (\$14.37 GJ⁻¹), whereas the Greenpeace scenario has the highest (\$25.36 GJ⁻¹). We used probabilistic simulations based on multi-factor distributional sampling of impact and cost metrics to estimate the overlapping likelihoods among scenarios to understand the effect of parameter uncertainty on the integrated recommendations. Our simulation modelling implies that, despite inherent uncertainties, pursuing a large-scale expansion of nuclear-power capacity offers the most sustainable pathway for South Korea, and that adopting a nuclear-free pathway will be more costly and produce more greenhouse-gas emissions.

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1. Introduction

Global anthropogenic greenhouse-gas emissions exceeded 45 Giga tonnes of carbon dioxide equivalent (Gt CO₂-e) in 2009, and the energy sector emitted about 69% of those emissions (World Resources Institute, 2013). Decarbonising the energy sector is thus the most effective and important approach for reducing society's total emissions. However, in many countries with high population density such as South Korea (509 people km⁻²), India (406 km⁻²), Japan

(350 km⁻²), Vietnam (280 km⁻²), United Kingdom (257 km⁻²) and Germany (235 km⁻²), renewable energy resources are insufficient to provide all or even most of their total final energy consumption (MacKay, 2008; World Resources Institute, 2013). Moreover, continued economic growth in Asian countries that currently relies on fossil fuels will increase their energy consumption (Chen et al., 2007) and their future greenhouse-gas emissions. South Korea has been experiencing all these aforementioned conditions – high population density, insufficient renewable energy resources and rapid economic growth – so it represents an ideal case study to quantify the most sustainable future energy mixes under such constraints.

The South Korea Ministry of Knowledge and Economy released the *Sixth National Electricity Generation Plan* in February 2013, which included a projected need for an additional electricity-generating

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capacity of 21 GW of coal, 12 GW of liquefied natural gas and 15 GW of nuclear power by 2027, including facilities currently under construction (The Ministry of Knowledge and Economy, 2013a). This is the baseline (default) plan for the future of electricity generation in South Korea. In March 2012, Greenpeace also published a South Korean version of their *Energy Revolution* template report (done now for many countries), which proposed to phase out nuclear power by 2030 and reduce fossil fuel-power supply substantially (Greenpeace Korea, 2012). The Greenpeace plan is the only published future energy-generation plan that insists on a nuclear-free and renewable-centred energy system in South Korea. While the government Plan did not appear to weight environmental issues such as climate change or long-term sustainability seriously, given its emphasis on an on-going and dominant role for high-carbon fossil sources (coal and gas), the Greenpeace plan failed to appreciate the real-world physical limits of renewable energy in South Korea (Hong et al., 2013a). Neither did the Greenpeace plan quantify the negative impacts of renewable energy, including greenhouse-gas emissions from bioenergy consumption (Yoon et al., 2010), land transformation for bioenergy production and wind power (Costanza et al., 1997), balancing costs of intermittent renewable sources (Albadi and El-Saadany, 2010), or additional transmission and other system costs for non-traditional electricity grids that deploy non-dispatchable power sources at high penetration (Dale et al., 2004; Milborrow, 2001; OECD/Nuclear Energy Agency, 2012). In essence, both the divergent government and Greenpeace plans appear to have major problems in delivering practical outcomes for environmental sustainability.

After the 2011 Fukushima-Daiichi nuclear accidents in Japan (Hong et al., 2013b), the previous Japanese government suggested the possibility of a future nuclear-free pathway, but recent quantitative analysis has shown that this would increase negative environmental, economic and social impacts for the country (Hong et al., 2013b) and the 2013 incumbent government has backed away from such proposals (Warnock, 2013). In February 2013, the World Health Organization published a report on the results of a detailed health-risk assessment from the Fukushima-Daiichi nuclear accidents (World Health Organization, 2013). The report concluded that, despite widespread public anxiety, the potential dangers to and long-term health impacts on the general populace of the Fukushima region and beyond will remain negligible. Prior to the crisis, 94.2% of Korean survey respondents accepted that South Korea required nuclear power; after the nuclear event (about two months later), this support had dropped, but by less than 20% (to 74.8%) (Lee, 2011b). This majority support persisted despite regular petitions against nuclear energy by some environmental-advocacy organisations and the media (Tan, 2013). Moreover, independent studies have repeatedly shown that to reduce greenhouse-gas emissions globally by mid-century, nuclear power is one of the only effective mitigation options that are currently technically and economically feasible to deploy at a large scale (Brook, 2012; Kharecha and Hansen, 2013). An economic, scientific and environmental rationalist must therefore consider the important role of nuclear power in South Korea's future (Jeong et al., 2010).

In this paper we used a range of independent, deterministic external cost metrics, coupled with probability simulation modelling, to compare transparently and objectively the economic and environmental implications of the South Korean government scenario (The Ministry of Knowledge and Economy, 2013a) with the Greenpeace *Energy Revolution Plan* (Greenpeace Korea, 2012). For further differentiation, we added two scenarios that model higher penetrations of nuclear energy: an 'environmentally conscious' mix and a nuclear-intensive future. Our results show that based on economic, environmental and social grounds, nuclear energy deserves a prominent role in reducing greenhouse-gas emissions in South Korea. Understanding the real-world physical and economic limitations of renewables and the potential role of large-scale nuclear power (or, alternatively, the impacts of a nuclear-free pathway) in South Korea is key to

understanding the energy-related issues in many other countries with high population density and substantial projected economic growth.

2. Methods

2.1. Production and consumption

A realistic scenario must rest upon plausible assumptions of future changes before analysing energy production and consumption mixes. For this evaluation, we projected that the South Korean population will increase until 2030 (from 49 million in 2010 to a peak of about 52 million people), then reduce gradually through to 2050 (to 48 million), whereas the nominal gross domestic product (GDP) will rise consistently until 2050 (from \$20,532 per capita in 2010 to \$69,286 in 2050) (Korean Statistical Information Service, 2013; The Ministry of Knowledge and Economy, 2013a; The World Bank, 2013). All scenarios we map in this paper considered currently operating or under-construction technologies along with possible (near-commercial) future technologies (International Energy Agency, 2012). These new technologies included the next generation of utility-scale nuclear fission power plants, small modular reactors, hydrogen production from nuclear power, larger and deeper-anchored offshore wind power turbines (> 5 MW and > 30 m), conventional and enhanced (engineered) geothermal power, ocean power other than tidal power (wave and current power), and advanced fuel cells. Further, a smart grid in South Korea will be deployed regionally by 2020, and nationally 2030, if the *Sixth National Electricity Generation Plan* is followed (The Ministry of Knowledge and Economy, 2013a). Plug-in hybrid vehicles and hydrogen (fuel-cell) vehicles will start to increase market penetration by 2020 (The Ministry of Knowledge and Economy, 2013a). The associated increase in grid-distributed batteries and smart-energy-conservation technology should allow the intermittency of renewable energy sources to be managed more smoothly than is possible at present (Ipakchi and Albuyeh, 2009). We are aware that carbon-capture-and-storage (CCS) might also assume an important role in the future (Scott et al., 2013). However, we did not consider carbon-capture-and-storage in our calculations because it is not commercially available at scale, it requires a price on carbon emissions to be viable compared to non-CCS plants (Hamilton, 2011; Lenzen, 2010; Rubin et al., 2007), and it still possesses a series of major barriers in South Korea (Chae and Kwon, 2012).

The projected fuel price for fossil fuels (coal \$1.9–5.3 GJ^{−1}, gas \$10.7–16.3 GJ^{−1}, and oil \$15.9–29.0 GJ^{−1}) and nuclear power (\$0.5–1.1 GJ^{−1}) followed the median values of the predictions by The Department of Energy and Climate Change UK (2012), and other international organisations (International Energy Agency, 2012; International Energy Agency and OECD Nuclear Energy Agency, 2010). The per-energy-unit capital cost and operation and maintenance costs of the various technologies tend to decrease as installed capacity increases (International Energy Agency and OECD Nuclear Energy Agency, 2010); however, the long-term fuel-price and damage-cost projections involve considerable guesswork. We thus constructed a probability simulation to account for this uncertainty to provide explicit bounds for the projected costs of each scenario. We assessed the domestic sustainability of each energy-production option for South Korea using external cost methodologies (Roth and Ambts, 2004).

2.2. Scenarios

We used both final energy consumption and electricity-generation-by-source to model different energy-mix scenarios (the government plan, the Greenpeace scenario, an environmentally conscious nuclear scenario, and a nuclear-intensive scenario) (Figs. 1 and 2). The four scenarios represented different 'opinions' and policy

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