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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.

1. Introduction

Global anthropogenic greenhouse-gas emissions exceeded 45 Giga tonnes of carbon dioxide equivalent (Gt CO_2-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 Ambs, 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

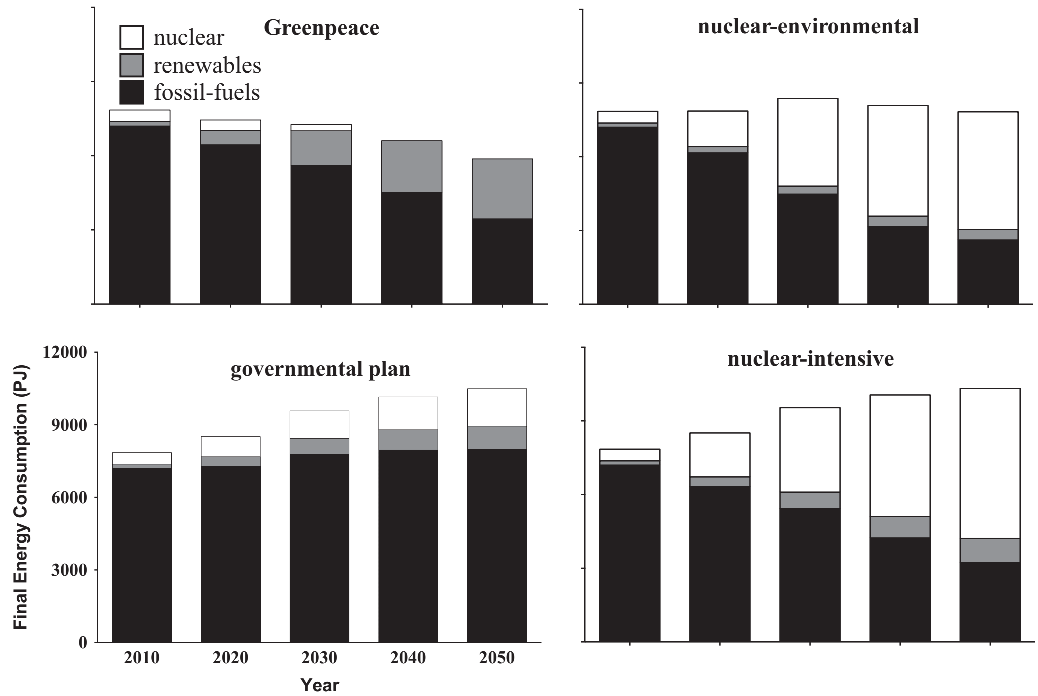

Fig. 1. Total final energy-consumption mixes (principally industrial heat, electricity and transport) of four proposed scenarios (Greenpeace: low demand and nuclear-free; environmentally conscious nuclear: moderate demand and high nuclear share; nuclear-intensive: high demand and high nuclear share; government plan: high demand and low nuclear share) analysed herein between 2010 and 2050 (*y*-axis: final energy consumption (PJ), *x*-axis: projection per decade. Energy provision categorised as: renewables: solar, onshore and offshore wind, ocean, hydro and geothermal power; fossil-fuels: coal, gas and oil).

'perspectives' that could influence the choice to implement particular technologies beyond what a strictly empirical judgment would dictate. To compare the influence of different energy sources on the total costs, we added an auxiliary scenario: the nuclear-low-demand scenario.

The government plan was derived from the official *Sixth National Electricity Generation Plan* (The Ministry of Knowledge and Economy, 2013a), the Greenpeace *Energy Revolution* template (Greenpeace Korea, 2012) and the *First National Energy Plan* (National Energy Commission of Korea, 2008) for South Korea. It assumed that the demand-side management of the Sixth National Electricity Generation Plan will be achieved successfully, but the current increasing trends in final energy (from 7849 PJ in 2010 to 10490 PJ in 2050) and electricity consumption (485 TW h in 2010 to 856 TW h in 2050) will continue. To support the increased final energy consumption in this scenario, the Plan suggested that South Korea will rely on further expansion of fossil fuels (gas, oil and coal) and nuclear energy. Fossil fuels will produce 76% of final energy consumption in 2050 (compared with 91% in 2010).

The Greenpeace scenario was a contrasting future vision, with energy consumption assumed to decline continuously until 2050 to 5870 PJ, via the envisaged deployment of energy-conservation and energy-efficiency measures, irrespective of population and GDP increases and industrial needs. Notably, the scenario aimed to phase out nuclear power by 2040, which is a zero-emission power source on the generation side, and replaced most of the energy supply gap with renewables. However, Greenpeace underestimated the current state of coal consumption, and so here we modified the scenario using the correct statistics for South Korea (Korean Statistical Information Service, 2013). The Greenpeace plan will derive 62% of its electricity generation from intermittent sources (wind and solar power), and 58% of total energy consumption from fossil fuels (coal, oil and gas) in 2050. To achieve these targets, the transportation sector and the industrial sector will need to reduce energy consumption by 34% and 38%, respectively, of 2010 levels by 2050. This will require not only energy efficiency and lower utilisation, but also substantial structural changes in the industrial and other sectors.

In contrast, our environmentally conscious nuclear scenario stipulated that total final energy consumption will rise until 2030 (8581 PJ) given our projected increases in the population and GDP, but after 2030, a declining population and greater energy efficiency will lead to a small reduction in final energy consumption (down to 7829 PJ in 2050). This scenario replaces virtually all fossil-fuel sources with nuclear power, generating 84% of the electricity, and 97% of the heat consumption in 2050. Oil produces a small share of the total final energy consumption ($<30\%$) for mostly non-energy consumption and transportation, and natural gas provides about 7% of the electricity in 2050.

Our nuclear-intensive scenario followed the total final consumption of the government plan, whereas it closely mirrored the fossil-fuel reductions of the Greenpeace scenario. Here, nuclear power should fill the entire gap between decreasing fossil-fuelled energy production and increasing consumption. Electricity (34%) and heat (32%) sources, including heat from industrial nuclear power plants, will be the major energy forms required in 2050. Nuclear power will provide 84% of the electricity, and 88% of the heat in 2050, with an accelerated expansion of nuclear capacity after 2030.

Finally, the nuclear low-demand scenario followed the total final consumption of the Greenpeace scenario, and it paralleled the final energy-supply mix and electricity-generation mix of the nuclear-intensive scenario (Appendix A). The scenario thus excluded the effect of energy-consumption trends, and it contrasted the effectiveness of different energy-generation options.

2.3. External cost analyses

To evaluate energy or electricity networks, the multi-criteria decision-making analysis (MCDMA) method has been used widely (Hong et al., 2013a, 2013b; Wang et al., 2009). This method has

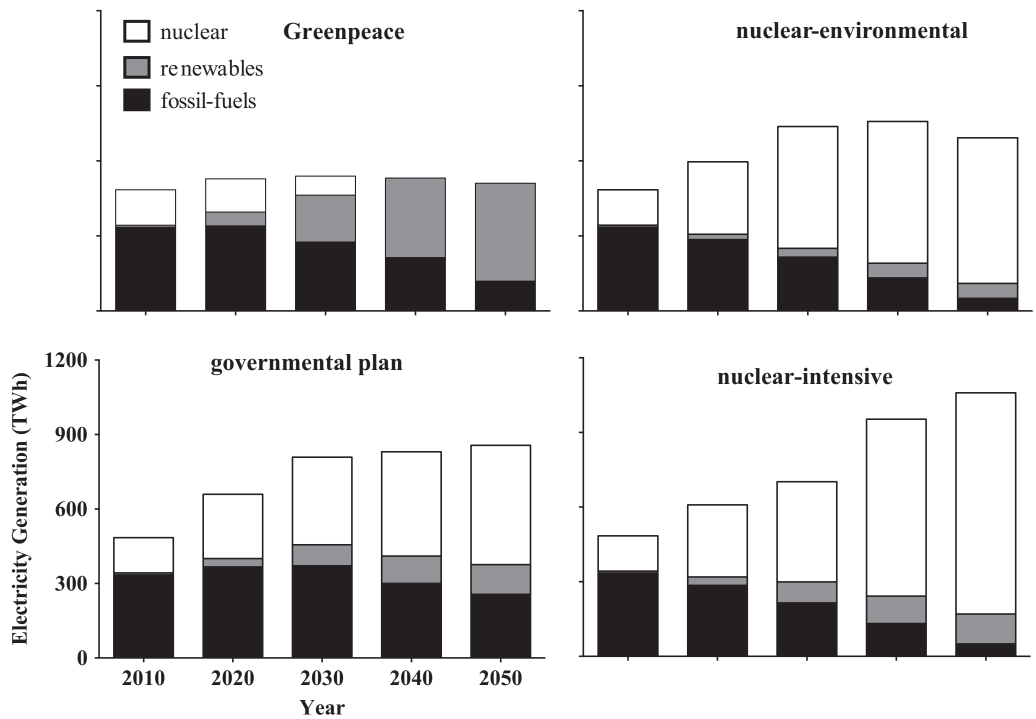

Fig. 2. Electricity-generation mixes of four proposed scenarios (Greenpeace: low demand and nuclear-free; environmentally conscious nuclear: moderate demand and high nuclear share; nuclear-intensive: high demand and high nuclear share; government plan: high demand and low nuclear share) analysed herein between 2010 and 2050 (*y*-axis: electricity consumption in TW h, *x*-axis: projection per decade. Energy provision categorised as: renewables: solar, onshore and offshore wind, ocean, hydro and geothermal power; fossil-fuels: coal, gas and oil).

some key advantages for analysing energy systems: it can (i) assess a range of criteria with various units at different scales, (ii) use metrics that reflect public interest, and (iii) be adjusted by decision makers or experts using appropriate and context-specific weightings. However, the approach is not able to assess the disadvantages or benefits of a single scenario without another for comparison (i.e., it is a relative analysis tool). Moreover, some important elements like greenhouse-gas emissions (or any others) can be ignored deliberately with a zero weighting. Finally, the magnitude of negative impacts is defined explicitly because of the different units.

An alternative approach is external cost analysis methods, which can be more difficult to parameterise, but offer some advantages over multi-criteria decision-making analysis: the former (i) accounts explicitly for externalities in energy costs without comparison to other scenarios (Roth and Ambs, 2004), (ii) can reflect uncertainties with a range of monetary values applied (Friedrich, 2004), and (iii) provides the capacity to predict and analyse yearly sustainability changes or trends of alternative scenarios without the need for scenario comparison. External cost analysis requires that we reflect all negative economic, social and environmental impacts with a monetary term (Roth and Ambs, 2004); here we used US$ (2010 value) and $ GJ^{-1} as base units.

We used a multi-criteria decision-making analysis (with ordered rankings) to compare energy options (Wang et al., 2009), and applied external cost analysis to summarise yearly energy costs of each scenario for each decade from 2010 to 2050. Sustainability metrics included the levelised cost of electricity, heat-generation costs, and fuel costs for transport and other consumption activities (Appendix B). The levelised cost of electricity is determined by initial investment, lifespan, capacity factor, fuel costs, and operation and management costs (Roth and Ambs, 2004). Note that this analysis did not consider any forms of governmental or external subsidy or penalty (such as production credits, carbon taxes or emissions-trading permits). We are aware that external cost analysis cannot provide the real-world damage or benefit costs, but here we used the methodology to understand the different impacts of each criterion.

We divided indirect costs into two categories: external costs (social and environmental damages generated by energy production or consumption activities (Roth and Ambs, 2004)) and additional costs (extra economic costs that do not generate any other serious social or environmental problems). External costs include greenhouse-gas emissions (Yoon et al., 2010), air-pollutant emissions (CO, NO_x, SO_x, particulate aerosols, and volatile organic compounds) (National Institute of Environmental Research, 2010; U.S. Energy Information Administration, 2012), land transformation (Costanza et al., 1997; Jung et al., 2011b), safety (probable accident assessment with costs) (Burgherr and Hirschberg, 2008; Laes et al., 2011; Sathaye et al., 2012), freshwater consumption (Evans et al., 2009; Fthenakis and Kim, 2010; Jacobson, 2008), and heated water-discharge impacts (Korean Power Exchange Organisation, 2013; Lee, 2011a). Additional costs included nuclear-related costs: spent-fuel management (Feiveson et al., 2011; World Nuclear Association, 2012, 2013) and decommissioning costs of a nuclear power plant (The Ministry of Knowledge and Economy, 2013b), renewable energy-related costs: balancing costs (technical costs) (Dale et al., 2004; Milborrow, 2001), and additional backup requirements (physical costs) (Barton and Infield, 2004; Hong et al., 2013a), additional transmission costs (Mills et al., 2009; U.S. Energy Information Administration, 2012), and hydrogen production costs (Elder and Allen, 2009).

Estimating external costs is a complex task due to the uncertainty of ascribing a monetary value to social and environmental impacts (costs) (Friedrich, 2004). To overcome these challenges, we used data from peer-reviewed literature and governmental documents to define the external (damage) costs and their uncertainty ranges. Roth and Ambs (2004) surveyed the damage costs of greenhouse-gas emissions using a 'global warming potential' benchmark. Based on this analysis, we determined the damage costs of greenhouse-gas emissions at between \$9.9 t^{-1} and \$41.6 t^{-1} of carbon dioxide equivalents. Air-pollutant costs follow Friedrich (2004) and Jung et al. (2011a) (\$0.65–50.82 kg^{-1}, depending on air pollutants). We used the land-service value (Costanza et al., 1997; Jung et al., 2011b) to determine the lost-land value, and for the area of land transformed by stationary power plants, both permanent and temporary changes are considered to define the upper and the lower limits (Denholm et al., 2009) (\$35,960–2291,675 km^{-2} year^{-1}, depending on land characteristics). Unlike other external costs, the rare accident-related costs (safety costs) included both probability and external costs. The safety cost analyses were based on the rare accident probability p and the impact of the accidents I of each energy-generation option (Eq.(1)) (Laes et al., 2011):

$$\text{accident costs} = \Sigma_i p_i \times I_i \quad (1)$$

Here we applied the incident probability defined in the 2012 Intergovernmental Panel on Climate Change renewable energy report (Sathaye et al., 2012), and the impacts based on peer-reviewed literature of related research (Burgherr and Hirschberg, 2008; Eeckhoudt et al., 2000; Hirschberg et al., 2004; Laes et al., 2011; Sovacool, 2008). The impacts included the direct damages and external costs by fatalities, injuries and evacuates. Photovoltaic and wind power have the lowest and second-lowest external costs (median: \$5.66 × 10^{-5} MW h^{-1} and \$4.37 × 10^{-4} MW h^{-1}, respectively) and oil and coal have the highest and the second-highest costs (median: \$5.77 × 10^{-2} MW h^{-1} and \$4.04 × 10^{-2} MW h^{-1}, respectively). Although the safety cost of nuclear power is accounted as \$6.94 × 10^{-3} MW h^{-1} (median), it might be improved further with deployment of the next-generation of nuclear power (currently pre-commercial or being demonstrated) (Brook, 2012).

Additional costs only encompassed additional economic components other than the levelised cost of energy. In 2013, the South Korea Ministry of Knowledge and Economy announced a new scheme for the costs associated with spent nuclear-fuel management and decommissioning (The Ministry of Knowledge and Economy, 2013b). The scheme increased the nuclear-related management costs by about \$4 MW h^{-1}, above the current cost of \$5 MW h^{-1}, which is about 10% higher than the current levelised cost of nuclear power in South Korea. The levelised cost of gas power of the Greenpeace scenario should be increased by 2050 to satisfy the loss-of-load probability by using more peaking, open-cycle plants to enhance system reliability (Keane et al., 2011; Ueckerdt et al., 2013). However, here we assumed a maximum of \$20 and a minimum of \$0 MW h^{-1} cost increases, on the optimistic assumption that the smart grid might help to manage effectively such intermittency constraints. In reality, transmission spending has a critical role in determining the location of renewable systems, such as onshore or offshore wind power. The levelised cost of the system should include transmission and distribution costs (Dale et al., 2004; OECD/Nuclear Energy Agency, 2012). Here we followed the fuel-cost predictions by the U.S. Energy Information Administration (2012).

2.4. Probability simulation

The overlapping uncertainty bounds across proposed scenarios can cause confusion regarding 'total' costs, the sum of energy costs, and additional and external costs of a given scenario. To analyse the sensitivity of these deterministic results to cost uncertainties, we used a probability-based resampling approach. Given each uncertain future and randomly generated sub-element values within a defined distributional range, we compared four scenarios to clarify the probability that each scenario could result in the lowest cost among all scenarios. For the simulation, we generated 100,000 sets of random variables ν_r, which include the various drivers of energy costs, external costs and/or additional costs (Appendix B). The variables are sampled from Gaussian distributions with a 99.7% confidence level (3σ) between the upper and lower bounds of the cost ranges. The variables followed default correlation coefficients (Awerbuch, 2006; Korean Statistical Information Service, 2013) (Appendix C). This allowed placing most variables within the cost ranges, but also including some rare occasions. For each set of randomly drawn ν_r, we calculated $C_{r,s}$ (ν,e), which is the sum of the total expected cost of each scenario s within each random value set r:

$$C_{r,s}(\nu, e) = \Sigma_{r,s} f(\nu_r, e_s) \quad (2)$$

where e is the energy produced by each source within a scenario. We then compared the costs of scenarios with the same random value set to calculate the overall probability.

3. Results

3.1. Criteria ranking

The multi-criteria decision-making analysis with ranking orders (Wang et al., 2009), quantified for all energy production options using the 2010 median values, are shown in Table 1. A lower value indicates lower negative impacts. Although this analysis did not include particular socio-political weightings (Hong et al., 2013a, 2013b), it provides an indication that increasing nuclear power would have the lowest overall negative impact as measured by costs. Nuclear power provides the lowest overall sum-rank metric, with hydro-energy and bioenergy recording the two highest.

Table 1
Rankings of all analysed energy production options based on quantifiable criteria. A lower number means a lower negative impact.

	Energy cost[a]	Greenhouse gases	Air pollutants	Land changes	Safety issues	Freshwater	Heated water	Spent nuclear fuel	Decommission	Balancing	Backup	Transmission	Overall (sum)
Nuclear	1	–	–	1	3	–	3	1	1	–	–	1	11
Geothermal	3[b]	–	–	7	2	7	–	–	–	–	–	4	20
Coal	2	3	4	4	10	–	2	–	–	–	–	2	27
Solar[d]	10	–	–	–[c]	1	2	–	–	–	3	3	9	28
Ocean	5	–	–	8	5	1	–	–	–	1	1	7	28
Gas	6	1	1	1	8	5	1	–	–	–	–	5	28
Wind	4	–	–	5	4	3	–	–	–	2	2	10	30
Oil	9	2	3	1	9	4	–	–	–	–	–	5	33
Bio	8	4	2	6	7	6	–	–	–	–	–	3	36
Hydro	7	–	–	9	6	8	–	–	–	–	–	7	37

[a] Governmental subsidy is not considered.
[b] No geothermal power in Korea in 2010; value based on literature review.
[c] No measurable impacts.
[d] Rooftop photovoltaic only.

3.2. Energy costs

Although nuclear power is touted as an expensive energy source due to its high initial investment, it is in fact the cheapest electricity-generation option for South Korea ($40 MW h^{-1} in 2010) on a levelised-cost basis. In addition, the levelised cost of electricity methodology fails to consider the intermittency of variable renewable sources, required electricity storage and other additional costs (Ueckerdt et al., 2013). Here we used the levelised cost of electricity to calculate the economic cost, and added the other 'additional costs' to provide a more realistic 'total' cost assessment. Currently, the levelised cost of solar power is far higher ($791 MW h^{-1}) than any of the other options. However, in 2050 with a potential rapid cost-reduction rate for photovoltaic panels, solar power might eventually become a cheaper option ($152 MW h^{-1}) than natural gas, oil and bioenergy, excluding intermittency considerations. We assumed that the nuclear fuel price (uranium) might double by 2050 (International Energy Agency and OECD Nuclear Energy Agency, 2010; The Department of Energy and Climate Change UK, 2012), which would increase the levelised cost up to $68 MW h^{-1}. With fast reactors and new forms of fuel recycling such as pyro-processing, however, nuclear-fuel cost might actually reduce over time (Brook, 2012; Till and Chang, 2005).

The total electricity cost per unit of electricity delivered in the nuclear-intensive scenario, calculated as the levelised cost of electricity ($67.9 MW h^{-1}), is about a half of the Greenpeace scenario ($137.6 MW h^{-1}). The levelised electricity cost of the government plan scenario ($90.6 MW h^{-1}) is also lower than the Greenpeace scenario. The environmentally conscious nuclear scenario has the second-lowest levelised cost of electricity ($68.9 MW h^{-1}). The projected total yearly electricity cost of the environmentally conscious nuclear scenario is the lowest ($47.7 billion year^{-1}) in 2050, followed by the Greenpeace scenario ($70.2 billion year^{-1}) and the nuclear-intensive scenario ($71.9 billion year^{-1}). The government plan scenario has the highest total electricity cost ($77.5 billion year^{-1}), but direct comparison of these scenarios on a total-cost basis is fraught because of their different energy-demand profiles. The unrealistically optimistic energy-demand projection of the Greenpeace scenario, for example, reduces the total electricity cost despite its high levelised cost of electricity.

Due to the high dependency on fossil fuels and the volatility of fuel prices (The Department of Energy and Climate Change UK, 2012), the total energy cost of the government scenario, including electricity, heat and other sources of transport and industrial consumption, varies widely (range: $14.12 GJ^{-1} to $24.45 GJ^{-1} in 2050). On the other hand, the uncertain future energy costs of renewable energy sources are the drivers of the uncertainty of the Greenpeace scenario (range: $16.54 GJ^{-1} to $28.44 GJ^{-1}). The nuclear-intensive scenario provides the lowest median cost ($13.30 GJ^{-1}), followed by the environmentally conscious nuclear scenario ($13.52 GJ^{-1}). The high energy costs of renewable energy sources give rise to the higher total energy cost of the Greenpeace scenario ($23.34 GJ^{-1}). Although the Greenpeace scenario requires only about half of the total final energy consumption compared to the nuclear-intensive scenario, the difference of the total energy cost is $<2\%$ (the Greenpeace scenario: $137.0 billion year^{-1} and the nuclear-intensive scenario: $139.6 billion year^{-1}) in 2050. The total energy cost of the nuclear low-demand scenario is $92.8 billion year^{-1}, which is more comparable based on total cost because it has the same final energy consumption as the Greenpeace scenario.

The relatively high energy cost of the Greenpeace scenario indicates that its low total electricity cost is driven by the unrealistically low electricity-consumption prediction, not by decreased renewable energy costs (Polimeni and Polimeni, 2006; Sorrell, 2009; Yoo, 2005). Moreover, this estimated cost of the Greenpeace scenario did not include the early forced-closure costs of fossil fuels and nuclear power plants, such as government-assisted compensation payments to utilities. This is likely to cause an increase in the economy-wide levelised electricity costs of the Greenpeace scenario. Other than the Greenpeace scenario, all others assumed a full, expected technical lifespan of power plants without forced closures.

3.3. Greenhouse-gas emissions

Based on the historical greenhouse-gas inventories for the South Korean economy (Yoon et al., 2010), we calculated the possible greenhouse-gas emissions (CO_2, CH_4, and N_2O) of all scenarios considering only domestic emissions during the energy production and consumption phases in South Korea, rather than total life-cycle emissions. The Greenpeace scenario did not clearly differentiate life-cycle and domestic emissions, such that it did not include any emissions arising from the production, operation or decommissioning of renewables. Bioenergy emits greenhouse gases during its consumption phases, whereas other renewables do not, and all renewable sources involve the emission of greenhouse gases during their life cycle due to the embedded carbon intensity of their infrastructural production facilities. Here we only included the emissions from bioenergy during the consumption phase based on the greenhouse-gas inventories for South Korea (Yoon et al., 2010).

Overall, the environmentally conscious nuclear scenario emits 73 Mt year^{-1} of greenhouse gases (13.0% of the 2010 emissions) in 2050, whereas the Greenpeace scenario results in more than twice that amount (189 Mt year^{-1}) (Fig. 3). During the scenario-projection period, the government plan increases greenhouse-gas emissions by $>5\%$ to 2050 above 2010 levels. The nuclear-intensive scenario, which consumes the same final energy as the government plan, emits only 133 Mt year^{-1} (24% of 2010 emissions) in 2050. The greenhouse-gas emissions intensity of the environmentally conscious nuclear scenario is 9 kg GJ^{-1} year^{-1}, whereas the Greenpeace scenario is 32 kg GJ^{-1} year^{-1}. Under the nuclear-intensive scenario, emission intensities would fall to 13 kg GJ^{-1} year^{-1}, while accommodating a growth in total energy production on par with the government plan.

The relative proportion of nuclear power relative to coal and gas explains the large differences in cumulative greenhouse-gas emissions between the government plan (25051 Mt) and the nuclear-intensive scenario (15146 Mt) by 2050. The environmentally conscious nuclear scenario emits the least cumulative greenhouse gases in 2050 (12849 Mt), and the Greenpeace scenario (16981 Mt in 2050) would pass that level at some point between 2035 and 2036. Even the nuclear-intensive scenario, with far greater final energy production, emits lower cumulative emissions than the Greenpeace scenario (-1835 Mt), with most of its emissions coming from peaking gas and non-electricity sectors.

3.4. Indirect costs: External and additional costs

Compared with the costs arising from greenhouse-gas emissions and air pollutants, all other externalities are negligible (Appendix D). Unsurprisingly, the environmentally conscious nuclear and the nuclear-intensive scenarios deliver a lower overall external cost ($0.40 GJ^{-1} and $0.55 GJ^{-1}, respectively) than the others in 2050, because nuclear power produces virtually zero greenhouse gas and air pollutant emissions, even when management of spent nuclear fuel is considered. The Greenpeace scenario requires more than three times higher external costs ($1.54 GJ^{-1}) than the environmentally conscious nuclear scenario in 2050 due to the high greenhouse-gas emissions and air pollutant costs of bioenergy consumption driven by solid biomass for stationary power plants, and the use of fossil gas for balancing. Interestingly, despite the higher renewable-energy penetration of the Greenpeace scenario, the higher fossil-fuel shares

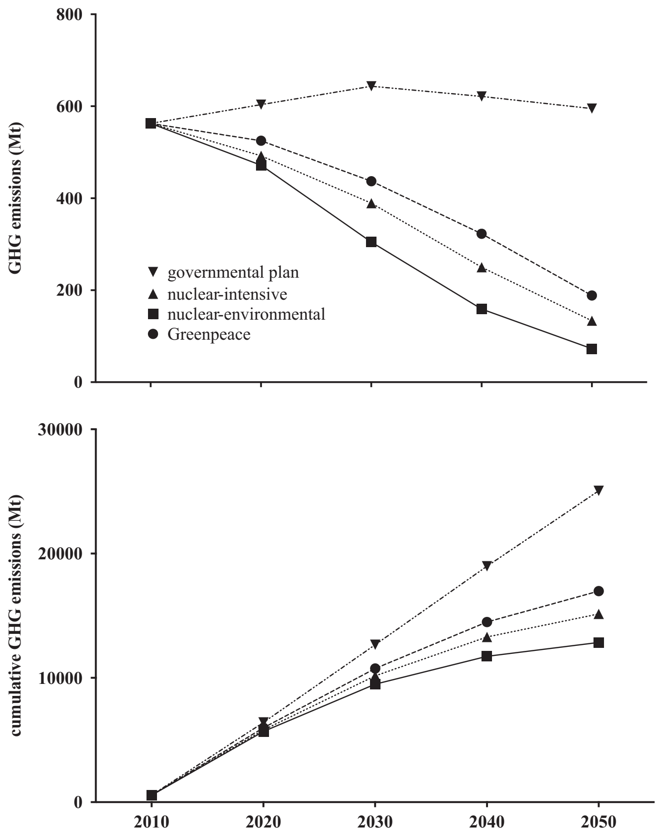

Fig. 3. Annual (top) and cumulative (bottom) greenhouse-gas emissions from energy sectors in South Korea by scenario (Greenpeace: low demand and nuclear-free; environmentally conscious nuclear: moderate demand and high nuclear share; nuclear-intensive: high demand and high nuclear share; government plan: high demand and low nuclear share) from 2010 to 2050.

increase the safety-related costs ($0.0086 GJ^{-1}). The environmentally conscious nuclear scenario and the nuclear-intensive scenario have lower safety-related costs than the Greenpeace scenario ($0.0066 GJ^{-1} and $0.0059 GJ^{-1}, respectively).

Additional costs did not include fundamental infrastructure costs, such as levelised cost of electricity, fuel-costs, and operation and management costs, but instead included unexpected indirect economic costs. Throughout all simulation years, nuclear power-related additional costs, spent-fuel management and decommissioning costs for both nuclear power-based scenarios overwhelm the other additional costs (Appendix D). However, the next generation of nuclear power would likely mitigate spent-fuel management costs by recycling fuel and reducing the volume and radiotoxic lifespan of the residual waste stream (Brook, 2012). Nuclear power requires $3.95 MW h^{-1} (maximum $5.57 MW h^{-1}), whereas other sources require nothing. The transmission expenditure is the next-highest cost. Naturally, the Greenpeace scenario, with a far greater reliance on distributed energy systems, requires the highest cost ($2.76 MW h^{-1}), and the environmentally conscious nuclear scenario results in the lowest cost ($1.34 MW h^{-1}). Overall, the government plan provides the lowest additional cost per unit final energy consumption ($0.32 GJ^{-1}) than any other scenario, as a result of the higher energy-intensive mixes (fossil fuels), and lower nuclear power dependency than the nuclear-centred scenarios. Despite having zero nuclear-related costs, the additional cost per unit final energy consumption of the Greenpeace scenario ($0.49 GJ^{-1}) is higher than the environmentally conscious nuclear scenario ($0.45 GJ^{-1}).

In terms of the total indirect cost, the sum of additional and external costs, all scenarios except the government plan are forecast to show decreasing total indirect costs over time. Despite the Greenpeace scenario having the lowest additional cost, the extensive total external cost (environmental and social damage costs) offsets any advantage. The environmentally conscious nuclear scenario and the nuclear-intensive scenario reach $6.7 billion year^{-1} ($0.85 GJ^{-1}) and $11.2 billion year^{-1} ($1.06 GJ^{-1}), respectively. The Greenpeace scenario ends up costing $11.9 billion year^{-1} ($2.02 GJ^{-1}) in 2050, although the nuclear low-demand scenario requires only a half ($5.64 billion year^{-1}) of the Greenpeace scenario. Thus it is clear that, based on the integration of these objective metrics, a higher nuclear power share will reduce economic, social and environmental damages in a country like South Korea.

3.5. Total cost

Our deterministic modelling reveals that the total sum of energy, external and additional costs for each scenario constitute each one's respective 'total' cost (Fig. 4) (details in Appendix D). The environmentally conscious nuclear scenario and the nuclear-intensive scenario have the lowest total cost per unit final energy consumption ($14.37 GJ^{-1}, for both), and the government plan ($23.32 GJ^{-1}) follows. The Greenpeace scenario has the highest uncertainty range (the difference between the lowest and the highest is about $14.47 GJ^{-1}), and the environmentally conscious nuclear scenario provides the lowest ($7.73 GJ^{-1}), followed by the nuclear-intensive scenario ($7.82 GJ^{-1}). In contrast to the other scenarios, even though the increasing ratio of the total cost falls after 2030, the total cost of the government plan increases constantly from $139.2 billion year^{-1} in 2010 to $244.6 billion year^{-1} in 2050 (Appendix D). The environmentally conscious nuclear scenario requires $112.5 billion year^{-1} in 2050, and the Greenpeace scenario ($148.9 billion year^{-1}), with the nuclear-intensive scenario ($150.7 billion year^{-1}) following. The nuclear low-demand scenario needs $98.4 billion year^{-1} despite the equivalent consumption trend with the Greenpeace scenario. This implies that the Greenpeace plan constitutes the worst-case scenario in terms of uncertainty and total cost, regardless of future energy consumption trends.

3.6. Probabilistic simulation

The scenario ranking based on long-term total costs leads with the environmentally conscious nuclear (lowest), followed by the Greenpeace scenario (second lowest), the nuclear-intensive scenario (third lowest), and the government plan (highest) (Table 2). However, when total costs are standardised per unit final energy consumption, the probability simulation using a Gaussian distribution with default correlation coefficients (Appendix C) shows that the Greenpeace scenario fails to achieve low costs in any iteration. Even on a total-cost basis, the Greenpeace scenario outperforms the nuclear-intensive scenario in 72% of cases, but the nuclear-intensive scenario yields a lower total cost per unit final energy consumption than the Greenpeace scenario in all iterations. The Greenpeace scenario achieved a lower total cost per unit final energy consumption than the government plan in only six of 100,000 iterations (i.e., 0.006% of cases). The comparison between the Greenpeace scenario and nuclear scenario with the Greenpeace demand profile (nuclear low-demand) clearly reveals that a renewable energy-centric scenario will not be able to achieve a lower total cost than a nuclear-focused scenario for any equalised level of total energy consumption. This analysis also confirms that the unrealistically low final energy consumption prediction reduces the total cost of the Greenpeace scenario, but renewable energy sources do not. Using a different distribution method (uniform distribution) and different sets of correlation coefficients (Appendix F) do not noticeably change these results. Thus, despite the inherent uncertainty of

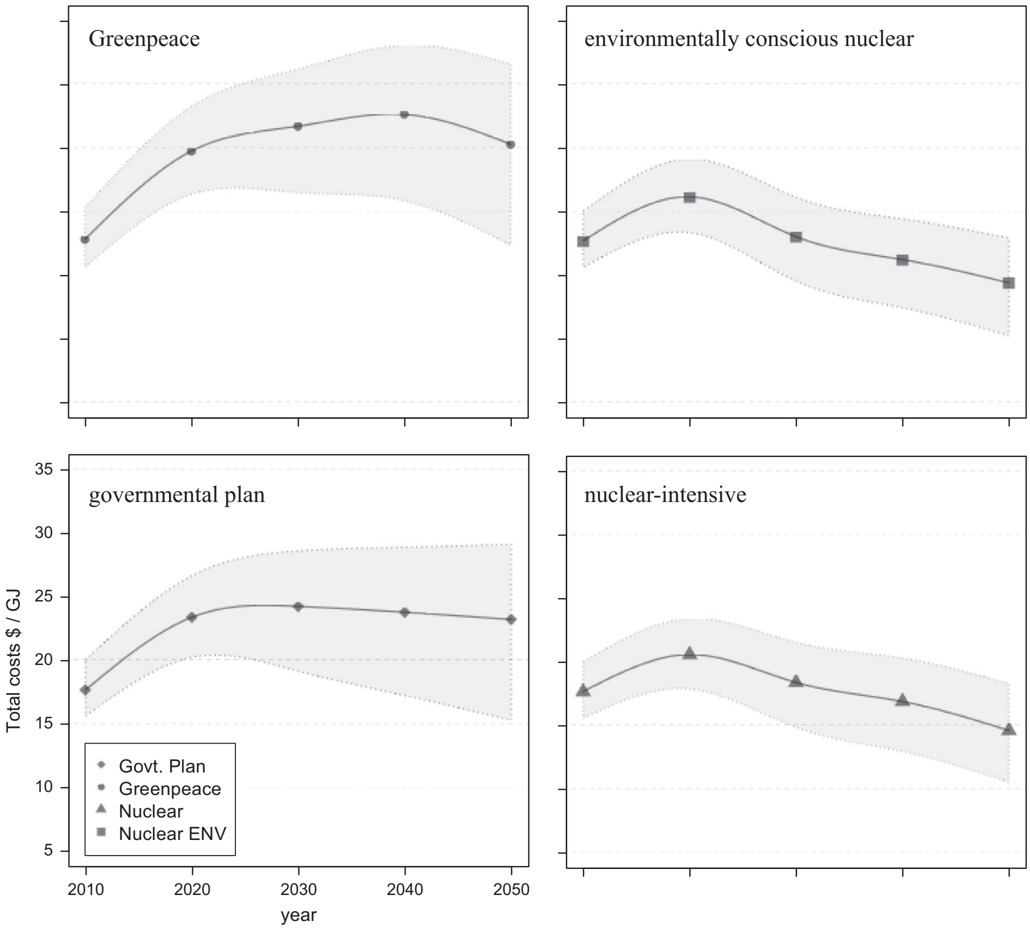

Fig. 4. Total costs per unit of final energy consumption ($ GJ^{-1}) for four scenarios (Greenpeace: low demand and nuclear-free; environmentally conscious nuclear: moderate demand and high nuclear share; nuclear-intensive: high demand and high nuclear share; government plan: high demand and low nuclear share) with uncertainty ranges (bold lines with markers indicate median cost, and shaded ranges indicate upper and the lower limits of each scenario, from top left clockwise: Greenpeace scenario, environmentally conscious nuclear scenario, nuclear-intensive scenario and the government plan).

the inputs, the environmentally conscious nuclear scenario has the highest probability of being the most sustainable option for the future energy mix of South Korea.

3.7. Pros and cons

The greatest purported advantage of the Greenpeace plan is the lack of fossil fuel dependencies and nuclear-related externalities. Yet despite its high renewable energy penetration in terms of total generating capacity, a major source of energy must continue to come from fossil fuels—predominantly expensive imported oil and liquefied natural gas. However, the Greenpeace plan's energy-demand forecast was implausible because it ignored both the projected economic growth of South Korea and the causal relationship between economic growth and energy consumption (Yoo, 2005). Because the realism of the Greenpeace scenario is contingent on reducing final energy consumption by a probably unrealistic margin compared with the government's 'business-as-usual' scenario (Polimeni and Polimeni, 2006; Sorrell, 2009; Yoo, 2005), a parallel wholesale reorganization of the nation's industrial and transportation infrastructure would be essential. Moreover, global warming over 2 °C (Peters et al., 2013) is likely to cause unexpected weather events in South Korea (IPCC, 2007) which are hostile to weather-dependent renewable energy systems (e.g., photovoltaic, ocean and wind power). Although the Greenpeace plan is not the worst-scoring scenario in terms of total cost (although it ranks worse than the nuclear-centred scenarios), it is the worst-scoring scenario in terms of total cost per unit final energy consumption. Moreover, it is arguably the least-practical case from the point of view of industrial development and economic growth.

Table 2
Cross-scenario comparison showing the probability that a scenario from the row is lower than a scenario (Greenpeace: low demand and nuclear-free; environmentally conscious nuclear: moderate demand and high nuclear share; nuclear-intensive: high demand and high nuclear share; government plan: high demand and low nuclear share) from the column.

$ GJ^{-1}	**Greenpeace**	**Nuclear (low-demand)**	**Nuclear (env)**	**Nuclear (intensive)**
Nuclear (low-demand)	1.000			
Nuclear (env)	1.000	1.000		
Nuclear (intensive)	1.000	1.000	0.532	
Govt. plan	1.000	< 0.001	< 0.001	< 0.001
Total cost				
Nuclear (low-demand)	1.000			
Nuclear (env)	1.000	< 0.001		
Nuclear (intensive)	0.280	< 0.001	< 0.001	
Govt. plan	< 0.001	< 0.001	< 0.001	< 0.001

This result is based on 100,000 simulations using a Gaussian distribution with default correlation coefficients (Appendix C). The upper table is based on the cost per unit final energy consumption and the lower table is based on the overall cost.

By contrast, low greenhouse-gas emissions, along with minimal social and environmental damages, are the major benefits of the environmentally conscious nuclear scenario. However, that scenario depends heavily on a single major energy source, which raises potential problems in terms of security of supply, energy diversity, and system-wide risks, as evidenced by the socio-political reaction against nuclear energy in Japan after the Fukushima events. To overcome the physical limit of locally obtainable uranium, it is likely that South Korea would expedite the commercialisation of next-generation nuclear power, such as fast-spectrum reactors with integral fuel recycling and inherent safety systems that can better protect against even rare external events (Till and Chang, 2005). To expand the utilisation of nuclear power, small modular reactors for industry and transportation will probably be required (Brook, 2012). The nuclear-intensive scenario shares similar disadvantages, but it requires an even more rapid roll out of nuclear plants. However, compared with the nuclear-construction history of South Korea (Korean Statistical Information Service, 2013) and the sustained building programs of other nuclear-intensive nations like France (Brook, 2012), the expected expansion rate is conceivable and realistic. Additionally, the nuclear-intensive scenario does not require any industrial changes to deliver a more sustainable energy future than the Greenpeace scenario.

4. Discussion

We have reviewed, quantified, simulated and critiqued a range of plausible future scenarios for energy production and consumption in South Korea through to 2050, using external costs, integrated (multi-criteria) decision rankings, and probabilistic simulations, to arrive at three main conclusions: (i) nuclear power has a key role to play in efficiently mitigating greenhouse-gas emissions for this country, given real-world geophysical, environmental and cost constraints, (ii) the Greenpeace scenario compares poorly to other options on environmental, cost and energy grounds; it is likely to have substantially higher total external cost than the nuclear-dominated scenarios, despite producing only about half the final energy, and (iii) despite the uncertainties and difficult-to-quantify public concerns, the nuclear-focused scenarios offer the most environmentally sustainable option for South Korea based on objective analysis of impact metrics.

Authoritative reviews of the economics of climate change mitigation typically argue that there is no such thing as a 'silver bullet' for sustainable energy technology (Stern, 2007). Renewable resources are widely touted as 'clean' energy sources and they obviously can fill important energy-supply niches in appropriate situations (Greenpeace Korea, 2012). However, it is difficult to envisage how a high penetration of renewable energy can reliably meet the requirements of industrially and commercially intensive national electricity grids, especially in nations with heavy constraints on natural resources, without a substantial requirement for fossil-fuel backup capacity, and other life-cycle processes, which produce a sizeable carbon footprint (Hong et al., 2013a; Nicholson et al., 2010). Our analysis clearly demonstrates that the anecdotal public preference for renewables and an associated anti-nuclear tendency, as encapsulated in the Greenpeace *Energy Revolution Plans*, can severely limit the possibility of achieving an efficient, cost-effective and sustainable pathway.

5. Conclusions and policy implications

Ultimately, our modelling suggests that a pathway featuring a strong role for nuclear energy is probably the most sustainable electricity-generation option for South Korea, if the goal is to mitigate climate change while permitting economic growth and ensuring a reliable electricity supply. The principal barriers for establishing a sustainable energy mix in South Korea is the lack of will to implement evidence-based energy policies and governmental and public apathy on the need to mitigate greenhouse-gas emissions (Hong et al., 2013a). To overcome these barriers, South Korea: (i) needs to define short- to long-term national greenhouse-gas emission reduction targets from fossil-fuel consumption, and (ii) establish national energy policies that are validated scientifically (e.g., via modelling) with the target while paying due attention to the physical and economic limitations of renewable energy. This process would provide a comprehensive pathway for developing an environmentally and economically sustainable future energy mix, and represent an ideal example to nations struggling with similar issues. Although our analysis is based on the case study of South Korea, our methodology and approach are likely to apply to other nations with a geographically isolated and small land area, and high population density, with few modifications. For a country like South Korea, it ultimately has no other sensible option but to increase the role of nuclear power.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2014.05.054.

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