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Evaluating options for sustainable energy mixes in South Korea using scenario analysis

Sanghyun Hong [a], Corey J.A. Bradshaw [a,b], Barry W. Brook [a,c,*]

[a] The Environment Institute and School of Earth and Environmental Science, The University of Adelaide, Adelaide, South Australia 5005, Australia
[b] South Australian Research and Development Institute, P.O. Box 120, Henley Beach, South Australia 5022, Australia
[c] Centre for Energy Technology, The University of Adelaide, South Australia 5005, Australia

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A B S T R A C T

To mitigate greenhouse gas emissions, coal-fired electricity infrastructure needs to be replaced by low-carbon electricity generation options. Here we examine a range of possible alternative scenarios for sustainable electricity generation in South Korea, considering both physical and economic limits of current technologies. The results show that South Korea cannot achieve a 100% renewable energy mix and requires at least 55 GW of backup capacity. Given that constraint, we modelled seven scenarios: (*i*) the present condition, (*ii*) the First National Electricity Plan configuration, (*iii*) renewable energy (including 5 GW photovoltaic) with fuel cells or (*iv*) natural gas backup, (*v*) maximum renewable energy (including 75 GW photovoltaic) with natural gas, (*vi*) maximum nuclear power, and (*vii*) nuclear power with natural gas. We then quantify levelised cost of electricity, energy security, greenhouse gas emissions, fresh water consumption, heated water discharge, land transformation, air pollutant emissions, radioactive waste disposal, solid waste disposal and safety issues for each modelled mix. Our analysis shows that the maximum nuclear power scenario yields the fewest overall negative impacts, and the maximum renewable energy scenario with fuel cells would have the highest negative impacts.

1. Introduction

South Korea, a small but highly populous country that underwent rapid industrialisation and economic growth over the last 30 years, is now the one of the world's largest greenhouse gas emitters (607.6×10^6 t [Mt] of carbon dioxide equivalents [CO_2-e] yr^{-1}) [1]. In 2010, the electricity-generation sector emitted 34% of South Korea's total emissions, to generate 440 terawatt hours (TWh) from 77.4 GW of the total generating capacity. During that year, coal-fired power generated 43% of the total electricity consumed, and emitted 180 Mt CO_2-e. Transformation of the electricity structure from carbon-based to alternative power therefore plays a crucial role in reducing national greenhouse gas (GHG) emissions. For this reason, the South Korean government announced the First National Energy Plan in 2008 [2], which aims to increase renewable-energy penetration as well as the proportional contribution of nuclear power, but this plan considers neither the physical limits of renewable energy nor any potential negative outcomes of the proposed configuration.

To reduce GHG emissions, many have insisted that increasing renewable energy penetration is essential [3]. Even in South Korea, one study asserts that a 100% renewable energy mix is possible by 2050 [4]. However, that study did not attempt to quantify the maximum capacity of renewable energy resources and downplayed any negative economic and environmental impacts. It also failed to consider the intermittency of renewable energy sources, instead only counting gross annual generation, and with no attempt to ensure that supply always matched demand. Despite renewable energy's common soubriquet of 'clean energy', its adoption can incur social, economic and even environmental problems [5–7].

In contrast to previous studies, here we objectively quantify the physical limits of six energy-mix scenarios in South Korea to ascertain realistic targets. The scenarios include: (*i*) the present condition, (*ii*) the First National Electricity Plan configuration, (*iii*) renewable energy (including 5 GW photovoltaic) with fuel cells or (*iv*) natural gas backup, (*v*) maximum renewable energy (including 75 GW of peak photovoltaic) with natural gas (*vi*) maximum

* Corresponding author. The Environment Institute and School of Earth and Environmental Science, The University of Adelaide, Adelaide, South Australia 5005, Australia. Tel.: +61 8 8303 3745; fax: +61 8 8303 4347.
E-mail address: barry.brook@adelaide.edu.au (B.W. Brook).

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nuclear power, and (*vii*) nuclear power with natural gas to cover peak power needs. We compare all scenarios using the following sustainability criteria (defined in detail in Section 3.1): levelised cost of electricity, energy security, greenhouse gas emissions, fresh water consumption, heated water discharge, land transformation, air pollutants, radioactive waste disposal, solid waste disposal and safety issues.

2. Assumptions

Our analysis focuses exclusively on the present capacities of electricity generation and trends in consumption to examine alternative scenarios to the current generation structure. Therefore, we did not anticipate future electricity trends or peak-shaving measures, or future scenarios to minimise uncertainties. We therefore made five main assumptions to simplify the comparisons: (*i*) there is no existing power supply options in South Korea other than electricity loads; (*ii*) any technically possible generation options, which are already installed commercially or being installed currently, can be considered (i.e., we do not anticipate future technological advances); (*iii*) generated electricity can be transmitted everywhere without limits or loss; (*iv*) there are no economic limits or social barriers; (*v*) electricity generation and demand fluctuation shorter than 1 h can be met or compensated somehow.

For our analysis, all indicator values should be transparent and objective. However, we also applied some negative values to nuclear power, such as nuclear-waste management and decommissioning costs [8]. Meanwhile, we did not include some renewable energy-related problems, such as construction material consumption [9], noise [10], additional balancing and transmission costs [11], impact on visual amenity [12] or ecosystem degradation by land-use changes [13]. Unlike nuclear or fossil fuel power generation, only the total accident costs of fatalities are calculated for solar photovoltaic and wind power (i.e., they exclude injuries and evacuates).

3. Methods

3.1. Terms

There are five terms that should be defined: (*i*) 'generator capacity' or 'installed capacity' refer to the total (peak) capacity of electrical generation equipment in a power station or system; (*ii*) 'capacity factor' refers to the ratio of the average load on (or power output of) a generating unit or system compared to the capacity (nameplate) rating of the unit or system over a specified period of time; (*iii*) 'levelised cost of electricity' refers to a total life-cycle cost per kilowatt hour (kWh) or megawatt hour (MWh); (*iv*) 'electricity grid' refers to an electricity transmission and distribution system; (*v*) 'gross generation' or 'gross electric output' mean the total generation of electricity produced by an electric power plant or system over one year [14].

3.2. Data acquisition

Our modelling is based on South Korea's hourly electricity load and four weather datasets for 2010. First, we obtained hourly electricity load data on the transmission side from the Korea Power Exchange. Then to simulate wind power output, we collected onshore and offshore wind speed data from 37 Korea Meteorological Agency's Automatic Weather Stations and 8 weather buoys across the country and coastal waters. Third, for hypothetical solar power output, we obtained measured solar irradiation data from 22 major cities. Finally, we acquired tidal information on the west coast to examine simulated tidal power output.

3.3. Modelling

We transformed each collected dataset into 8760 hourly bins. We filled missing bins, which total about 1.9% of 394,245 data, with the average of the same time points of the site in a year. For wind power, we adjusted the hourly wind speed data at the height of the automatic weather stations to the wind power station's hub height using a wind-gradient equation:

$$V_m(h) = V_{\mathrm{hub}}{}^*(h_{\mathrm{hub}}/h_m)^{\alpha} \tag{1}$$

where V_m = measured wind speed, V_{hub} = hub height wind speed, h_{hub} = hub height, h_m = measured height and α = the Hellman exponent that relies on the characteristics of a measured site [15]. We then simulated the estimated wind speed at hub height using the VESTAS V112 3.0 MW onshore and offshore wind turbine model. As a result, average wind power capacity factors were ~30% for onshore and 34% for offshore wind turbines, which are about 5% higher than Korea Power Exchange's records [16].

For solar photovoltaic output, we selected a BP-Q-235-W photovoltaic module with a normal operating temperature assumption. The simulated capacity factor (based on irradiance data) was 11.5%, which is 1% lower than Korea Power Exchange's records [16]. There were no tidal power stations in 2010; however, the Sihwa Lake Tidal Power Station began operating in 2011. We therefore assigned the operating characteristics of Sihwa Lake Tidal Power Station as a fundamental tidal power model [17].

3.4. Sustainability assessment

We based the sustainability of each electricity generation option on putative negative environmental, economic and social outcomes. We used a multi-criteria decision-making analysis method where the criteria and dimensions follow the guidelines of the International Atomic Energy Agency [18], which is in cooperation with United Nations Department of Economic and Social Affairs, the International Energy Agency, Eurostat and the European Environment Agency. Among 30 indicators, we selected 10 relevant ones for which data were available for South Korea. For the economic dimension, we assessed levelised cost of electricity, which includes the lifespan of facilities, interest rate, fuel costs, operation and management costs, and initial outlay, and energy security (imported energy fuel costs). For the environmental dimension, we examined GHG emission intensity per MWh (domestic GHG emissions during the generation phase), fresh water consumption intensity and heated water discharge per MWh, power density per km^2 (an index of land transformation per MW), and air pollution intensity per MWh. The social dimension was the impact of energy-related accidents.

We calculated overall sustainability as the sum of the three dimensions, with each dimension being the average of the sub-sustainability indices. According to the different perspectives, different weightings can be used to modify the sub-sustainability indices. The setting of these parameter values should be transparent and evidence-based; we used statistical values from South Korea wherever possible. However due to the high uncertainty and the lack of information of some indicator values, such as fresh water consumption, heated water discharge, and land transformation of some renewable energy sources, we were obliged to apply the averages of the highest and lowest values sourced from the relevant literature.

4. Capacity limits

4.1. Physical limits

Maximum solar irradiation in South Korea is about 1433 kWh of heat energy m^{-2} $year^{-1}$ [1], but to operate solar thermal power, the minimum solar irradiation must be at least 2000 kWh m^{-2} $year^{-1}$ [19]. In the case of photovoltaic, we consider only rooftop-installed systems because of insufficient land area for larger-scale facilities. On the assumption that 50% of public buildings and 25% of private buildings are available, a total of 324 million BP-Q-235-W solar PV panels can be installed on 541 km^2 of area, resulting in a peak generating capacity of 75.2 GW [20].

According to Kim [21] and Song [22], 1219 km^2 is usable for onshore wind power, and between 1208 km^2 and 1989 km^2 are accessible for offshore wind power. That area excludes already designated social or economic areas, such as buildings, farms, shipping lanes, military zones, fish farms or natural parks. For offshore wind power, we considered only the areas with <30 m of water depth, based on the average water depth of European Union wind power stations [23]. Because the distance between wind power stations should be at least 5–8 times the diameter of the wind turbine's blades [24,25], a maximum 8.7 GW of onshore and 14.2 GW of offshore wind power capacity can be installed within South Korean territorial land area and waters, respectively.

In 2011, the first tidal power plant, Sihwa Lake Tidal Power, began operating with 0.254 GW of generator capacity [16]. Other than this plant, three more sites on the west coast are planned, with a total 2.7 GW of generator capacity, and two other sites are being considered, with 1.1 GW of total capacity [26]. Few other places have suitable coastal geography.

At present, additional large hydro power plants are no longer under development because of their negative environmental and social influences, such as land transformation, ecosystem degradation, deforestation and submerged residential areas; however, small-scale hydro power using existing facilities, including agricultural reservoir, irrigation dam, power plants and fish farming sites, are common and have few negative aspects [27,28]. From this perspective, an additional 0.5 GW of total generator capacity is possible over the present capacity of 1.6 GW [29]. For pumped hydro storage, the current status of 4.7 GW generator capacity with 8 h of maximum supply, cannot be exceeded [29].

4.2. Domestic limits

According to the Renewable Energy Report 2010 [2], the maximum by-product-gas generator capacity from the iron smelting industry is 5.5 GW, including present generators. The capacity factor is about 10%, as most of the generated electricity is consumed on the site, and the gas has low heat value [30].

Bio-energy is mainly limited by fuel supply in South Korea. There were 8 million pigs in 2010 [1]. One pig produces 6.25 kg of manure per day, so each year 114.1 m^3 of biogas is produced from one pig [31]. Assuming 20% of the total produced swine manure in South Korea is converted to energy (>80% of animal manure is converted to fertilizer [32]), 163.5 GWh of electricity can be generated per year [31]. Furthermore, biomass power plants with 0.1 GW of total capacity can generate 779.1 GWh from 1,562,731 m^3 of wood [33,34]. Both cases considered the other uses of bio-energy, for example, fertilizer, re-use or recycling of wood resources, and heat consumption.

There were 14 landfill-gas power facilities in South Korea in 2010 [16] and 14 more possible sites with a total generator capacity of 0.003 GW [35]. Additionally, South Korea generates 3,107,784 tonnes of combustible waste per year [1]. If half of this is converted into refuse-derived fuel, which is the most energy effective methods for waste energy, then 253.5 GWh of electricity can be generated [36,37].

In total, there are about 116 GW of cumulative potential renewable energy capacity for electricity, including current installed capacity, yielding 150,243 GWh of gross generation (Fig. 1). In 2010, South Korea consumed 440,874 GWh of electricity, with a demand peak of 66.6 GW and a baseload minimum of 40 GW [1,16]. To meet the demand by renewable energy sources, the supply should therefore provide at least 40 GW of electricity continuously, and be able to ramp up to 66.6 GW (there is also a need for a reserve margin of ∼20% to cover contingencies such as generator failures [38]). However, even if total gross generation from all renewable energy sources is somehow always consumed, there is still a shortage of 290,631 GWh of electricity per year. Moreover, the average capacity factor is only about 12.5%; thus, continuous supply with even the minimum load is unlikely. This result clearly identifies that massive backup capacity from fossil or nuclear sources is required.

5. Hourly modelling

We built six hourly electricity generation models based on different technology mixes to meet the hourly electricity loads of South Korea in 2010. In the case of conventional power facilities, nuclear and coal power supplied baseload power, and natural gas, petroleum and diesel power were used to meet intermediate power requirements. Hydro power and pumped hydro storage were used to meet intermediate and peak electricity demand. For the focused renewable energy scenarios, intermittent power outputs from tidal, solar and wind power were consumed first as a 'base supply', and other power systems were then used to generate the remainder, such that supply always met demand (on an hourly basis).

Overall, the total generation capacity of the renewable energy scenarios is higher than any other scenario, but the gross generation of electricity is lower (Table 1). This is because of the low capacity factor of renewable energy and the required backup capacity to cover the intermittency of renewable energy sources. Moreover, both renewable energy scenarios with 5 GW of photovoltaic derive >80% of gross generation from natural gas or fuel cells.

Table 2 presents the detailed generation shares of the proposed scenarios. An expansion of photovoltaic power does not help to reduce the required peak backup capacity; instead, it simply acts to save some liquefied natural-gas fuel. For instance, 75 GW of photovoltaic capacity provides 70,640 GWh more electricity than 5 GW of photovoltaic, but it requires a minimum of twice to a maximum of five times more initial outlay. Despite the expansion, the renewable energy scenario with a peak supply of 75 GW of photovoltaic capacity still requires a minimum 299,130 GWh of backup supply. The renewable energy scenarios with 5 GW of photovoltaic capacity consist of 75,318 GWh of renewable energy supplied by renewable energy, hydro power and pumped hydro storage, and 368,584 GWh of backup capacity supplied by natural gas power or fuel cells, for example. The nuclear power scenarios have 391,895 GWh or 313,516 GWh of nuclear power supply, and 40,274 GWh or 117,313 GWh of natural gas capacity as a main backup power, respectively. Neither the renewable energy or nuclear scenario includes coal, diesel or petroleum power.

6. Sustainability assessment

6.1. Environmental impact

GHG emission intensity is calculated using the carbon inventory figures for South Korea [39]. The maximum nuclear power scenario

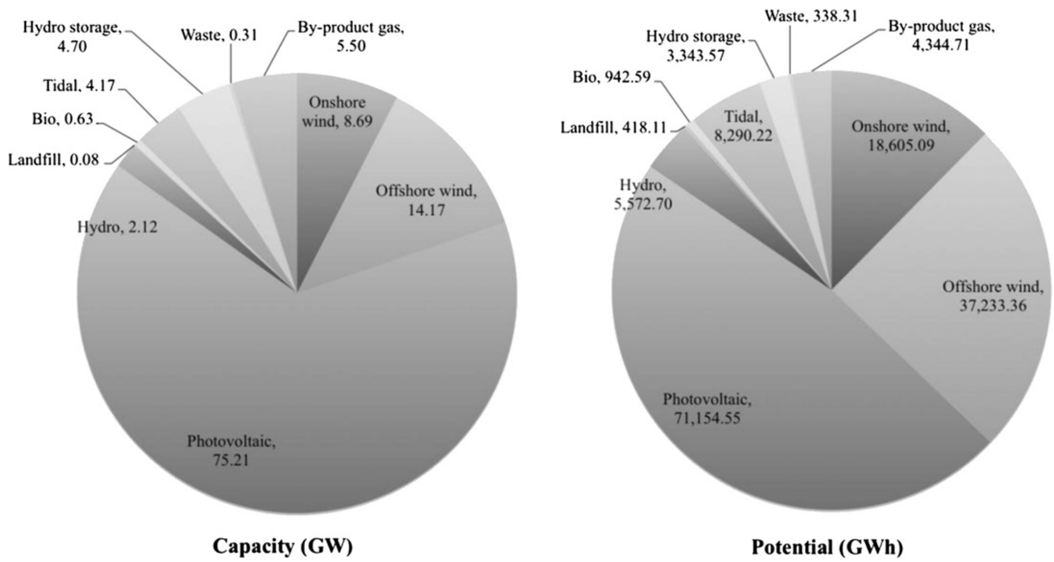

Fig. 1. Capacity limits (peak capacity) in GW and generation limits (electricity output) in GWh of renewable energy sources in South Korea, based on assessed physical and socio-political constraints.

produces the lowest GHG emissions, with 74 kg CO_2e MWh^{-1} for domestic generation. However, the renewable energy scenarios result in >384 kg CO_2e MWh^{-1}, which is higher than the maximum life-cycle emissions of the nuclear scenario due to the far greater reliance on backup power from fossil fuels. The renewable energy scenario with 75 GW of photovoltaic emits 449 kg CO_2e MWh^{-1}, and the renewable energy (including 5 GW of photovoltaic) with natural gas (542 kg CO_2e MWh^{-1}) emits more than the current condition. To avoid dangerous climate change, emission intensity should be lower than 150 kg CO_2e MWh^{-1} [40,41]. From this perspective alone, the maximum nuclear power scenario is the only acceptable one.

Despite the assumption that all solar panels are installed on rooftops, the power densities of the renewable energy scenarios are about 21 MW km^{-2} based on a literature review [1,5,16,42]. Compared to the present condition (333 MW km^{-2}), this represents a one-tenth reduction of current densities. Meanwhile, the power density of the maximum nuclear power scenarios is 482 MW km^{-2}. Thus, the nuclear power scenarios claim 153 km^2 of land requirements for total generator capacity, whereas the renewable energy scenarios require >4756 km^2 of total area, excluding rooftop photovoltaic capacity. As we assumed that solar panels are installed on rooftops, the maximum renewable energy scenario (including a massive expansion to 75 GW of photovoltaics) requires the same amount of land as other renewable energy scenarios.

Using pollutants (SO_2, NO_x, and CO) as environmental-impact proxies follows National Air Pollutant Emission Inventories [43]. Fuel cells and nuclear power emit nearly zero air pollutants, so the renewable energy (including 5 GW of photovoltaic) with fuel cells scenario emits the least amount of air pollutants (0.34 kg MWh^{-1}). The maximum nuclear power scenario emits the second-lowest quantity of air pollutants (0.38 kg MWh^{-1}), and those emissions are virtually all due to natural-gas-sourced peak supply needs. However, compared with the present condition, the maximum nuclear power scenario discharges only 7% of current pollutants.

We examined two types of waste: solid and radioactive waste. The major source of solid waste is coal power. Most renewable energy and nuclear power technologies do not produce solid waste, although bio and waste energy produce solid wastes [44,45]. No scenarios (excluding the current condition and the Plan scenarios) use coal power, so their solid waste generation is negligible (<0.017 kg MWh^{-1} for the nuclear power scenarios, and <0.14 kg/MWh^{-1} for the renewable energy scenarios). Nuclear power produces a quantity of controlled radioactive waste [46]; however, coal power produce about twice that amount of uncontrolled radioactive waste into landfill sites or the air [47]. The renewable energy scenarios will produce zero radioactive waste, and the maximum nuclear scenario will produce 0.63 g MWh^{-1} of controlled waste. The Plan scenario will produce 0.34 g MWh^{-1} of controlled waste, and release 0.50 g MWh^{-1} of uncontrolled waste.

Nuclear and fossil-fuel power sources are renowned as a massive water consumers for cooling of discard steam; however in reality, none of the conventional power plants consumes fresh water in South Korea because of their coastal location and consequent use of sea water [1]. Therefore among all introduced systems, hydro power and pumped hydro storage consume most fresh water by evaporation [3,48,49]. Interestingly, the renewable energy with fuel cells scenario consumes the most fresh water (3.21 kl MWh^{-1}) given their reliance on fuel cells (>44% of the total). The major heated water discharging sources are nuclear (127.34 kl MWh^{-1})

Table 1
Total installed capacity of electricity generation capacity in South Korea in gigawatts (GW, left) and gross generation in 2010 (GWh, right). These data are based on hourly electricity modelling for five alternative energy plans, and the actual 2010 situation for South Korea.

	Installed capacity (GW)	Generation (GWh)
Current	77.6	440,874
The Plan	89.1	447,342
Renewables with fuel cells	100.8 (5 GW photovoltaic)	455,695
Renewables with natural gas	100.8 (5 GW photovoltaic)	455,695
75 GW photovoltaic with max renewables	170.8 (75 GW photovoltaic)	450,850
Nuclear	72.2	441,543
Nuclear with natural gas	71.0	441,224

Table 2
Gross electricity generation (GWh) of proposed scenarios for South Korea. These data are based on hourly electricity modelling for five alternative energy plans, and the actual 2010 situation.

	Current	The plan	Renewables with fuel cells	Renewables with natural gas	75 GW photovoltaic with max renewables	Nuclear	Nuclear with natural gas
Nuclear	142,459	211,623	0	0	0	391,895	313,516
Backup[a]	85,217	45,380	368,584	368,584	299,130	40,274	117,313
Fossil fuels[b]	205,196	157,387	0	0	0	0	0
Renewables	4260	28,674	75,317	75,317	145,957	3797	3823
Hydro	3521	4245	5459	5459	5717	4698	4698
Storage[c]	221	33	6335	6335	45	103	71
Total	**440,874**	**447,342**	**455,695**	**455,695**	**450,849**	**440,766**	**439,419**

[a] Backup power supply includes either natural gas or fuel cells.
[b] Fossil fuel power supplies exclude natural gas.
[c] Storage is pumped hydro storage.

and fossil fuel (100.28 kl MWh^{-1}) power generation [3,48–50]. Inevitably, the maximum nuclear power scenario will discharge the largest quantity (120.2 kl MWh^{-1}), but as noted above, it need not use fresh water supplies.

6.2. Economic impact

Economic impact is based on the levelised cost of electricity, as estimated using the National Renewable Energy Laboratory calculator [51]. We included nuclear waste and decommissioning costs of nuclear power (\$4.5 MWh^{-1}) [46]; however, we did not consider any renewable energy-related end-of-life issues. The present condition costs \$78 MWh^{-1}, but the renewable energy scenarios with fuel cells and natural gas cost \$ 330 MWh^{-1} and \$128 MWh^{-1}, respectively. The maximum renewable energy scenario (including 75 GW of photovoltaic) requires \$241 MWh^{-1}. Previous survey studies have suggested that a typical South Korean household is willing to pay \$1.5 per month (about \$5 MWh^{-1}) for renewable energy sources [52]. Based on this, even when assuming the highest willingness to pay value, the maximum renewable energy scenarios do not qualify as 'acceptable' in cost terms.

Conversely, the maximum nuclear power scenario costs the least, at \$75 MWh^{-1}. Even though the initial outlay (capital costs plus financing) per MW of nuclear power is higher than conventional power plants, the fuel cost is about one fifth of coal, and one sixteenth of natural gas (South Korea imports almost all of its fuel). Consequently, the cheaper fuel cost lead to cheaper overall annual generation costs for electricity supply. After the Fukushima Daiichi accident in Japan in 2011, social acceptance for nuclear power has declined; however, 74.8% of respondents still agree that South Korea requires nuclear power (declining from 94.2% in 2009) [53].

The imported energy fuel cost per MWh represents the energy security indicator. The fuel costs only represent the importing cost without compensation or tax [1]. The maximum nuclear power scenario requires the lowest funds for importing (\$11.4 MWh^{-1}), due to the cheaper fuel cost of nuclear power. For comparison, the current condition requires \$39.3 MWh^{-1}, and the renewable scenarios (with 5 GW of photovoltaic) require \$77.6 MWh^{-1}.

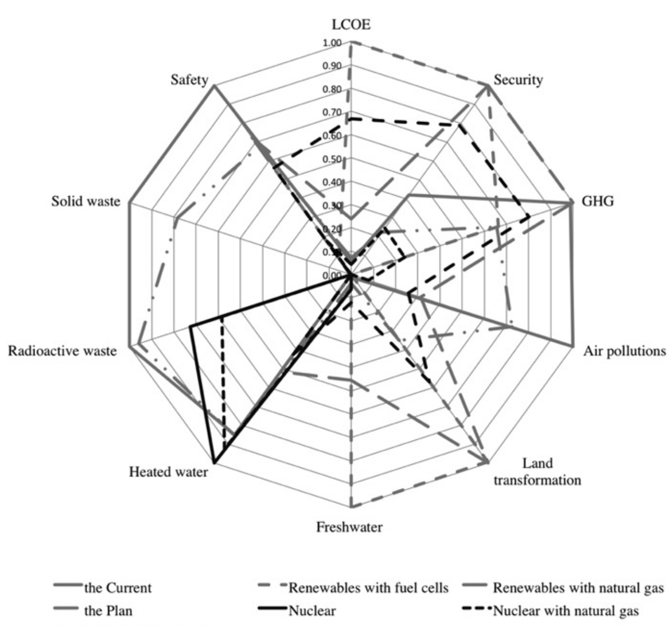

Fig. 2. Normalised results of negative impacts of ten sustainability criteria (max = 1, and min = 0). Lower numbers mean lower negative impacts.

6.3. Social impacts

Since the Fukushima Daiichi accident, the safety of nuclear power and its social acceptance are the hottest issues [54,55]. However, despite its perception as having low in social acceptability due to perceived safety concerns, actuarial data shows that nuclear power is actually statistically safer than fossil fuels or most renewable sources [56,57]. The loss-of-life data on energy-related accidents shows the fatality rate of nuclear power is 0.03060 fatalities GWy^{-1}, including the modelled latent fatalities of the Chernobyl accident, and other smaller-scale radioactive releases. For comparison, coal power has 0.12 fatalities GWy^{-1} within Organization of Economic Cooperation Development (OECD) member countries, and 0.569 fatalities GWy^{-1} including non-member countries. Among renewable energy resources, biomass records the highest rate (0.0149 fatalities GWy^{-1}). Wind power in United Kingdom has had 4 fatalities and 1500 accidents between 2007 and 2011 [58].

We estimated the maximum consequences of energy-related accidents by including the damage and external costs of fatalities, injuries, and evacuates [59]. The external costs include resource costs, opportunity costs, mental trauma, food and land contamination, dis-utility costs, and other possible economic losses. However, due to the lack of information, in the case of solar photovoltaic, onshore and offshore wind power, we calculated the direct damage costs of fatalities only. The accident costs of nuclear power are \$1.38 $\times$ 10^{-3} MWh^{-1}, the highest costs are \$5.77 $\times$ 10^{-2} MWh^{-1} for oil power, and the lowest costs are \$ 5.87 $\times$ 10^{-5} MWh^{-1} for solar photovoltaic. Overall, the maximum nuclear power scenario has the lowest costs (\$3.32 GWh^{-1}), and the renewable energy with natural gas has the highest costs (\$18.32 MWh^{-1}).

6.4. Sustainability assessment

Fig. 3 presents the total sustainability of each proposed energy mix option using the following 'impact' (I) equation:

$$\text{impact} = \sum_{\text{indicators}(i)} v_i * w_i \tag{2}$$

where v = the normalised value of impact i to n, and w = its weight. The economic index is normalised by the levelised cost of electricity, the environmental index is the average of normalized GHG emission intensity, water consumption intensity and land transformation intensity, and the social index is the normalized sum of all air pollutants. This process gives the same weight to each environmental, economic and social influence. Thus, the sum of all values of each energy mix option is the negative impact value (lower values imply a less-negative impact).

The result with the same weight value for all indicators ($w = 1$) is presented in Fig. 2. In theory, other weights could be applied that place greater or lesser emphasis on either economic, environmental or social concerns, and this could affect the relative rankings of the scenarios. However, such adjustments are necessarily arbitrary and contingent on personal or socio-political norms. The maximum nuclear power scenario records the highest rank (negative) on heated water discharge, while the current condition ranks worst on safety, solid waste, radioactive waste (including emissions of particulate radioisotopes from fossil-fuel combustion), and air pollution. The renewable energy scenarios commonly have higher negative values for the economic dimensions, greenhouse gas emissions and land transformation.

To reduce the impact of a single indicator, we used the criteria (dimensions) and sub-criteria (indicators) structure. Total negative values are the sum of the dimensions, and the dimension values are the average of related indicators. Compared with the current condition, all scenarios reduce environmental and social negative impacts. In particular, the nuclear power scenario has the lowest values for all dimensions. Overall, the current condition has the highest total negative value (1.93), and the maximum nuclear power scenario has the lowest (0.26), followed by the nuclear power with natural gas scenario (0.59). Based on these conclusions, the maximum nuclear power scenario is the most desirable pathway for South Korea to achieve the highest sustainability of the electricity-generation sector.

For other nations, the result might be different depending on varying geographical, social and economic characteristics. These differences can result in different weightings for each indicator [60]. For example, Japan might choose to apply similar weightings to South Korea, due to similar geographical and social structures such as landscape, population density, per capita electricity consumption and industrial structures. Due to the recent Fukushima Daiichi nuclear crisis [46], with public opinion running against nuclear power, the Japanese may elect to reduce the weights for nuclear power. As another example, the low population densities of Australia and United States, which are only 3 and 32 persons km^{-2}, respectively, could opt to (for instance) reduce the importance of land and water consumption indices [61].

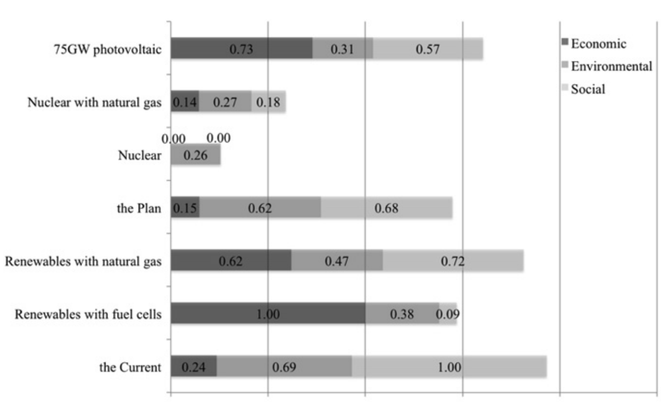

Fig. 3. A normalised result of negative economic, environmental and social impacts based on various sustainability criteria. The economic index includes levelised cost of electricity, environmental criteria include greenhouse gas emissions, land transformation and water consumption, and social criteria include air pollutant emissions.

7. Conclusions

Ours is the first attempt to analyse sustainable energy options in South Korea holistically across the entire electricity sector based on an hourly modelling approach. For our scenario analysis, we applied the physical and fuel limits of renewable, nuclear and fossil energy resources under six scenarios to deliver four main conclusions: (*i*) renewable energy cannot provide total electricity consumption in South Korea; (*ii*) a massive expansion of solar power will act to save only a small amount of backup fuel at greatly increased costs; (*iii*) a pathway to maximize renewable energy causes more environmental and economic disadvantages than the *status quo* or higher nuclear power penetration options; and (*iv*) maximizing nuclear power is the most sustainable option for South Korea.

There are a number of issues that prevent a complete comparison among scenarios, such as radioactive, heavy metal and ash wastes, safety issues or accidents, social stigmas, visual pollution (i.e., unattractive infrastructure), landscape changes and other aspects of social acceptance. The perceived and real dangers associated with radioactive waste are often unacceptable to people, and require a combination of public education and further technical progress [62]. From an engineering standpoint, Generation IV nuclear fission power plants can substantially reduce the amount and radiotoxic lifespan of fission waste and greatly extend fuel supplies through advanced recycling methods [41]. Nuclear power is also statistically safer than hydro or fossil fuel power, in terms of the number of direct fatalities or injured [56,63], and next-generation plants further improve this advantage using passive safety systems. Besides, renewable energy sources are also not immune to social stigma and planning and siting impediments, especially when built out at a large scale [12,64,65]. For instance, Stephenson and Ioannou [12] surveyed renewable energy acceptance trends in New Zealand and showed that about 81% of respondents are supportive of wind power, but only 46% are supportive when wind power plants are located within 2 km from their home, and only 20% are supportive if noise can be heard in their home.

A pathway focused on renewable energy does not solve all environmental, economic and social problems in South Korea. Our analysis clearly shows that an overemphasis on renewable compared to nuclear energy can in fact aggravate environmental problems. The principal barriers to wider adoption of nuclear power are not conditional on physical, reliability or economic constraints, but rather are linked to anecdotal public beliefs on renewable energy and inadequate evaluation on alternative energy options. To mitigate climate change effectively while supporting economic growth and a reliable and expanded electricity supply, South Korea has to consider increasing the role of nuclear power.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2013.02.010.

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