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At the crossroads: An uncertain future facing the electricity-generation sector in South Korea

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Abstract

Nuclear energy has provided a major source of clean electricity for South Korea over decades. However, the South Korean Government announced an energy transition roadmap aiming to reduce nuclear shares and increase renewable shares. However, given the nation's high population density, the maximum share of renewable sources for electricity generation in South Korea is constrained. The roadmap was silent on how to fill the gap between a reduced nuclear output and the limited renewable potentials. The tacit alternatives are fossil fuels, and their deployment will become the key determining factor on how South Korea approaches the problem of greenhouse gas emissions reductions. We used scenario analysis to investigate two fossil-intensive cases, alongside a hypothetical renewable case. On the basis of the comparison of the three scenarios with other countries, we provide an insight into the feasibility and limitations of the nonnuclear options and propose the techno-economic requirements for avoiding the worst outcomes.

KEYWORDS

carbon emissions, energy transition, fossil fuels, nuclear phase-out, renewable resources

1 | UNCERTAIN FUTURE OF ELECTRICITY GENERATION IN SOUTH KOREA

Over the past few decades, nuclear power has provided the majority share of clean electricity in South Korea and has been a bedrock of economic development. However, following a vigorous public debate in that country on the merits of nuclear energy versus other forms of low-carbon electricity generation, a citizen's jury was appointed by the government to gauge public opinion on the matter. On October 20, 2017, the jury released a decision that construction of two nuclear reactors (Shin Kori 5 and 6) ought to continue through to completion but also recommended a reduction in the nuclear share over the longer term by pursuing a higher future share of renewable energy (Office for Government Policy Coordination, 2017). Based on the citizen's jury report (which is not legally binding), the government subsequently published an energy transition roadmap (hereafter "the roadmap"), which aimed to increase the share of renewable electricity generation in South Korea to 20% by 2030, up from 7% in 2017. The roadmap also included terms that proposed prohibiting any licence extensions for existing nuclear power plants and the cancellation of all construction proposals for any new nuclear reactors with the goal of reducing the number of reactors to 14 by 2038 (compared with 24 in 2017, and 28 projected for 2022; Ministry of Trade Industry and Energy, 2017).

However, the roadmap was silent on a critical question: How will South Korea fill the gap between the reduced nuclear and its physical constraints on renewable energy generation (Hong & Brook, 2018) if the nation also intends to reduce carbon emissions from its electricity generation as per the 2015 Paris Climate Agreement (NRDC, 2015)? Currently, the generation gap between the 30% nuclear and 7% renewable share is met almost entirely by fossil fuels (coal 40% and gas 22%). If fossil fuels replace nuclear, annual carbon emissions from electricity generation will increase substantially, whereas if growth in renewables serves only to replace nuclear (as has occurred recently for Germany, Amelang, 2017; Reed, 2017), then emissions reduction will stall. Considering the scale of economy and the current emissions profile of South Korea, failing to meet its carbon-reduction target will have a significant negative impact on the global efforts (Normile, 2017). To answer these question, we speculate on three potential future electricity mixes based on the roadmap and current conditions for South Korea. We then investigate the feasibility, limitations, and requirements of each case by comparing with other Organisation for Economic Cooperation and Development (OECD) member states.

2 | CARBON EMISSION IN SOUTH KOREA

Annual carbon emissions in South Korea 2014 (the latest year with complete data) was 568 million tonnes (Mt) of CO_2, ranked fourth of 35 OECD member states following the United States (5,176 Mt CO_2), Japan, (1,189 Mt CO_2), and Germany (723 Mt CO_2; OECD, 2017); this is an increase of 145% compared with 1990 levels. Turkey (142%) and Chile (158%) were only two other OECD member states that experienced carbon emission rise to an equivalent extent (i.e., >100% from 1990 to 2014). (By contrast, during those same 25 years, 18 OECD member states reduced their annual carbon emissions.) The annual per capita carbon emissions of South Korea were sixth in the world at 11.3 t $person^{-1}$ following Luxembourg (16.6 t $person^{-1}$), United States (16.2 t $person^{-1}$), Australia (15.8 t $person^{-1}$), Canada (15.6 t $person^{-1}$), and Estonia (13.3 t $person^{-1}$). South Korea recorded the highest per capita carbon-emission growth (108%) between 1990 and 2014 among all OECD member states.

South Korea has submitted internationally its intention to reduce greenhouse gas emissions to 37% below the business-as-usual level of 851 Mt CO_2eq by 2030 (NRDC, 2015). Compared with the goals of other OECD member states, such as European Union (40% below 1990 levels by 2030) and Japan (15% below 1990 levels by 2030, excluding land use and land-use change), the emissions-reduction target of South Korea (81% above 1990 levels by 2030) is clearly not ambitious. If all countries were to adopt the same modest goals, then global average temperatures would be anticipated to rise well above 2 °C compared with the preindustrial period by 2050 (CAT, 2017). Indeed, even those collective carbon-reduction proposals submitted by the other OECD member states are not sufficient to limit the global average temperature rise below the Paris Agreement level (1.5–2 °C; Hulme, 2016). Deeper and more rapid emission cuts will be necessary to avoid potentially disastrous environmental and economic problems (Figueres et al., 2017). We argue that to respond appropriately to global benchmarks, South Korea—as one of the world's largest carbon emitters—must expect to have stronger greenhouse gas emission reduction targets than at present. However, given that nuclear power has provided emission-free baseload power in South Korea, removing it from the electricity portfolio is likely to make any such aspiration all but impossible to achieve (Hong, Qvist, & Brook, 2018).

3 | FUTURE ELECTRICITY MIXES

According to South Korea's draft 8th Electricity Generation Plan (Park, 2017), peak electricity demand in 2038 is expected to be 113.5 GW, but peak-generation capacity will need to be 138.5 GW to incorporate a reserve margin of 22%. If annual generation growth follows the peak demand growth rate proportionally, then annual electricity demand will reach 609 TWh of in 2038, compared with 543 TWh in 2016 (KESIS, 2017). Note that this demand forecast does not incorporate the potential electrification of transport sector (498 TWh of final energy in 2016).

The flagship goals of the roadmap are to achieve 20% renewables by 2030 and limiting the total capacity of nuclear power to 16.4 GW by 2038 (Ministry of Trade Industry and Energy, 2017), the latter yielding about 136 TWh of final energy (assuming a capacity factor of 90%).[1] If the renewable share continues to grow at the same rate thereafter, it will reach about 30% (183 TWh) by 2038. Nuclear and renewables, together, would then provide about half of the total annual electricity demand.

How, then, can the other half of the electricity-demand equation be solved without an expanded nuclear option? The only feasible options available on the market today are the two fossil fuel-based power sources (natural gas and coal), additional renewables, or some combination of these (Figure 1). Below, we analyse the two extreme cases to highlight the probable technological, economic, and environmental issues related to a future increasing fossil fuel share in South Korea:

- Case 1 (similar to the current German solution): Annual generation of coal will remain at current levels (214 TWh), and gas will meet peak demand (76 TWh).
- Case 2 (akin to the historical United Kingdom [UK] pathway): Gas becomes the major source of electricity (290 TWh) and replaces coal power.

[1] 6.1 GW * 8,760 (hours a year) * 0.95 = 50,765 GWh.

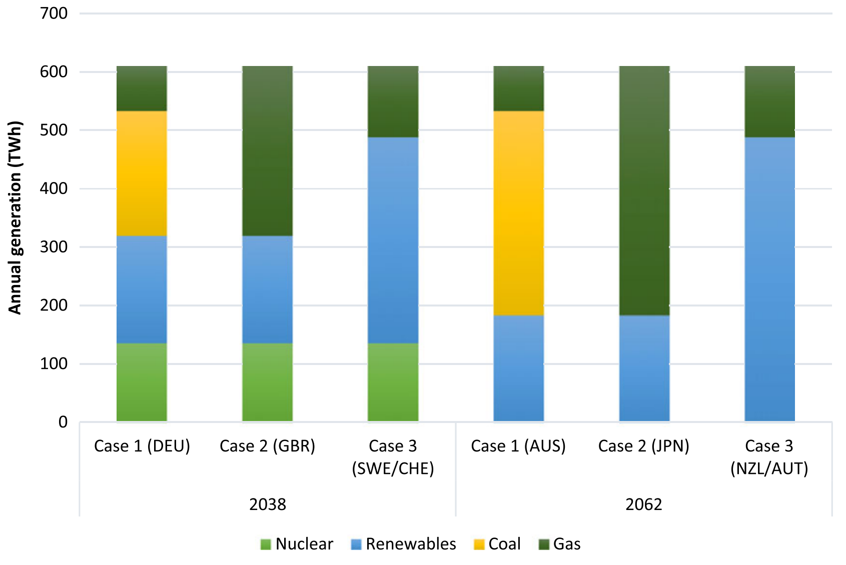

FIGURE 1 Electricity generation (terawatt hours, TWh) and share (%) of three hypothetical future scenarios for South Korea, based on a mix of nuclear, renewables, coal, and gas, each for two-time points (2038 and 2062), with OECD analogies

If cutting carbon emissions from electricity generation, combined with a nuclear phase-out, are two resolute objectives of a future electricity mix for South Korea, and gas remains at the current level, then renewables will need to replace the entirety of coal generation.

- Case 3 (the Swiss/Swedish pathway): Renewables become the major source of electricity (352 TWh), and gas remains at current levels (121 TWh).

If the licence extensions for existing nuclear power plants are prohibited, and no new nuclear power is constructed after the completion of Shin-Kori 5 and 6 (scheduled for 2022, with a 40-year lifespan), then South Korea should achieve a nuclear-free electricity mix by 2062. Predicting long-term electricity demand is fraught with uncertainties due to changing socio-economic drivers such as demographic, industrial, technological, and other behavioural changes. However, given that the future population of South Korea is not expected to increase significantly over the long-term future (Raftery, Li, Ševčíková, Gerland, & Heilig, 2012), it is unlikely that its electricity demand increases substantially (unless electric vehicles become ubiquitous). We therefore conservatively assume, for the purposes of this analysis, that long-term electricity demand will remain at the 2038 level (609 TWh) thereafter. Based on this demand profile, we extended our thought experiment to cover three potential future electricity mixes by 2062 (with the most similar/matching OECD country given in brackets):

- Case 1 (Australia): Coal replaces nuclear whereas gas remains at 2038 level.
- Case 2 (Japan): Gas is the main source of electricity generation.
- Case 3 (New Zealand or Austria): Renewables are the main source of electricity generation, and gas supports peak demand.

4 | CASE 1: TOWARD AUSTRALIA VIA GERMANY

The roadmap has a similar target with the German Energy Transition ("Energiewende"), which seeks to close all nuclear reactors by 2022 and increase the share of renewable sources to by 80% by 2050 (Amelang, 2017). For reference, renewables currently generate about 30% of the annual electricity generation in Germany, with nuclear and coal at 14% and 44%, respectively (International Energy Agency, 2017), with wind as the main source (40% of the total renewable generation) of renewable electricity. Dispatchable renewable sources, such as hydroelectricity (12%) and biomass/waste combustion (28%), also supply a large fraction of the renewable electrical energy generated. Although Germany has spent €189 billion since 2000 to increase renewables, the proportional share of coal share has not reduced and will remain in the electricity generation portfolio through to 2050 (Amelang, 2017; Reed, 2017).

For Australia in 2015, coal (63%) was the main source of electricity, followed by gas (21%) and renewables (14%). Although Australia's renewable shares are lower than the hypothetical Case 1 for South Korea in 2062, Australia still arguably represents this case most closely, because of its high share of coal and gas. Greenhouse gas emission intensities for Australia's electricity sector (755 kg MWh^{-1} in 2015) is >40% higher than those of South Korea (526 kg MWh^{-1} in 2015; IEA, 2017). Increasing the share of coal generation will also inevitably lead to higher air pollution compared with nuclear, which have health risks and cause numerous environmental problems (Hansen et al., 2013).

Given the lower construction costs of gas or traditional coal power plants compared with a modern nuclear station, and with typically much shorter construction periods, fossil fuels can readily replace nuclear. However, increasing carbon intensity is a major issue for Case 1 and will lead to a failure to meet South Korea's agreed emissions-reduction target. Carbon-capture-and-storage technologies are the potential saviour of this case, but its technological and economic feasibility remains questionable (Leung, Caramanna, & Maroto-Valer, 2014). Further, replacing nuclear with coal will increase the electricity price slightly, given that nuclear power is now the cheapest option in South Korea (KESIS, 2017). Higher renewable shares will increase the electricity price due to the inherent high generation cost of renewables, especially when considering balancing and storage needs (Alexander, James, & Richardson, 2015).

5 | CASE 2: TOWARD JAPAN VIA THE UK

The natural gas share for electricity generation in the UK has increased rapidly since the 1990s following the Thatcher-driven coalmine closures and North Sea hydrocarbon expansion. Gas had reached ~30% of its electricity generation by 2015, with nuclear at 21%. Although the UK still has a higher reliance on coal than Case 2 (in 2038 for South Korea), in terms of total fossil fuel and nuclear shares, this scenario resembles the UK situation in 2015. Following the Fukushima Daiichi incident, Japan stopped all nuclear power plants, and fossil fuels, with an increasing reliance on gas (now at 40% of electricity supply, with fossils fuels at 73% of the total), illustrating a situation somewhat analogous to Case 2 for South Korea in 2062. At present, the gas share of electricity generation in South Korea is much lower (22% in 2016) than the annual gas generation projected for Case 2. However, given the currently low capacity factor of gas-fired power (41% in 2016) in South Korea (KESIS, 2017), a shorter construction time and lower overnight costs than a nuclear power plant, a future focus on combined-cycle gas plants and shift away from nuclear (both 38% in 2038, and 70% gas in 2062) seems technically feasible.

Gas has lower greenhouse gas emission intensities (470 g CO_2e kWh^{-1} for life-cycle emissions and 64.2 t CO_2 TJ^{-1} during generation) compared with coal (970 g CO_2e kWh^{-1} and 98.3 t CO_2 TJ^{-1}, respectively; IPCC, 2006; NREL, 2017). Given that nuclear is a zero-carbon-emission source at generation, a shift from nuclear to gas will cause a net increase in greenhouse gas emissions from electricity generation (e.g., the UK stands at 349 kg MWh^{-1} in 2015, with a lower nuclear, lower coal, and higher gas share than South Korea at 526 kg MWh^{-1}). In contrast, post-Fukushima Japan has slightly higher greenhouse gas intensities (540 kg MWh^{-1}) than South Korea. A higher gas share of Japan lowered its greenhouse gas intensities, despite a lower nuclear share.

One of the main motivations behind the antinuclear movement in South Korea is public fear of nuclear accidents and their subsequent health effects. However, gas has a far worse safety record than nuclear power, in South Korea (or indeed anywhere else). Compared with nuclear power, which is yet to record a single fatality in South Korea, a gas explosion in Daegu killed over 100 people (Associated Press, 1995). The price volatility of natural gas, which because of its substantial influence of the levelised cost of gas-derived electricity can lead to significant electricity price fluctuations, is a major economic problem of gas-based power systems (van de Ven & Fouquet, 2017). The UK reduces this risk by sourcing 45% of their demand domestically (British Gas, 2016) and has Japan diversifies its import sources (EIA, 2017). Given that South Korea does not have any domestic gas reserves, the entire gas demand for electricity generation must be imported. As such, high reliance on a single source with high price volatility will clearly increase uncertainty in its economic condition.

6 | CASE 3: TOWARD NEW ZEALAND OR AUSTRIA VIA SWITZERLAND OR SWEDEN

Some OECD-member states do have >60% of renewable shares, such as Iceland, Norway, New Zealand, Austria, Canada, and Portugal. The maximum share of nonhydroelectric power is about 57%, for Denmark. Given the renewable share (58% in 2038 and 80% in 2062), and nuclear and gas shares of Case 3, either New Zealand or Austria might serve as an example for South Korea by 2062, with Switzerland or Sweden a midrange example by 2038.

The major renewable source is hydroelectric power for both Austria (69% of the total electricity consumption) and New Zealand (56%). The major hurdle of Case 3 is the technical (or geographical) feasibility of renewable sources on the southern Korean peninsula. The feasible maximum annual generation from renewable sources, including hydroelectric, wind, solar, and bioenergy, has been estimated in prior modelling to be limited to 150 TWh (Hong, Bradshaw, & Brook, 2013). Even if the generation efficiency of nonhydro renewable technologies increases significantly (e.g., to 33% by 2038), the maximum potential annual supply will still be no more than ~200 TWh. Therefore, supply 80% in 2062 (i.e., ~487 TWh), or even 58% in 2038, from domestic renewable sources such as wind, solar, and hydroelectricity, is completely unrealistic. Bioenergy can be produced, with fuel imported from foreign countries, but bioenergy is not considered environmentally friendly in terms of either net greenhouse gas emissions nor land use and associated ecosystem impacts (Manning, Taylor, & Hanley, 2015).

Even if the geographical limitation could hypothetically overcome, a high share of variable renewables such as wind and solar will increase grid-management and load-balancing costs including curtailment, frequency management, voltage regulation, and backup/storage costs (Brouwer, van den Broek, Zappa, Turkenburg, & Faaij, 2016). The poor management of voltage and frequency control across electricity networks can cause a catastrophic blackout across the entire grid, as was evident in the September 28, 2016 in South Australia (AEMO and Manitoba HVDC Research Centre, 2017). Moreover, analysis has shown that as the share of variable renewables climbs, there is a reduction in the usability of electricity so generated, due to mismatches with electricity demand (Steinke, Wolfrum, & Hoffmann, 2013). As such, high management costs, low capacity factors and usability, and high levelised costs of high-penetration renewable energy sources that includes full system costs will almost certainly increase the average electricity price of South Korea in under Cases 3 and 6.

7 | THERE ARE NO "NO REGRETS" CASES

Overall, Case 1 is environmentally disastrous due to its high greenhouse gas emissions and rise in local air pollution levels. Although grid flexibility is higher than for Case 3, the higher renewable shares compared with the current situation might even become an issue for Case 1. Case 2 has lower greenhouse gas emissions than Case 1. However, under either of these scenarios, South Korea will fail to decarbonise its electricity generation sector and so breach its international climate commitments. A high gas share provides sufficient flexibility to the electricity grid and will reduce the balancing problem outlined in Case 2. Although the overnight investment costs for Case 2 is likely to be lowest among the three cases for 2038 (two decades hence), the cost volatility of imported gas sources could lead to major economic problems. Case 3 is the most environmentally friendly in terms of greenhouse gas emissions, but the geographical limitations of renewable sources is a serious barrier that cannot be resolved by any current technological innovation or economic mechanism.

Moreover, about 1,792 PJ (498 TWh) of final energy demand for transport in 2016 was not included in the demand projections (KESIS, 2017). Current oil-based vehicle fuels will need to be substituted, with either hydrogen fuel cells or battery-powered electricity if South Korea is to decarbonise its transport sector. Despite the potentially substantial increase in annual electricity demand due to a need to produce hydrogen (via electrolysis of water) or charging batteries, the draft 8th Electricity Generation Plan did not include any assessment of the potential impact of the increase. Under any of the Cases we examined, strong demand-side energy efficiency measures (technological improvement, economic incentives, etc.) would need to be introduced to limit the future increases in electricity demand. A modelling study, which evaluated the theoretical potential of renewables in South Korea (Hong et al., 2013), concluded that the maximum annual production would be <150 TWh. Given the limited land area and high population density, but long coastline of South Korea, offshore renewable energy locations would need mapping and assessment for potential exploitation.

Technological development in renewable energy has led to higher efficiency and lower installation and management cost (Rubin, Azevedo, Jaramillo, & Yeh, 2015). Despite such efforts and advances, however, a wind turbine cannot generate electricity in becalmed conditions, and a solar panel cannot generate electricity at night or under cloudy skies. Energy storage can provide multiple benefits to the electricity grid with high variable renewable penetration, including as load shifting, demand-side management, and voltage and frequency control (Luo, Wang, Dooner, & Clarke, 2015). Due to the required scale and economic feasibility, pumped-hydro storage has, to date, been the main form of energy storage deployed for use in electricity-grid management worldwide (Department of Energy, 2015). However, because the geographically available locations for hydroelectric power and pumped-hydro storage is already almost fully exploited in South Korea, retrofitting conventional hydroelectric power plants to use pumped hydro storage systems is the only economically viable option at scale. Large-scale electrochemical energy storage systems can be commercialised, but their economic feasibility at scale has not yet been proven (Luo et al., 2015).

It is therefore highly likely that, should the announced antinuclear policies prevail, the future power mix of South Korea will be based principally on imported fossil fuels. Some advanced coal-fired power plants, such as integrated coal gasification combined cycle power generation systems, offer a higher generation efficiency than conventional coal power plants (Hoya & Fushimi, 2017). Currently, 300 MWe of integrated coal gasification combined cycle is being operated in South Korea, with another 400 MWe plant under construction. Although advanced coal power plants might lower the carbon emissions during combustion (approximately 85% of the emissions of equivalent conventional coal-fired power plants) due to the higher generation efficiency, carbon-capture-and-storage technologies will be an essential component for deep cuts to greenhouse gas emissions under a nuclear-free future. Unfortunately, given the technological and economic problems (and public concerns) facing carbon-capture-and-storage (Leung et al., 2014), it is unrealistic to expect commercialisation in the foreseeable future. If it is not commercialised in a timely manner, it is virtually inevitable that South Korea will not be able to decarbonise its entire energy sector even in the long-term future.

Nuclear power can, if supported by policymakers and the public, overcome most (if not all) of the technical problems that renewables and carbon capture and sequestration face. Nuclear power in South Korea has historically recorded the highest level of reliability (>95% capacity factor) and safety (0 fatalities) of any energy source; the lowest generation cost (it is cheaper than coal [imported fuel] in South Korea, even including decommissioning and spent-fuel-management costs) and greenhouse gas emissions (40 g CO_2e kWh^{-1} for life-cycle emissions and 0 t CO_2 TJ^{-1} during generation; Hong & Brook, 2018). Currently, the construction cost of nuclear power in South Korea is reasonably low (<2010 US$ 3,000 kW^{-1}) compared with other western systems, due to a standardised manufacturing process and repeated builds of new plants (Lovering, Yip, & Nordhaus, 2016). Technological development of nuclear reactors, in contrast to renewable energy sources, bolds the promise of providing reliable, clean, and safe energy, in the form of electricity, heat, and as a derivative: synthetic fuels (e.g., hydrogen; Brook, Blees, Wigley, & Hong, 2018).

8 | SOUTH KOREA'S ELECTRICITY SECTOR AT THE CROSSROADS

The electricity sector of South Korea stands at a crossroads, with four possible directions to travel including a nuclear pathway. Unfortunately, one of these pathways (a high-nuclear scenario) now seems closed. The energy transition roadmap released in late 2017 by the South Korean government did not consider long-term energy-deployment trajectories. Given the insufficient renewable potential of the Korean peninsula, coupled with an isolated grid network, high population density, and intense economic activity, the road to a destination of high renewable shares seems destined to traverse much rocky and hazardous terrain. As a consequence, South Korea will also certainly end up following the path toward high-density sources of fossil energy: coal and gas. However, any such decision will increase greenhouse gas emissions and air pollution, substantially increase the nation's reliance on energy imports and lead to serious environmental, economic, and social problems in the future.

Fortunately, South Korea still has time and sufficient capability to avoid this energy future. It is one of a few countries to have built sufficient expertise, experience, and domestic manufacturing facilities to be in a favourable position to expand its reliance on nuclear power in the decades to come. However, the public unacceptance of nuclear power remains a barrier to its large-scale deployment. It is a political "hot potato," with the (very) low probability but high impact (economically and psychologically) incidents that have occurred in recent decades in the former Soviet Union and Japan constituting the major challenge to the further deployment (Chung, 2018; Hasegawa et al., 2015; Miyazaki & Hayano, 2017). The public debate on Shin Kori 5 and 6 was a good example of the importance of public education to overcome the public unwillingness. Persistent efforts to engage the public in a dialogue about the nation's energy future, based on logic, analogy, and scientific evidence, should provide more opportunities for nuclear power in South Korea. It is not too late to backtrack. South Korea can still reconsider its roadmap, and in doing so, set an example to the world on carbon mitigation.

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