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Full-length article

Feasibility trade-offs in decarbonising the power sector with high coal dependence: The case of Korea

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ABSTRACT

Decarbonising the power sector requires feasible strategies for the rapid phase-out of fossil fuels and the expansion of low-carbon sources. This study assesses the feasibility of plausible decarbonisation scenarios for the power sector in the Republic of Korea through 2050 and 2060. Our power plant stock accounting model results show that achieving zero emissions from the power sector by the mid-century requires either an ambitious expansion of renewables backed by gas-fired generation equipped with carbon capture and storage or a significant increase of nuclear power. The first strategy implies replicating and maintaining for decades the maximum growth rates of solar power achieved in leading countries and becoming an early and ambitious adopter of the carbon capture and storage technology. The alternative expansion of nuclear power has historical precedents in Korea and other countries but may not be acceptable in the current political and regulatory environment. Hence, our analysis shows that the potential hurdles for decarbonisation in the power sector in Korea are formidable but manageable and should be overcome over the coming years, which gives hope to other similar countries.

Introduction

Many countries have embarked on profound transformations of energy systems to minimise their climate impacts while supporting economic development. Especially urgent are transitions in the power sector given its large climate impact, readily available low-carbon power generation technologies, and the importance of clean electricity for decarbonising other economic sectors such as industry, transportation, and buildings. Many governments, therefore, have committed to eliminating or radically reducing CO_2 emissions from their power sector by mid-century or earlier. This requires a radical and rapid transition of electricity supply to one or several low-carbon technologies such as nuclear power, renewables, or carbon capture and storage (CCS). Are such transitions realistic in countries like the Republic of Korea that currently rely heavily on fossil fuels?

Scholars have traditionally assessed the feasibility of the power sector decarbonisation by modelling plausible scenarios of the evolution of power sector technologies that can, on the one hand, provide a reliable and adequate supply of electricity [1,2], and on the other hand, reduce carbon emissions to meet the targets [3,4]. Power sector decarbonisation scenarios tend to respect known constraints that affect the speed and scale of electricity decarbonisation. These constraints include the availability of natural resources, such as hydro, solar, and wind power [5], and land for biomass production and for storing captured

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Abbreviations: CO_2, carbon dioxide; CCS, carbon capture and storage; MW, megawatt; GW, gigawatt; UAE, United Arab Emirates; NPSP, National Power Supply Plan; OECD, Organisation for Economic Co-operation and Development; NDC, Nationally Determined Contributions; GHG, Greenhouse Gas; IPCC, Intergovernmental Panel on Climate Change; IAMs, Integrated assessment models; KEPCO, Korea Electric Power Corporation; Mt, Megaton; Gt, Gigaton; PV, Photovoltaic; UK, United Kingdom; TWh, Terawatt-hour; FGD, Flue gas desulphurisation; GDP, Gross domestic product; US, United States.

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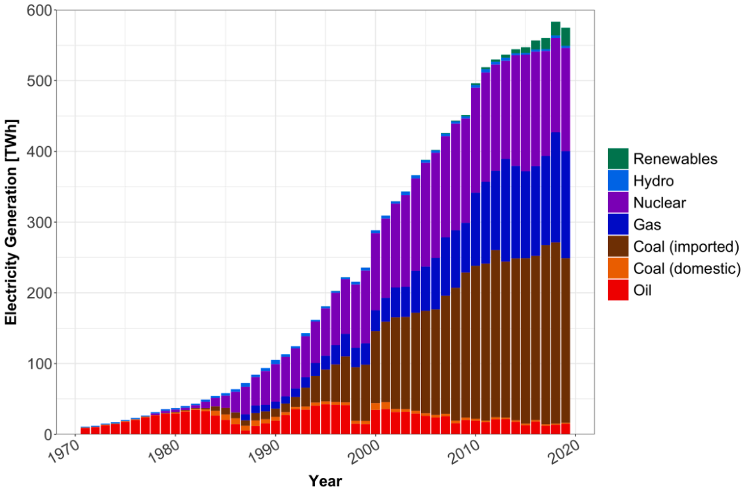

Fig. 1. Electricity mix in Korea over time.

CO_2 [6]. Other constraints include the time necessary for newer low-carbon technologies (e.g., CCS and electricity storage) to become widely commercially available, accessibility of financial resources [7], the social acceptance of new technologies [8], and the resistance of carbon-intensive sectors to phase-out of fossil fuels [9].

Although some of these constraints are already routinely incorporated in energy transition scenarios, there are proposals to improve underlying energy models to include as many other factors and parameters as possible [10,11]. One of the valuable tools to represent long-term decarbonisation pathways in the power sector is integrated assessment models (IAMs), which typically produce a set of cost-effective technology portfolios without specific technology mandates or market regulations [12]. However, several concerns remain with the IAMs that endogenise technology investments, such as lack of transparency [13] and uncertainties inherent in assuming a variety of model parameters [14]. It seems unlikely that future models will be able to incorporate all or even the most critical constraints because some of them are hard to quantify or generalise across countries, technologies, or time periods. Furthermore, it is often difficult to disentangle individual constraints from the aggregate effect of multiple and interacting factors, some of which may be unobservable. Hence, there have also been calls for assessing the feasibility of energy transition scenarios based on historical experience [15,16].

Several methods have recently been proposed for assessing the feasibility of near-term coal phase-out pledges [17], expansion of solar and wind power [18], and decline of fossil-powered electricity [19]. Yet most of this work has focused on assessing a particular aspect of decarbonisation at the global or continental level while leaving the feasibility trade-offs between multiple interacting technologies in national decarbonisation scenarios largely unexplored.

To fill the gap in the literature, a new approach to constructing and assessing the feasibility of decarbonisation scenarios is especially needed in Korea, which has an impressive national decarbonisation target that would require rapid power sector transformation. The target may or may not be ambitious because Korea currently relies heavily on coal and has a relatively limited hydro-, wind-, and biomass power potential, while at the same time, the nation is a large, wealthy, and technologically advanced economy that is a leader in many energy technologies including nuclear power. To support policymakers in making concrete plans, such decarbonisation scenarios should contain maximum detail about near- and longer-term electricity systems at any given point in time. In the case of Korea, several sectoral-level decarbonisation pathways have been constructed [20,21]. Still, none included details at the level of individual power plants and associated feasibility assessments.

Thus, we set up the following research questions: 1) How feasible are electricity decarbonisation scenarios with alternative technology pathways based on Korea's long-term power supply plan? 2) What are the trade-offs between constraints in different generation technology mixes presented by the decarbonisation scenarios? The main objective of this paper is to assess the feasibility of the scenarios in light of the historical experience of energy transitions from Korea and other countries. We develop a set of detailed and maximally consistent electricity decarbonisation scenarios for Korea, exploring several controversial technology options based on a fine-grained capital stock accounting model fully compatible with plant-level historical data and government projections and plans. The realism of scenarios is then discussed using quantitative and qualitative measures such as the historical growth of each technology options and technology readiness. Our framework can be replicated to examine the feasibility of other countries' decarbonisation scenario in the sense that it requires simple calculations of the growth rates for generation technologies under national historical experience and decarbonisation scenarios, which is built on the concept of the feasibility space [16] and the recent analysis of feasible rates of expansion [18] and contraction of energy technologies [19].

The paper is constructed as follows. In the next section, we provide a background to the power sector in Korea and summarise the existing approaches to feasibility. The third section describes our model, the scenario logic, and the feasibility assessment method. The fourth and fifth sections report and discuss our results. In particular, we show that the major trade-off is between an ambitious build-up of nuclear energy, which is likely constrained by social acceptance, and rapid deployment of carbon capture and storage, which have uncertainties regarding technology readiness, costs, storage sites availability and unknown public attitude. The last section concludes by summarising results and recommendations for policies and further research.

Material and methods

Background to the power sector in Korea and climate and energy targets

To secure cheap and reliable electricity as a necessary means of industrial development, Korea has relied on fossil fuels and nuclear power in its power production since the 1970s for rapid economic and energy growth (Fig. 1). In particular, coal and nuclear power that serve as a base load account for about 70% of the total electricity supply [22]. This path frames three challenges to a rapid energy transition towards a low-carbon economy in Korea.

First, coal power plants in Korea are, on average, relatively young. Most large coal power plants (with capacity > 500 MW) have been built

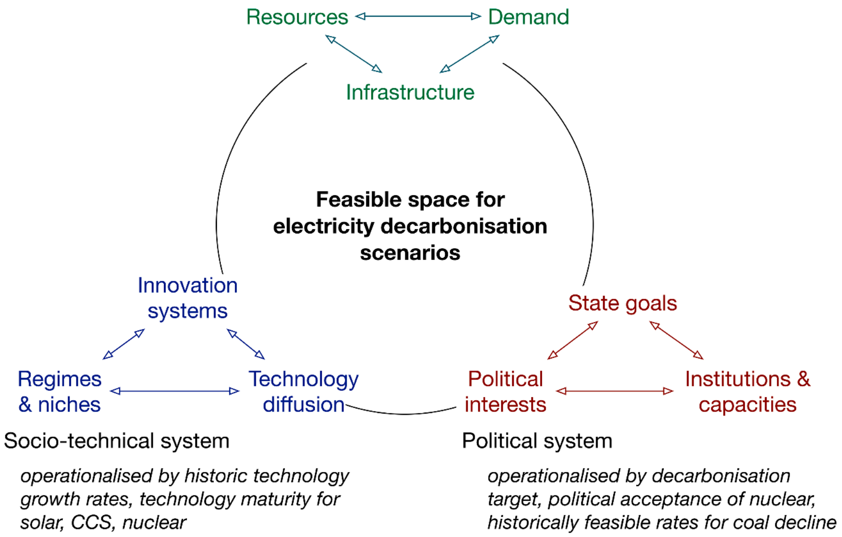

Fig. 2. Conceptual framework of feasibility spaces.

over the last 20 years. In addition, many coal-fired plants have been granted lifetime extensions to allow performance improvement retrofits (see Supplementary Note 1). Retiring young power plants runs a risk of stranded assets and is likely to encounter stronger resistance [17].

Second, Korea indicated an intention to phase-out nuclear power [23].[1] Korea is the fifth-largest nuclear power producer globally, and nuclear power accounts for about one-fourth of the country's electricity generation in 2019 [24]. Korea also exports nuclear technology to other countries, most recently to the United Arab Emirates (UAE). However, in recent years there have been calls to reduce the reliance on nuclear power due to the public's anti-nuclear sentiments that have emerged from several issues, such as safety concerns and mistrust of the government [25]. However, simultaneous nuclear and coal phase-outs like the one pursued by the 9th National Power Supply Plan (NPSP) [26] seem challenging as these are the nation's two main baseload electricity components.

Third, although the Korean power sector has experienced a steady growth of renewable capacity since 2013, the deployment of renewable sources remains limited to hydropower resources, most of which are already used, and to a lesser extent to wind and solar power production. In particular, wind power in Korea provides less than 1% of electricity generation, lagging far behind most other Organisation for Economic Co-operation and Development (OECD) countries [18]. Furthermore, despite its recent growth, solar power provided only 3% of the total electricity supply in 2020 [27]. All renewable sources combined provided about 6% of Korea's electricity supply, the second-lowest amongst G20 countries. This means that expanding renewables to substitute both nuclear and coal power rapidly would represent a severe challenge.

Against these significant challenges, the Korean government is committed to accelerating the energy transition. In 2015, Korea submitted its first Nationally Determined Contributions (NDC) and presented a revised NDC roadmap in 2021, which pledged to reduce its total Greenhouse Gas (GHG) emissions by 35% below 2018 levels by 2030 [28]. On July 14th, 2020, the government announced the Korean Green New Deal [29] to pursue a carbon-neutral society [21]. Most recently, in October 2020, the president of Korea declared to the international community its national plan to become carbon neutral by 2050 [20]. According to the plan, the government will promote the rapid deployment of renewable energy (primarily solar power and wind), boosting investment in green technologies such as electricity storage systems and CCS. The carbon neutrality target requires that Korea's power sector becomes carbon neutral or even carbon negative by 2050 as GHG emissions from electricity generation take a majority share (37.8% in 2017) of total emissions, and the sector is strongly coupled with other sectors of the economy [30].

Specifically for the power sector, the 9th NPSP was announced in December 2020, which lays out a forecast of national electricity demand, future annual plans for investment and retirement of generation units, and transmission and distribution facilities from 2020 through 2034. The plan also stipulates three implementation details about the gradual phase-out of coal and nuclear units, transitioning to renewable energy sources and natural gas. First, new coal and nuclear plants will not be allowed to come online after 2024. Second, existing coal-fired units will be either retrofitted into cleaner natural gas units or pushed into early retirement. Third, existing coal-fired units will be operated at a lower utilisation rate. Fourth, renewable capacity will be increased from 20 GW in 2020 to 78 GW in 2034, raising the share of renewable electricity to 26.3% by 2034. These specific plant-level targets for coal phase-out and renewables expansion provide a base for our scenario assumptions to make the results more realistic and sensible.

Feasibility of power sector decarbonisation

Reducing carbon emissions from electricity generation requires either substituting fossil fuel combustion with low-carbon power technologies, such as nuclear or renewables, or equipping fossil-based power plants with CCS facilities. All these solutions come with their feasibility constraints, which are detailed in a growing body of literature [31,32]. Our paper accounts for constraints arising from three co-evolving but distinct systems involved in any national energy transition – energy flows and markets (where techno-economic constraints arise), energy technologies in their socio-technical contexts (where socio-technical constraints arise), and political action and policies (where political constraints arise) [33]. We then operationalize the key constraints for each system based on previous research and available data (Fig. 2).[2]

Techno-economic constraints are directly incorporated into the logic of our scenarios and include supply-demand balance, infrastructure ageing, and availability of natural resources [33]. Specifically, all four

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[1] For example, the Korean 3rd energy basic plan (2019), which is the national energy demand and supply roadmap, supports a phase-out of nuclear power. However, it is worth to be noted that the new government has recently announced a plan to scrap the nuclear phase-out policy pushed by the previous government.

[2] For more details in the concepts presented in Fig. 2, see Cherp et al. (2018).

scenarios envision that electricity demand in Korea will steadily increase and stabilise in line with economic and population projections. Our scenarios also use a simplified relationship between the variable and non-variable sources to ensure their hour-by-hour system reliability. We further take into account the limited potential of hydro and wind power in Korea [34], focusing on other technological solutions to decarbonisation. Finally, in considering the feasibility of CCS, we refer to its prospects for diffusion, such as infrastructure requirements and geological potential for storage.

With respect to socio-technical constraints, our scenarios rely on sufficiently mature technologies to be rapidly expanded in Korea given national innovation systems in Korea as well as international technology diffusion [33]. Nuclear power technology has been used globally for over 60 years and in Korea for the last 50 years. Korea is one of the few advanced economies capable of maintaining, and until recently expanding, a robust domestic nuclear sector and supplying nuclear power to other countries, most recently to the UAE. On the other hand, nuclear power shows signs of stagnation and decline globally [35], and there is a debate about whether its costs decrease [36,37]. To assess the socio-technical feasibility of the future expansion of nuclear power in Korea, we compare projected growth rates in each of the scenarios with the rates observed in Korea historically. This approach builds on the idea that historical realities reflect the aggregate of causal mechanisms that will also shape the future. Such comparisons have been made globally [38–41] and for individual regions [18,42] but not for specific countries.

In comparison, the solar power sector is relatively new to Korea and began to develop only 1–2 decades ago but is steadily expanding in Korea and around the world. Deploying solar power on a large scale would require addressing the challenge of its intermittency, with which various technological and market-based solutions are now being experimented. To assess the feasibility of rapid solar power expansion, we compare its required expansion rates with the maximum growth rates so far achieved around the world [18]. We apply a similar method to assess the feasibility of wind power deployment, a more mature renewable power technology globally that has experienced delayed introduction in Korea.

The third key carbon mitigation technology, CCS, is technologically ready [43] but at the moment exists primarily in demonstration plants and none in Korea except one demonstration project[3] scheduled to operate from 2025. It will arguably take more time to make CCS available and widespread in the country. To assess the feasibility of CCS deployment, we compare the scale of deployment in Korea with the worldwide scale of deployment envisioned in ambitious global decarbonisation scenarios such as the ones reported by the Intergovernmental Panel on Climate Change (IPCC) Special Report 1.5 [44] and more recently developed by the International Energy Agency [45].

Finally, political constraints may also limit the expansion of low-carbon technologies. One type of political constraint may be the resistance of the coal sector to the early retirement of coal power plants, as documented by Geels, Berkhout [10]. It may be one of the reasons for keeping countries from committing to coal phase-out [17]. To parametrise this concern, we assess the feasibility of coal power phase-out in Korea using the historical rate of fossil-based power decline achieved in different countries as reported by Vinichenko, Cherp [19]. Other political constraints may limit the expansion of nuclear power or renewables. In particular, political opposition to nuclear power slowed down or stalled its development in many countries [35], and it also faces strong opposition in Korea.[4] Also, acceptance of the local community has become the biggest obstacle to the diffusion of renewables, as also widely documented in other countries [8]. In our assessment, we use near- and mid-term government plans as a proxy for the political feasibility of expanding nuclear and renewables.

The feasibility of climate action is both non-binary and dynamic [16,31]. To reflect the non-binary nature of feasibility, we do not rule out specific scenarios but rather quantify how much a particular scenario transcends relevant feasibility thresholds indicating stronger feasibility challenges. We reflect the dynamic nature of feasibility constraints in terms of trade-offs between different scenario options since, over time, these constraints may also change for various reasons, including changes in costs, technology development, and geopolitics. Although some of these trade-offs may be overcome with significant financial investment, we do not conduct an economic evaluation of the scenario options because the constraints are not necessarily purely monetary but also involve political, regulatory, and infrastructural mechanisms.

Modelling long-term decarbonisation of the electricity sector

Plant-level analysis that enables the representation of existing stock and announced investment and retirement plans would be appropriate for addressing “what-if” questions regarding low-carbon energy transition. Previous studies have employed capital stock accounting models to improve transparency, reflect technology stock-specific policy measures, and alleviate issues associated with modelling uncertainties. The examples include models representing the stock turnover of energy-using assets such as buildings [46–48]. In addition, recent literature took a plant-by-plant accounting approach to the power sector modelling, assessing the impact on existing individual power plants (e.g., stranded assets [49] and the prioritisation of retiring power plants [50]) to achieve net-zero emissions. The main advantage of this accounting approach lies in its ability to represent technology- and vintage-specific policy instruments and government plans for individual power generation units. However, little attempt has been made to assess the feasibility of power sector decarbonisation scenarios based on a plant-level representation of the deployment of and substitution between alternative technology options to offer balanced insights into the required transition of the national power system.

To span realistic pathways to the power sector decarbonisation for feasibility assessments, we set up a model calibrated to historical plant-level stock data. Our model has three important aspects that originate from the detailed account of individual power plants. First, scenario outcomes are easily traceable and explainable due to the simplicity and transparency of the model. For instance, when we examine the results of installed capacity by technology, it is straightforward to compare them with the historical growth of generation assets. Second, the model allows for fulfilling more precise system reliability requirements for renewables-based decarbonisation. In our scenarios, the reliability requirement is benchmarked against the 9th NPSP. Last but not least, our modelling framework provides long-term projections that consider the construction and decommissioning plans, thereby promoting the credibility of feasibility assessment. Explicit representation of investment and retirement of major technology options based on the plant-level stock turnover model makes room for a detailed discussion of feasibility trade-offs, which is what the current study investigates.

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[3] https://www.bloomberg.com/news/articles/2021-05-10/pumping-co2-deep-under-the-sea-could-help-korea-hit-net-zero

[4] The new Yoon administration has presented a plan to reverse the anti-nuclear policy of the previous government. The new government seeks to expand its nuclear power generation to more than 30 percent of its total energy generation by 2030 in order to boost the nation’s energy security and to better achieve the carbon neutrality target.

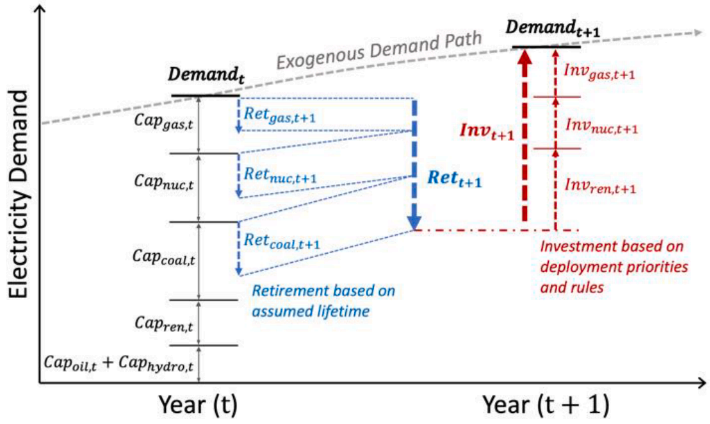

Fig. 3. Technical description of the stock turnover model. Notes: Annual installed capacities (“Cap”) consist of six technologies: coal, nuclear (“nuc”), natural gas (“gas”), renewables (“ren”), oil, and hydropower. The electricity demand increases by the net of total investment (“Inv”) and retirement (“Ret”) of power plants.

Table 1
Description of scenarios.

	Scenario	Coal power	Nuclear power	Expansion of renewables	Introduction of natural gas power with CCS
1	Baseline	Constant capacity	Constant capacity	To meet residual demand	None
2	ConstNuc	No new coal	Constant capacity	To meet residual demand	None
3	NoNuc	No new coal	No new nuclear	To meet residual demand	None
4	MidNuc	No new coal	Expansion to replace coal	To meet residual demand	None
5	ConstNucGasCCS	No new coal	Constant capacity	To meet residual demand	Expansion to meet flexibility requirements
6	NoNucGasCCS	No new coal	No new nuclear	To meet residual demand	Expansion to meet flexibility requirements
7	MidNucGasCCS	No new coal	Expansion to replace coal	To meet residual demand	Expansion to meet flexibility requirements
8	MidNucGasCCS_ER	No new coal & early retirement	Expansion to replace coal	To meet residual demand	Expansion to meet flexibility requirements
9	HiNuc	No new coal	Expansion to replace coal and gas	1% of the total installed capacity per year	None
10	HiNuc_ER	No new coal & early retirement	Expansion to replace coal and gas	1% of the total installed capacity per year	None

Methods

To establish a historical reference for scenario development, we collected individual plants’ installed capacity, construction completion date, decommissioning date, and annual utilisation rate data from 1961 to 2020 from the Korea Electric Power Corporation[5] (KEPCO). Data on country-specific emissions factors used for calculating CO_2 emissions was provided by the Ministry of Environment [30]. Several assumptions common across all scenarios are as follows:

- Electricity demand increases according to the prospect of the 9th NPSP—a 13.5% increase until 2034—with the growth rate remaining unchanged[6] afterwards (see Supplementary Note 2.1).
- Capacity factors for all technologies except for coal power plants are held constant, whereas capacity factors of coal power plants gradually decrease, as stated in the 9th NPSP.
- Coal and gas power plants have their designed lifetime of 30 years [20] except in scenarios envisioning the early retirement of coal power plants. In scenarios with on-time and early coal retirement, no more than four coal-generating units phase out simultaneously in any given year to lessen the impact on system stability. For the total 28 nuclear units, three units have their designed lifetime [21] of 30 years, 40 years for 19 units, and 60 years for the remaining units (see Supplementary Note 2.2 for more details).
- Like previous studies [51–54], gas power generation is linked to renewable power generation with the relationship governed by the system flexibility requirements implied by the 9th NPSP (see Supplementary Note 2.3).
- Renewables include solar and wind power, biomass, fuel cells, and marine power. The share of the energy storage system (ESS) integrated with renewables is held at its 2021 level (26.6%).
- Oil and hydropower generation stay unchanged. As oil power plays a minor and specific niche role in power generation, it does not contribute significantly to power sector emissions. Hydropower also plays a relatively small part in Korea and cannot be expanded due to its limited potential.
- In line with a national roadmap for CCS development [55], CCS-installed gas power is allowed to be introduced after 2030 in CCS-containing scenarios. The CO_2 capture rate is assumed to be 90% [56].

To operationalise plant-level retirement and investment, given the set of assumptions (for a more detailed description of scenario assumptions and variables, see Supplementary Note 2), we established a stock turnover model (Fig. 3). The model has two key features. First, the

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[5] We complied with annual statistics for individual power plants presented in the KEPCO reports. They are available at the following link (in Korean): https://home.kepco.co.kr/kepco/KO/ntcob/list.do?boardCd=BRD_000099&menuCd=FN05030103

[6] The electricity demand growth rate is held constant at 0.56%, which is close to the one (0.61%) proposed by the draft of the 10th NPSP (not yet confirmed as of Dec 31st, 2022).

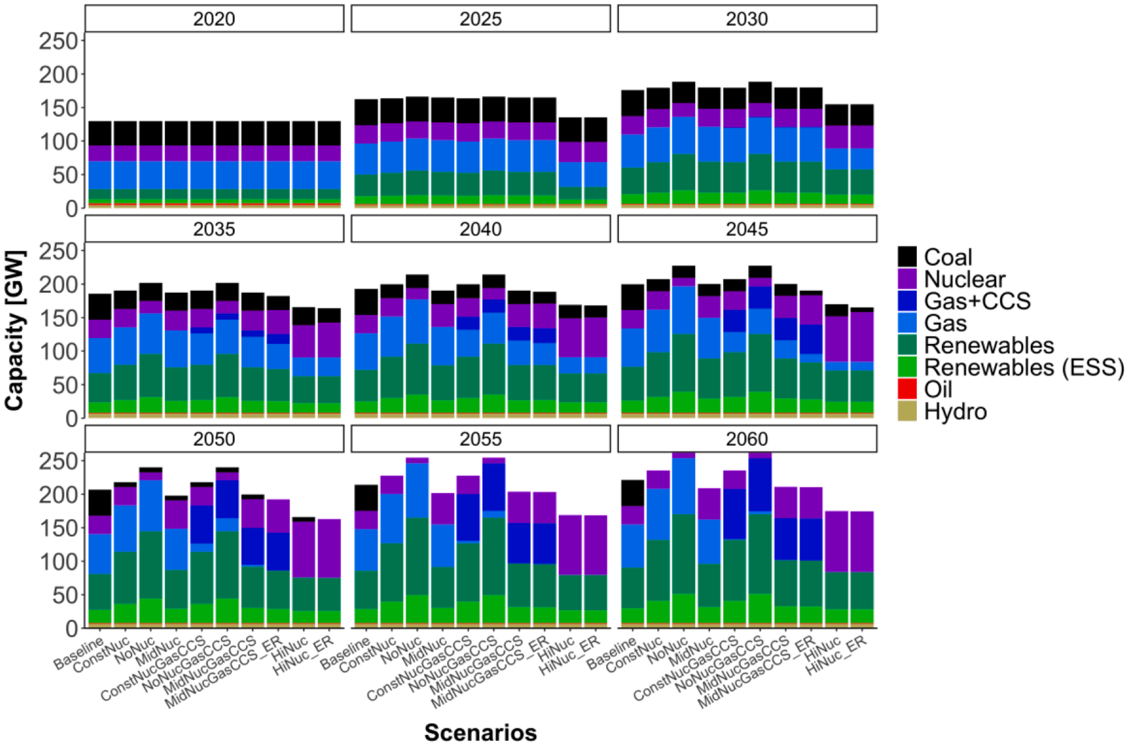

Fig. 4. Installed capacity by technology in the scenarios.

model specifies the total yearly installed capacity based on the age and capacity information of the individual power plants and its resulting electricity generation amount by technologies. Suppose, for example, a nuclear power unit with a nameplate capacity of 700 MW and a designed lifetime of 40 years was constructed in 2000, followed by the construction of another nuclear power unit in 2010 with a 500 MW capacity and 30 years. Unless new nuclear power units are introduced, the total installed nuclear capacity will decrease as much as 1200 MW in 2040 alone. Second, new capacity investment is determined based on the residual electricity demand, which equals an increase in electricity demand net of total retirement. This plant-level modelling approach makes our scenarios consistent with the existing power plant stock and the nation's technology-specific long-term investment plans.

In line with Korea's existing power plant stock and plans for new construction, we develop a total of ten scenarios that feature different levels of decarbonisation with the power sector's emissions ranging from 0 to 200 Mt CO_2 in 2050 (Fig. 6). They consist of one baseline scenario (Scenario 1 in Table 1) assuming constant coal and nuclear capacities, thereby presenting no particular feasibility challenges or emission reductions, and nine policy scenarios that vary in three respects (Table 1). First, we consider four different cases depending on the degree they allow the construction of new nuclear power plants: no new nuclear allowed to be introduced ("NoNuc"), current nuclear capacity held constant[7] ("ConstNuc"), new nuclear allowed to make up for coal power retirement ("MidNuc"), new nuclear allowed to make up for coal and gas power retirement ("HiNuc"). In our scenarios, the deployment of nuclear power determines how much renewables and complementary natural gas capacity is to be introduced. In NoNuc, ConstNuc, and MidNuc scenarios (Scenarios 2–8 in Table 1), the residual demand is fulfilled entirely by gas and renewables, with gas power deployed up to what is required for the system reliability and the remainder met by renewable energy. HiNuc scenarios (Scenarios 9–10 in Table 1) allow the introduction of the two planned 1400 MW-sized nuclear power plants (Supplementary Note 2.2).[8] The residual electricity demand is satisfied only by renewables without gas power until 2030. After 2030, the annual increases in renewable capacity in Scenarios 9 and 10 are 1% of the total installed electricity capacity while meeting the residual demand by nuclear power.[9] Second, the scenarios differ by whether CCS is installed for newly constructed gas units ("CCS"). Third, the scenarios differ on whether they allow for retiring coal power plants five years earlier than their 30-year lifetime to meet climate targets (suffixed as "ER").

Results

Scenario results

Our scenario results indicate that the planned phase-out of coal-fired power would necessarily require continued investments in renewables and gas power plants (Fig. 4). Significantly rapid deployment of renewable power, which amounts to an annual capacity increase of 1.5–3.0% over total system size, is to be undertaken in the short term by 2030. In particular, scenarios with stringent limits on nuclear (NoNuc and NoNucGasCCS), broadly in line with the current national policy, indicate that phasing out of coal and nuclear concurrently would require rarely-observed rapid, large-scale expansion of renewables. Note also that these scenarios would suffer from decreasing utilisation of overall

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[7] In other words, NoNuc stands for *no new additions* of nuclear power, while ContNuc stands for *no net change* in nuclear power capacity (i.e., the continuation of current capacity).

[8] Given that the construction duration for the previous nuclear power plants in Korea is 5-10 years, it would be reasonable to assume that no other nuclear units will come online by 2030.

[9] We check whether the technology mix in the HiNuc scenarios meets the system reliability requirements. It suggests that annual flexible generation shares are within a feasible range presented in the prior studies (see Supplementary Note 2.3).

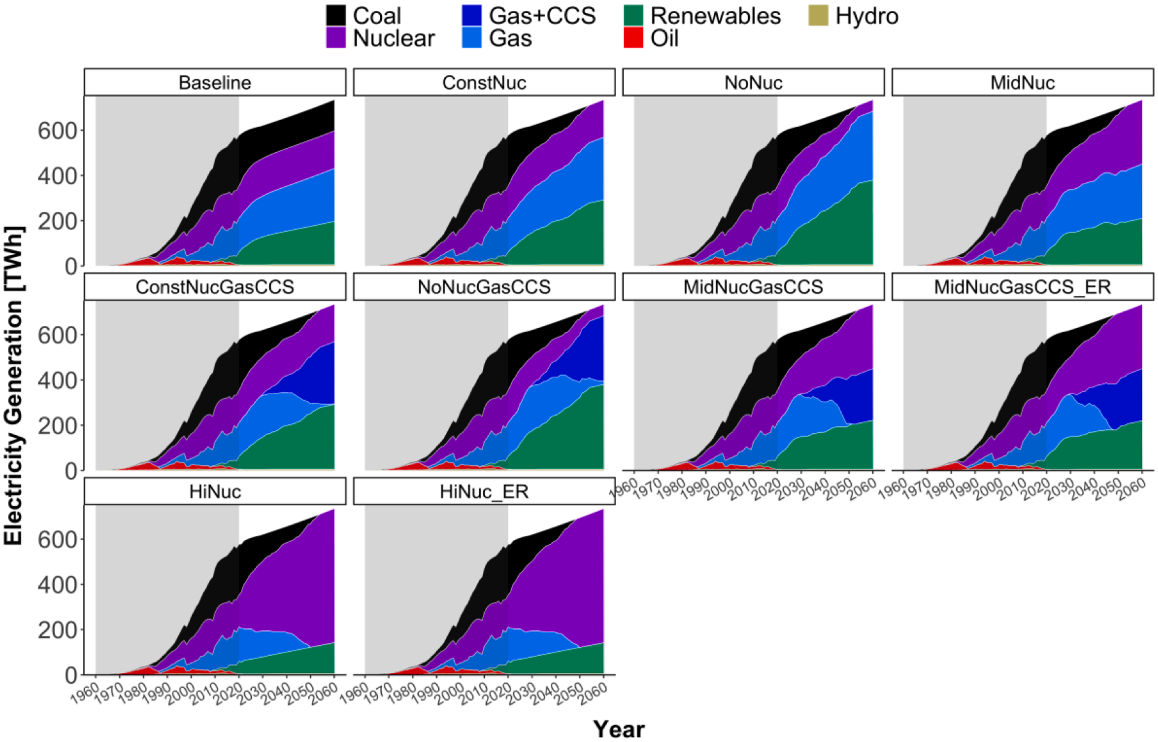

Fig. 5. Annual electricity generation by technology in the scenarios.

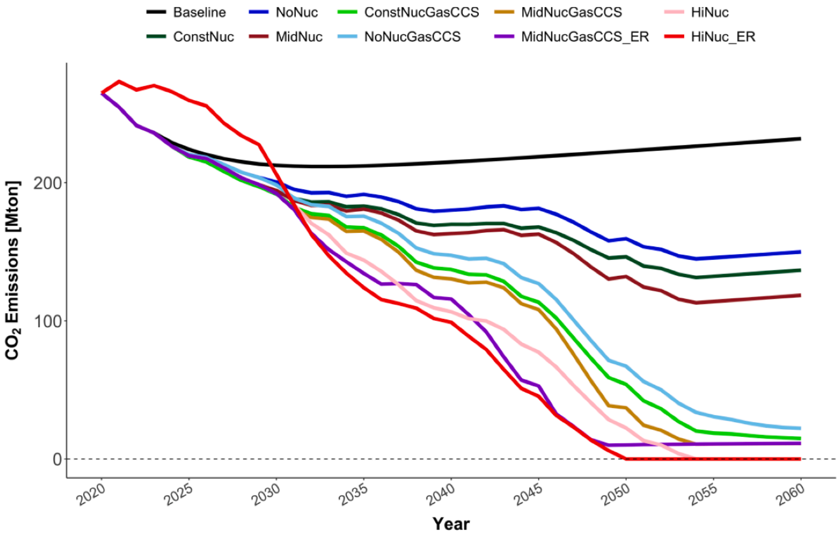

Fig. 6. Annual CO2 emissions in the scenarios.

generation assets due to the rapidly increasing share of renewable power (Fig. 5).[10]

Our results also indicate that in most scenarios, about six to eight 500 MW-sized gas power plants must be built every five years to fulfil the reliability requirement in response to the ramp-up of renewables. The exception is the HiNuc scenario, in which the phase-out of coal and gas power together requires additions of ten to twelve 1000 MW-sized nuclear units every five years with a relatively modest increase in renewable power.

Several significant findings emerge from comparing CO_2 emissions across our scenarios (Fig. 7). First, phasing out coal and expanding renewables together is not sufficient to achieve zero emissions in the power sector unless assisted by CCS or nuclear power. The three scenarios without CCS point to emissions reductions only up to about 40–50% of the current level, depending on whether nuclear is kept constant (ConstNuc), phased out (NoNuc), or moderately expanded (MidNuc). This result is primarily due to additional CO_2 emissions from natural gas units, which come online to fulfil the increasing flexibility requirement of intermittent renewable power.

Second, achieving zero emissions while phasing out nuclear power requires the rapid expansion of CCS-installed gas power in 2030–2050 (see NoNucGasCCS scenario). However, given its near-term emissions reduction is inadequate, the 2050 zero emission target is missed by five to ten years. The insufficient emission reduction is due to the additional

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[10] In the Section 4 in the appendix, we present annual capacity and generation by technology in the scenarios.

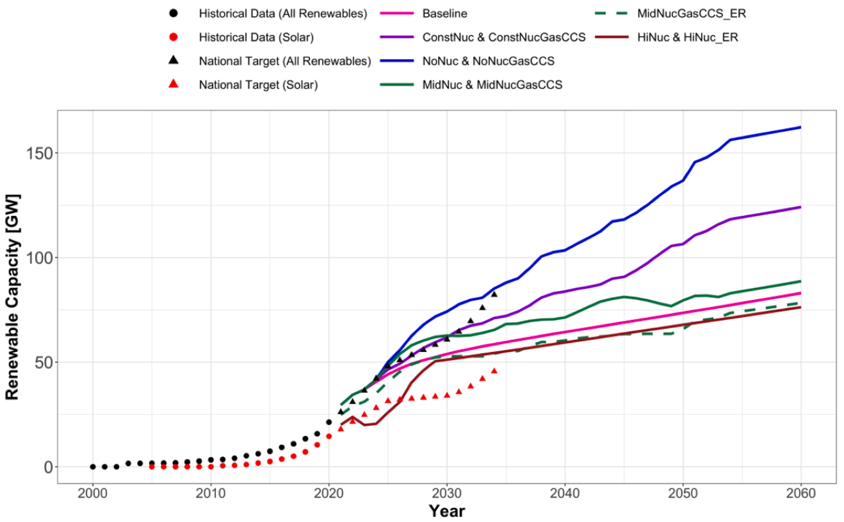
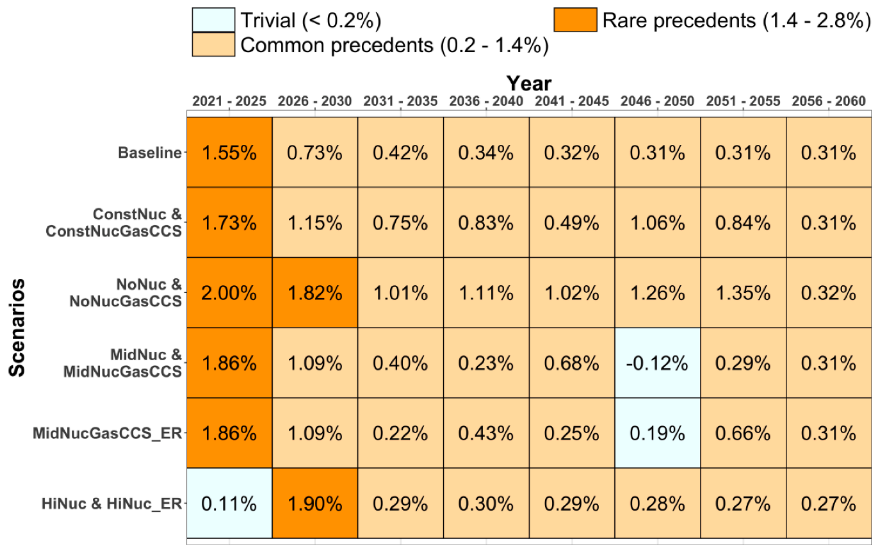


Fig. 7. Historical experience, national targets and scenario results of renewables.



Scenarios	2021 - 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 - 2050	2051 - 2055	2056 - 2060
Baseline	1.55%	0.73%	0.42%	0.34%	0.32%	0.31%	0.31%	0.31%
ConstNuc & ConstNucGasCCS	1.73%	1.15%	0.75%	0.83%	0.49%	1.06%	0.84%	0.31%
NoNuc & NoNucGasCCS	2.00%	1.82%	1.01%	1.11%	1.02%	1.26%	1.35%	0.32%
MidNuc & MidNucGasCCS	1.86%	1.09%	0.40%	0.23%	0.68%	-0.12%	0.29%	0.31%
MidNucGasCCS_ER	1.86%	1.09%	0.22%	0.43%	0.25%	0.19%	0.66%	0.31%
HiNuc & HiNuc_ER	0.11%	1.90%	0.29%	0.30%	0.29%	0.28%	0.27%	0.27%

Fig. 8. Growth rates of renewables in the scenarios as compared with worldwide maximum growth rates.

build-up of gas power without CCS between 2020 and 2030, which would not have occurred if new nuclear power had been allowed.

Third, expanding nuclear power to replace coal only (MidNuc) or coal and gas combined (HiNuc) presents more immediate, near-term emissions reductions conducive to the 2050 zero emission target than the other scenarios (Fig. 6). However, without concurrent early retirement of coal power, both MidNuc and HiNuc scenarios still miss the target by about five years. Note that the allowed expansion of nuclear power combined with early coal retirement makes the on-time achievement of zero emissions possible even without CCS-installed gas power.

Feasibility assessments

Feasibility of solar and wind power growth in scenarios

Fig. 7 illustrates the historical use of solar and wind power, national targets, and the envisioned use of renewables in our decarbonisation scenarios. The most ambitious growth of renewables is expected between 2020 and 2030, and it is much faster in no new nuclear scenarios where renewables and, to a lesser extent, gas power substitute for the rapidly declining coal generation. In comparison with the recent growth rates, the most ambitious scenarios would envision the growth of renewables at the end of the 2020s, which is about twice as fast as in 2015–2020. However, the growth of renewables so far has been accelerating, and therefore, such rates can be achieved in principle. Furthermore, similar growth has been planned in the 9th NPSP (Fig. 7), which signals the existing political commitment to expand renewables with that speed, at least in the near term. Fig. 8 shows an average of annual growth rates during every five years. It indicates that compared to the maximum rates of renewables deployment achieved in other OECD countries[11] [18], the rates of renewable expansion in Korea come across as ambitious and, on some occasions, rarely precedented.

Another important observation is that so far, the use of renewables in

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[11] When we define the thresholds for the growth rate precedents, we consider 34 OECD countries to ensure similarity in economic conditions (for the list of the countries, see Supplementary Note 3.1). One aspect of similarity with Korea is that the minimum rates for rare precedents (the third quartile) encompass relatively large countries. In addition, we rule out economies such as Ireland or Portugal that are ten times smaller than Korea because high change rates in these countries are more accessible due to their economic and geographic homogeneity.

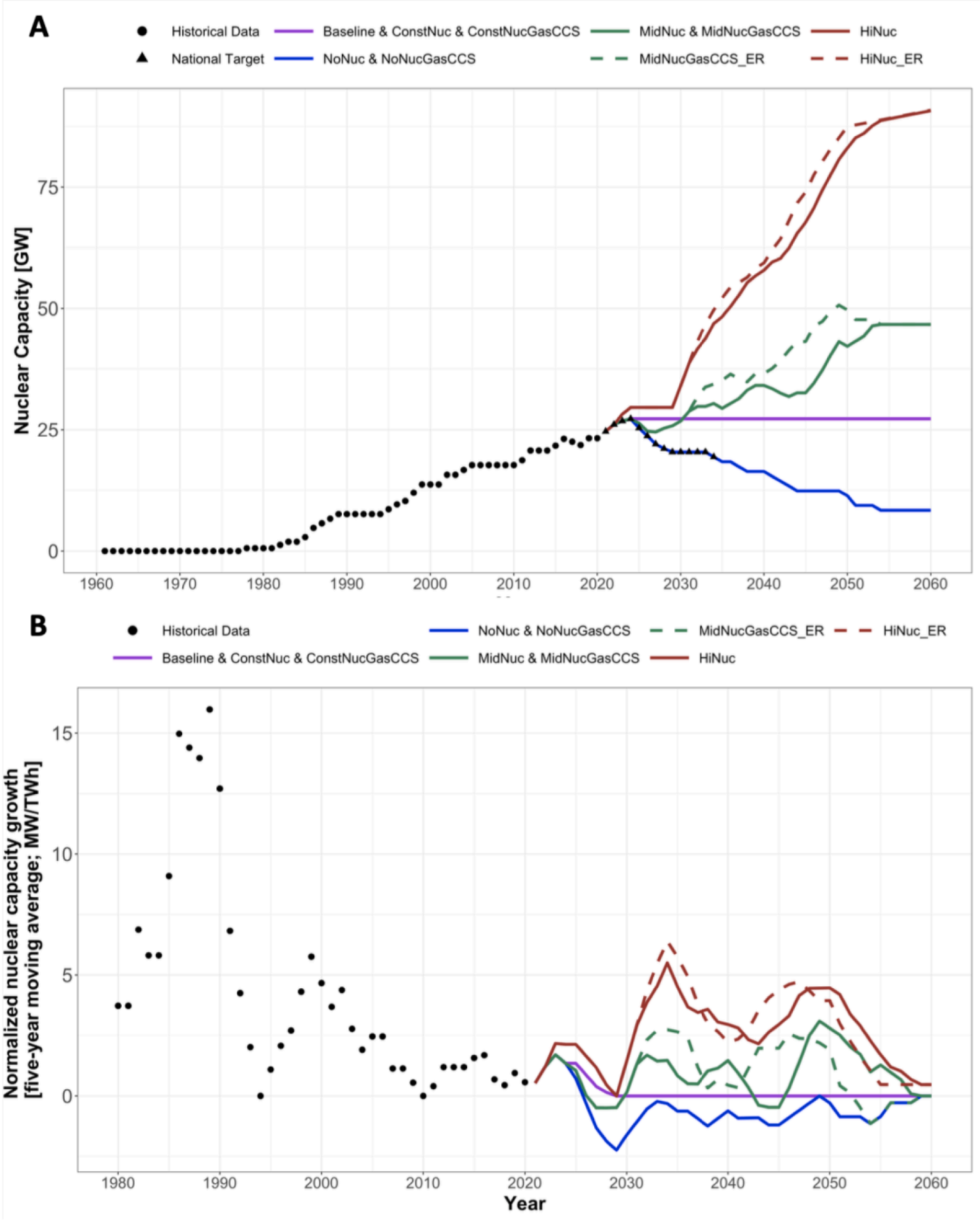

Fig. 9. Historical experience and scenario results for nuclear power.

Korea has been dominated by solar photovoltaics (PV). In contrast, wind power has significantly lagged behind other countries, possibly due to adverse geographic conditions, as observed in Japan [57]. The national plans envision the ambitious development of wind power (Fig. 7), as evidenced in recently launched projects.[12] However, there is uncertainty about whether these adverse conditions can be overcome, which would decrease the feasibility of achieving the national targets and the more ambitious scenarios.

Feasibility of nuclear power expansion

Fig. 9 shows historical trends, existing plans, and scenario projections for nuclear power, with the deployment levels and the growth rates, normalised to the total electricity supply separately displayed. Historically, nuclear power in Korea experienced the fastest growth around the mid-1980s. The scenarios project different levels of nuclear power growth ranging from its gradual phase-out to the most ambitious expansion in HiNuc and HiNuc_ER. However, even in the most ambitious expansion cases, the change is about three times slower than historically (see Supplementary Table 6 for more details).

Fig. 10 shows the heatmap of nuclear power growth in the scenarios compared to the growth rates observed historically in different countries worldwide. It should be noted that the rates of nuclear power growth in most periods and scenarios have been commonly observed historically.

Feasibility of coal decline

Fig. 11 shows the historical growth of coal power and its future development envisioned in the scenarios and the existing plans. The use of coal has rapidly increased from the 1980s onward, while all scenarios, except the Baseline, indicate its equally rapid decline. Though this is a radical reversal of the national historical trends, such rapid decline has

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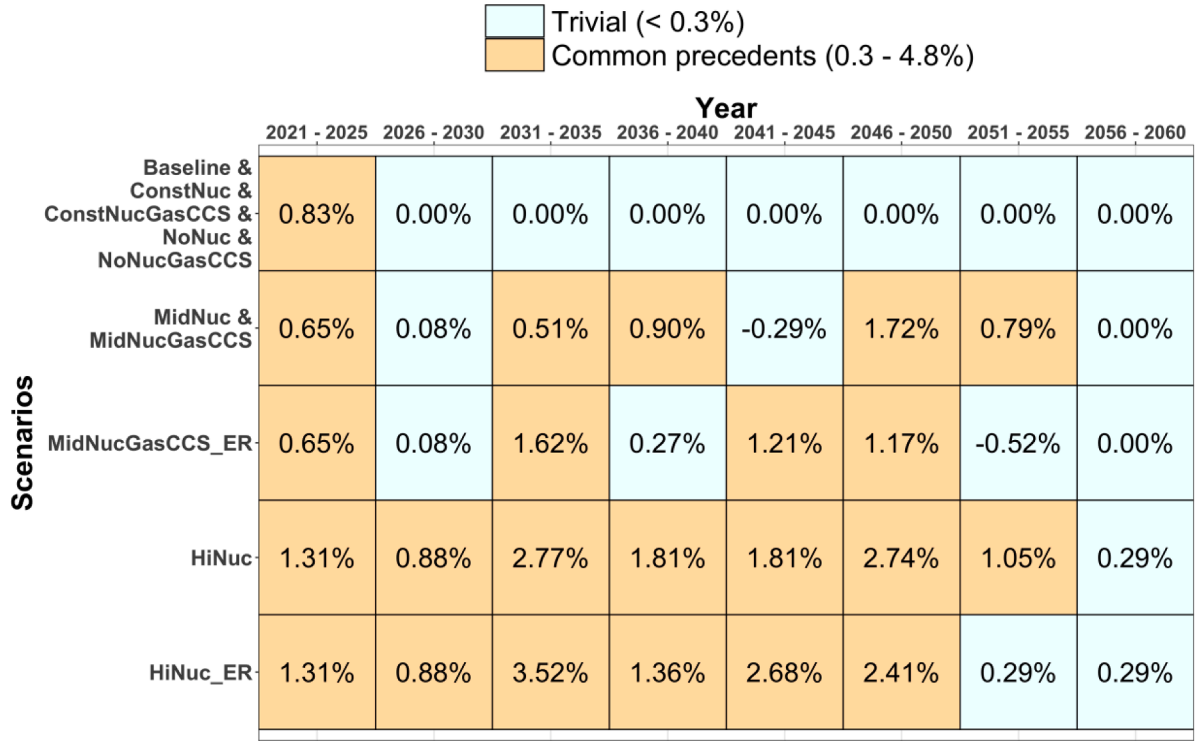
[12] See the related article in the following link: https://www.power-technology.com/news/south-korea-wind-farm/



🟦 Trivial (< 0.3%)
🟧 Common precedents (0.3 - 4.8%)

Scenarios	2021 - 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 - 2050	2051 - 2055	2056 - 2060
Baseline & ConstNuc & ConstNucGasCCS & NoNuc & NoNucGasCCS	0.83%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
MidNuc & MidNucGasCCS	0.65%	0.08%	0.51%	0.90%	-0.29%	1.72%	0.79%	0.00%
MidNucGasCCS_ER	0.65%	0.08%	1.62%	0.27%	1.21%	1.17%	-0.52%	0.00%
HiNuc	1.31%	0.88%	2.77%	1.81%	1.81%	2.74%	1.05%	0.29%
HiNuc_ER	1.31%	0.88%	3.52%	1.36%	2.68%	2.41%	0.29%	0.29%

Fig. 10. Nuclear power growth rates in the scenarios compared with historical rates worldwide.

been experienced in other countries [19]. For example, in the United Kingdom (UK), coal declined by over 30 percentage points of the national electricity supply between 2007 and 2017. The UK case provides a realistic albeit ambitious benchmark of what would need to happen in Korea (Fig. 11). While the rates of coal decline in the UK in the past and Korea in the future would be similar, this decline in the UK has followed three decades of decline preceded by several decades of ‘destabilisation’ [58], while in Korea, it would need to happen more rapidly. Furthermore, the average age of coal power plants in the UK at the start of its rapid decline in 2007 was 35 years [19], while in Korea, it is currently (as of 2021) 17 years.

To compare the required rates of coal power decline with a broader range of countries, we use ‘feasibility zones’ identified by Vinichenko, Cherp [19] to map the historical precedents of fossil fuel decline under different electricity demand growth rates in the same period. Fig. 12 maps the decline rates projected in our scenarios onto these ‘feasibility zones,’ producing a heatmap similar to that of the growth of nuclear and renewables. It shows that in the early 2020s, the decline of coal has rare precedents, but subsequently, it has either multiple historical precedents or is trivial.

Feasibility of CCS

CCS is a new technology; therefore, its feasibility cannot be comprehensively evaluated based on historical experience alone. Currently, Korea has two pilot projects with one planned project of 300 MW to be opened in mid-2020.[13] In the scenarios containing CCS, however, Korea would increase its capacity up to 70 GW, capturing around 60 Mt of CO_2 per year by 2050. This number is more than the amount of carbon captured (20 Mt of CO_2) by existing CCS facilities worldwide in 2020 and about 50 times of one captured (2.4 Mt of CO_2) by power plants in operation [59].

However, CCS technology is expected to develop and expand in the future. In the IEA’s central prospect, about 5.2 Gt of CO_2 will be captured globally by 2050, of these about 20% in the power sector (Koelbl, van den Broek [60] provide similar estimates). If the CCS-containing scenarios are realised, Korea’s power sector will be responsible for some 6% of the global CCS supply while accounting for only about 1.5% of the global electricity. Concerning the CCS for gas-powered generation, Korea would need to assume even more prominent leadership, becoming responsible for up to 14% (270 TWh) of the worldwide gas power generation, which the IEA estimates to be in the range of 2000 TWh/year by 2050. This means that Korea would need to become a global leader in CCS for gas power, requiring consistent support for its research, development and deployment.

Developing CCS in Korea would require deploying its three main components: CO_2 capture, transportation, and storage. For capture, van Ewijk and McDowall [61] propose to evaluate its feasibility using flue gas desulphurisation (FGD) as an analogue. Our CCS-containing scenario results show that the normalised rates of introducing CCS in Korea (7.1 – 14.4 GW/decade/Trillion USD of GDP) are comparable to the rates (11 GW/decade/Trillion USD of GDP) of historical FGD introduction (see Supplementary Note 3.3).

Concerning CO_2 transportation and storage, although CO_2 is known to be storable in oil and gas reservoirs or deep saline formations, only the latter option is currently available in Korea [62]. Potential storage sites are not fully defined, but there is a possibility that both Korea and Japan might seek offshore storage. In any case, storage is most likely far away from capture facilities, which would mean transporting up to 60 Mt of CO_2 per year. Transportation is a mature technology, but in the United States (US), only 17 Mt of CO_2 is transported.

Discussion

Korea’s long-term energy transition pathways examined in this study differ in their emphasis on different decarbonisation options. While all envision a rapid phase-out of coal power, the essential trade-off for achieving zero emissions is between a rapid expansion of renewables backed by gas power with CCS versus an increase in nuclear power.

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[13] The data on the pilot CCS projects completed or in development in Korea is provided by the Global CCS Institute (https://co2re.co/FacilityData).

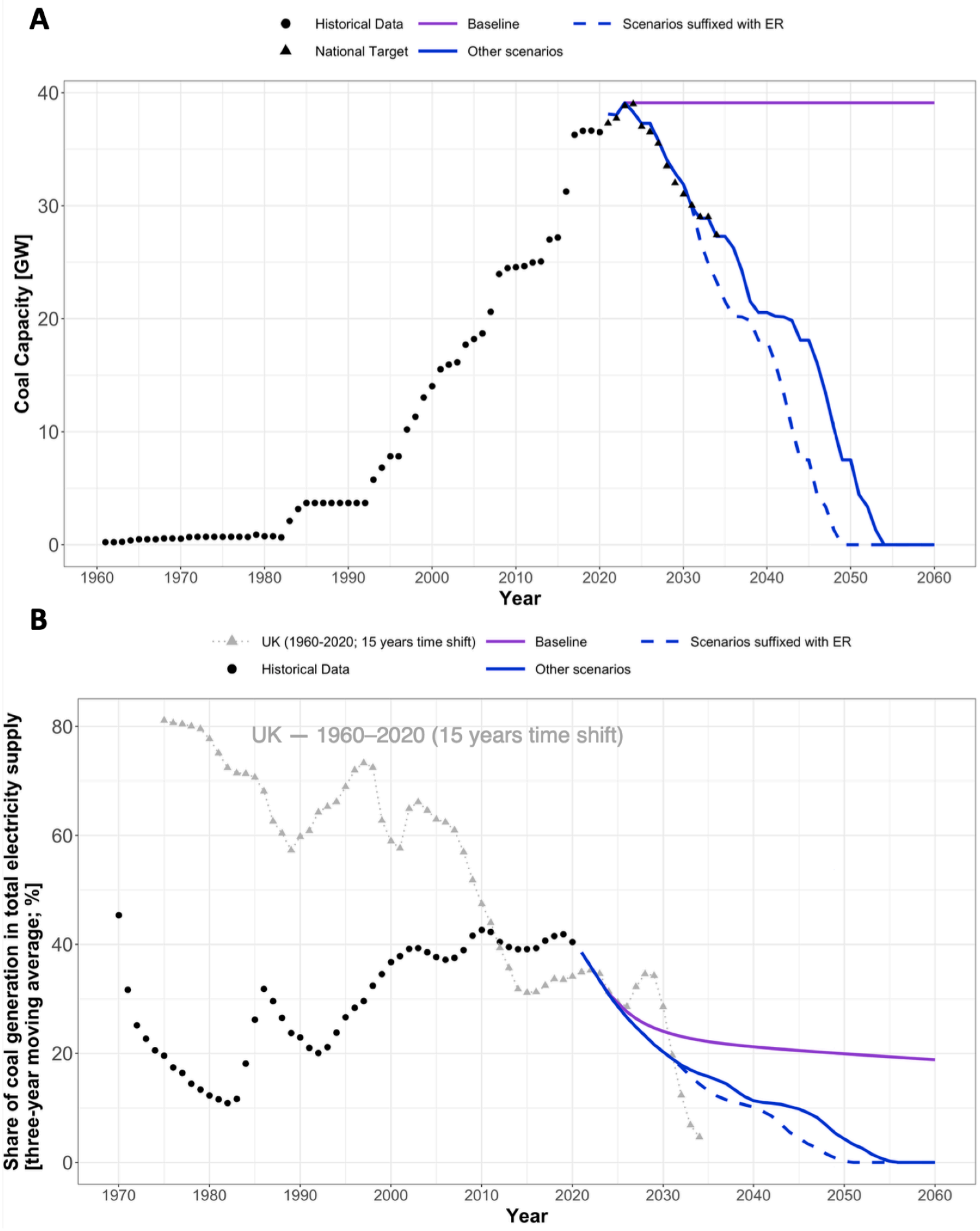

Fig. 11. Historical experience and scenario results of coal power.

Table 2 summarises the feasibility of these decarbonisation options in different scenarios against the above proposed feasibility criteria. Coal phase-out, which is required in all decarbonisation scenarios, would be a reversal of long-term trends and unprecedented for Korea. However, it is in line with the current government plans and has some international precedents, notably in the UK. The expansion of renewables in all scenarios except those with the rapid nuclear expansion is faster than recent national trends, but once again has some international precedents. It is also in line with the national plans and targets. Such expansion requires solar power to grow at its recent fast rates and wind power – currently lagging in Korea – to be deployed at rapid speed, as it was done in countries with more favourable geographical endowments. Although the expansion of renewables is still ambitious in the HiNuc scenario, it can be accomplished primarily by the growth of solar power with the already demonstrated speed. The expansion of nuclear power would be within the range of historically achieved growth rates in Korea and worldwide. However, it would contradict the recent government plans and thus may be considered politically less feasible. Finally, the expansion of CCS, which is especially needed in scenarios with nuclear power phase-out or stagnation, is a technologically new option with no international experience. Pursuing this option on the required large scale will likely require Korea to become one of the global pioneers in this area, which is currently not in its political commitments or plans.

Conclusion

This paper constructs ten scenarios of future electricity developments in Korea, of which six achieve zero emissions between 2050 and 2060. Analysis and comparison of these scenarios highlight the policy and practical challenges to the decarbonisation of the power sector in Korea and similar countries.

First of all, all zero-emission scenarios feature a complete coal power phase-out. The achievement of zero emissions by 2055–2060 requires that no new coal power plants are built, with none of the existing ones

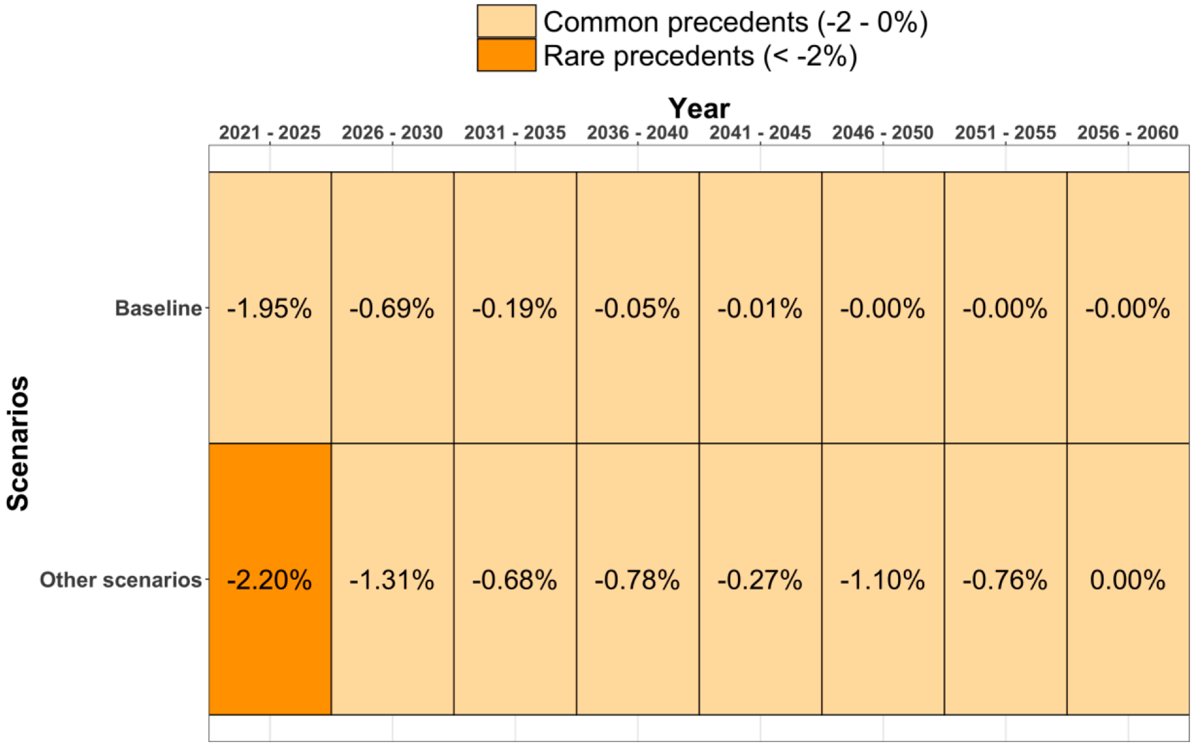

Fig. 12. Rates of coal power decline in scenarios as compared to historically observed decline rates.

Table 2

Feasibility of decarbonisation options in different scenarios[14].

Decarbonisation option	Scenarios	Domestic precedents	Compared to current plans	Experience of other OECD countries	Technology readiness
Coal phase-out	All	Unprecedented	Similar	Common precedents	N/A
Expansion of renewables	Baseline ConstNuc & ConstNucGasCCS NoNuc & NoNucGasCCS MidNuc & MidNucGasCCS MidNucGasCCS_ER	Faster than recent trends	Similar (if wind is excluded)	Rare precedents	Early adoption
	HiNuc & HiNuc_ER	In line with recent trends	Similar (if wind is excluded)	Common precedents	
Nuclear power	NoNuc & NoNucGasCCS	N/A	Similar	N/A	Mature
	Baseline ConstNuc & ConstNucGasCCS MidNuc & MidNucGasCCS MidNucGasCCS_ER	Slower than past growth	More ambitious	Common precedents	
CCS	ConstNucGasCCS NoNucGasCCS MidNucGasCCS MidNucGasCCS_ER	Unprecedented	More ambitious	Rare precedents	Demonstration

[14] We follow the IEA's technology readiness level ranges from 1(concept) to 11(mature). See the related article in the following link: https://www.iea.org/articles/etp-clean-energy-technology-guide.

serving more than their prescribed lifetime of 30 years. For a more ambitious goal of achieving zero emissions by 2050, coal power should be retired even earlier. Such early retirement is in line with Korea's national carbon neutrality ambition but would be unprecedented for Korea. It would need to follow in the footsteps of the pioneers of coal retirement, such as the UK, and most likely deal with significant adjustments in the coal sector.

Secondly, all zero-emission scenarios envision the rapid growth of renewable electricity, primarily solar and wind power. The ramp-up would imply continuing the existing rapid trends of solar power deployment, initiating an equally rapid deployment of wind (that in the past experienced difficulties in taking off in Korea), and taking the electricity system into new territory featuring high penetration of intermittent renewables. Such aspirations, at least in the near term, align with government plans and track records of international leaders in renewable power. In scenarios that envision a rapid expansion of nuclear power, the required growth of renewables is relatively modest and can be achieved mainly by maintaining the current solar power growth rates.

The remaining challenges involve a complex trade-off between CCS and nuclear power. On the one hand, heavy reliance on CCS would place Korea amongst world leaders in this new technology, which may be a challenge given its lack of fossil fuel resources and relevant technological experiences. Transportation and offshore storage of CO_2 may represent serious engineering challenges, raising the cost of electricity and provoking political and public opposition due to its sheer scale. While many of these challenges are uncertain and speculative in the case of CCS, the political challenges of expanding or even maintaining nuclear power seem very tangible, as clearly manifested in the government's current plans to phase out nuclear together with coal. Nevertheless, both Korea and other countries have historical experience of expanding nuclear power production at rates that, if replicated, would make CCS unnecessary. The bottom line is that at least one of these two options or their combination would help better to achieve zero emissions from the power sector no later than 2060. Therefore, the current government plans, which envision only very modest progress on CCS and nuclear phase-out, would need to be reconsidered to face this reality.

All in all, our scenarios identify that the challenges for decarbonising the power system in Korea are formidable but manageable. This message should also give hope to other similar countries. We also propose and illustrate a new method of evaluating the feasibility of climate strategies that can be used in Korea and beyond.

Yet, this paper is not without limitations. First of all, a richer set of technology scenarios can be developed to be more informative for policymakers. For example, considering the availability of major negative emissions technologies, such as bioenergy with CCS and direct air capture, can provide more comprehensive insights. In addition, our power plant stock accounting model does not explore the uncertainty associated with the rate of electrification of end uses (e.g., transportation, space heating, or industrial furnace). Future research would address the twin challenge of decarbonising the electricity sector while electrifying other economic sectors such as buildings, industry, and transportation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Datasets related to this article can be found at http://dx.doi.org/10.17632/py2fddx5ss.1, an open-source online data repository hosted at Mendeley Data (Hyun and Eom, 2022).

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rset.2023.100050.

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