Carbon Tracker Initiative SFO°C Solutions for Our Climate 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

End in sight: **How South Korea can force coal offline by 2028**

A resource planning analysis for South Korea's power system

Analyst Note

April 2021

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About us

Carbon Tracker Initiative is a team of financial specialists making climate risk real in today's capital markets. Our research to date on unburnable carbon and stranded assets has started a new debate on how to align the financial system in the transition to a low carbon economy.
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Chungnam National University is a national university located in Daejeon, South Korea. It is one of ten Flagship Korean National Universities. At this university, Professor Seungwan Kim leads Smart Energy Network Design (SEND) Lab. which belongs to the department of electrical engineering. The SEND Lab. is investigating optimal decision making in power industry based on market and system modelling.
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Solutions for Our Climate (SFOC) is a Korea-based group that seeks to advocates for stronger climate policies and reforms in power regulations. SFOC is led by legal, economic, financial, and environmental experts with experience in energy and climate policy and works closely with policymakers.
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1. Key Findings

A cost-optimized analysis for renewables investment schedule for South Korea shows that a more ambitious rollout of renewable energy is feasible, with 40 GW and 14 GW of solar and on-shore wind respectively by 2028, against 27 GW and 13 GW as proposed in the 9th Basic Plan. This would further support a speedier coal phase out.

All South Korean coal power plants will become unprofitable before the end of their planned operating lifetimes under current policies. The growing requirement for increased power system flexibility alongside tightening regulation means that even under existing policy, coal plant capacity factors will decrease, leaving units both operating and under construction unprofitable to run.

With our suggested renewables investment schedule and a carbon price regime, it is possible to phase out coal by 2028. This is the most cost-effective option for South Korea in its pursuit of 2050 carbon neutrality, allowing the power system to save $ 5.5 bn compared with a later phase-out scenario under a carbon tax regime and a standard renewables rollout plan. Moreover, a carbon price paired with policies promoting greater renewables penetration can deliver an even more effective change for the generation mix.

Most planned coal plant projects are projected to be unviable beyond 2030. This crunch point could be brought even further forward if spot power prices remain around current levels, or if a 2030 power sector emissions cap consistent with a 2050 net zero target is introduced.

2. Executive Summary

In October 2020, President Moon Jae-in pledged to have South Korea achieve carbon neutrality by 2050. However, the country's carbon-intensive power sector, with coal power accounting for approximately 40% of total electricity generation and a quarter of national emissions, remains a major obstacle to achieve this goal. Moreover, in December 2020, the 9th Basic Plan for Electricity Supply and Demand laid down a strategy to increase the share of generation capacity from renewable sources up to 40% by 2034.

In this report, we analyse the roadmap to a coal phase out that is effective to reach the 2050 net-zero commitment.

2.1 Renewables roll out can be accelerated beyond current government plans, to reach 40% by 2028

Assuming a maximum year-over-year growth rate of 32% for solar and 27% for wind, a least-cost optimization of renewables investment provides indication that the government target of renewables can be brought forward. Specifically, South Korea could reach more than 54 GW of installed capacity, solar and wind combined, by 2028. This would be three years ahead of schedule compared to what is provided in the official coal phase out roadmap, which sees the same amount of renewables installed in 2031. This is one of the checkpoints of the official coal phase-out policy, which remains inadequate if Korea is to enhance its NDC, which has been assessed as "highly insufficient". Several analyses[1] suggest that South Korea should phase its coal fleet by 2029.

Further, the analysis shows that this acceleration is achievable at lower cost than the current plan, when compared to a carbon tax baseline scenario.

2.2 Coal can be phased out earlier than planned

Under a carbon price regime and following the renewables investment schedule suggested by Carbon Tracker, it is possible to phase out coal by 2028.

We find this is not only cost-effective, but also achievable faster than planned under a carbon price-adjusted dispatch order assumption, combined with investments in solar and wind technologies.

Such a schedule would reduce operational costs of the whole system by $ 4 bn annually compared to a non-phase out scenario with a carbon pricing scheme implemented.

1. Climate Analytics (2020), Transitioning towards a coal-free society: Science-based coal pathway for South Korea under the Paris Agreement, https://climateanalytics.org/latest/south-korea-must-exit-coal-by-2029-tobe-in-line-with-the-paris-agreement/

These savings would sum up over 2020-2050 to generate an overall cost of $ 3.4 bn on a net present value basis, net of the higher incremental annual investments necessary to meet the 54 GW of installed renewable capacity by 2028.

This would mean an economic benefit of as much as $ 5.5 bn compared to the $ 8.9 bn net costs incurred if following the 9th Basic Plan renewables investment schedule, summarised in Table 1.

TABLE 1 – SUMMARY OF NPV CALCULATION UNDER DIFFERENT COAL PHASE OUT SCENARIO

Renewables investment schedule	Coal Phase Out Year	Renewables installed (GW)	Undiscounted initial	PV initial investment ($bn)	PV savings ($bn)	Overall NPV ($bn)
9th Basic Plan	2030	54 in 2031	(-)54.9	(-)41.7	32.8	(-)8.9
Accelerated, CTI	2028	54 in 2028	(-)52.0	(-)41.7	38.4	(-)3.4
Difference	-	-	2.9	(-)0.0	5.6	5.5

Source: Carbon Tracker analysis.
Note: Annual savings are calculated against a non-coal phase out scenario under a carbon price regime. Savings are kept flat at $ 4 bn after the 54 GW is reached in both scenarios. The lower undiscounted initial investments under the accelerated scenario are due to a different optimized composition of the renewable fleet, to which specific learning rates are applied.

2.3 All coal power plants will be unprofitable before the end of their expected lifetimes even under current environmental policies and power market regulations

Almost all power trade in the South Korean power market is spot based. Korea Electric Power Corporation (KEPCO) pays settlements to electricity generators at a limited or capped cost-plus price, which should not exceed the spot power price. Therefore, this mechanism, namely a total cost-guarantee system, allows a plant to recover its cost only in a context of high spot market prices.

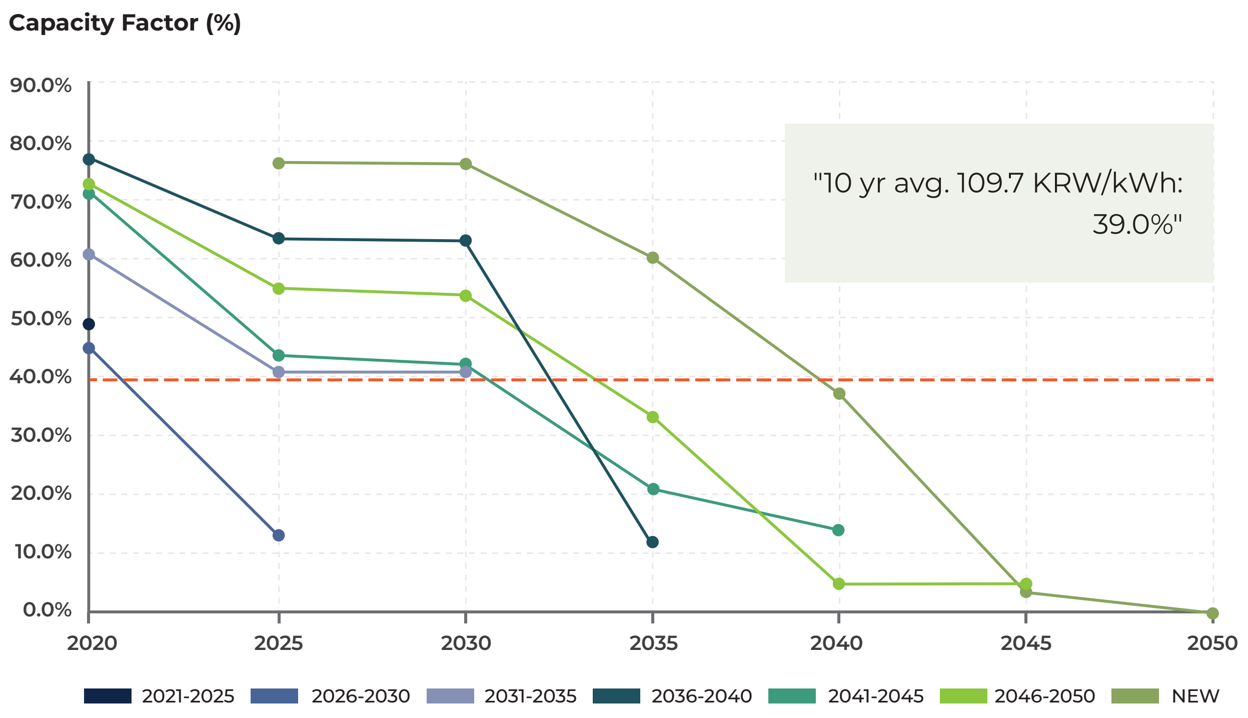
Based on data made available in investment documents for coal projects we have found that coal power plants should maintain a minimum capacity factor of at least 39% in order for the plants to be viable. This analysis assumes that spot power market prices (SMP) are at the past ten-year average price of KRW 109.7 per kWh. This represents a very conservative assumption, since that price/kWh is significantly higher than the current spot price of approximately KRW 68.5 per kWh[2]. Current spot prices will be even lower

when coal will be gradually phased out. The minimum capacity factor required to keep coal power plants viable will increase if the SMP level falls below the KRW 109.7 per kWh described above - this seems to be a more likely situation given recent power market trends (the recent five-year average SMP was KRW 82.7 per kWh), in which case coal power plants will need to be at a 79% capacity factor to stay afloat.

Simulations by Chungnam University reveal that even under a current policy scenario, and assuming that the SMP is at the aforementioned KRW 109.7 per kWh level, most coal power projects will not be commercially viable after 2030. In this scenario, furthermore, capacity factors of coal power plants will dramatically drop due to greenhouse gas emission regulations and increasing renewable generation requirements, making most coal power plants unable to recover costs between 2030 and 2035. Under the conservative assumption of a SMP of KRW 109.7, the seven new coal power plants under construction will become unprofitable between 2035 and 2040. However, this result will deteriorate faster with spot power market prices at lower levels, given that the recent five-year average SMP was KRW 82.7 per kWh. We would therefore argue that our analysis presents the upper bound of when plants are likely to become unprofitable, with significantly earlier shutdowns likely. This analysis does not assume a 2030 power sector emission cap consistent with a 2050 net zero emission target, which, if reflected, will provide an even worse outlook for coal power plants.

2. Korea Power Exchange (2021), https://www.kpx.or.kr/www/contents.do?key=414

FIGURE 1 – EXPECTED CAPACITY FACTORS OF COAL POWER PLANTS IN A CURRENT POLICY SCENARIO BY RETIREMENT DATE



Source: Chungnam National University analysis.
Note: The red line in the chart above is the minimum capacity factor that a plant should meet to be profitable, assuming SMPs are at its ten year average of KRW 109.7/kWh. All the different lines, such as "2021-2025" represent the year range the relevant coal power plants are planned to be decommissioned.

2.4 High level policy recommendations: level the playing field in the power market

We recommend that regulators and policy makers carry forward the discussion around an introduction of carbon prices and a dispatch system to mitigate the extra costs brought by fossil fuel generation and incentivize the transition to clean fuels. Carbon prices should be introduced in conjunction with other measures, critical to achieve a successful coal phase out:

- A renewables investment schedule as presented in section 5.2, coupled with a modernization of the power market, in order to allow a fair penetration of renewable energy sources in the system.
- An efficient implementation and integration of storage units in the power system, in order to secure the stability of the grid when paired to intermittent renewables.

The full list of operating storage units in South Korea, obtained through hydro-pumped technologies, is available in Table 10 of Appendix B.

The coal to gas switching announced by MOTIE, and available in Table 11 of Appendix B, will simply lead to a change in the source of a stranded assets risk, as addressed in Carbon Tracker's report "Whack-a-mole: Will South Korea's coal power transition be undermined by overcompensated gas?".[3]

Addressing the distortions currently existing in South Korea's power market plays a substantial role in managing the energy transition, as Carbon Tracker already elaborated in our Whack-a-mole report last year[4]. The capped cost-guarantee scheme applied to both coal and gas assets, allows KEPCO plants to be artificially profitable, while excluding renewables sources from a fair merit-order mechanism.

Subsidies should be redirected. Instead of supporting the profitability of coal units, drawing a distorted and archaic power market, they should incentivize the implementation of an accelerated renewables and storage fleet.

3. Carbon Tracker et al. (2020), Whack-A-Mole: Will South Korea's coal power transition be undermined by overcompensated gas? https://carbontracker.org/reports/whack-a-mole
4. Carbon Tracker et al. (2020), Whack-A-Mole: Will South Korea's coal power transition be undermined by overcompensated gas? https://carbontracker.org/reports/whack-a-mole

3. A stronger carbon price supported by a more ambitious renewable target can accelerate a coal phase out and save more than $ 5.5 bn

As addressed later on in chapters 4 and 5, Chungnam National University's analysis reveals that due to a rising renewable energy target and emission caps imposed on coal power generation, coal power plant capacity factors will dramatically drop in the next ten years.

This model was extended by Carbon Tracker, with technical support from Chungnam National University, to introduce a carbon price and renewables expansion into the analysis. We set the level of the carbon price to that observed at the time of analysis in the most liquid global carbon market, the EU Emissions Trading System.

Our analysis shows that a more ambitious renewables target, in place alongside an effective carbon price and accelerated coal phase out would lead to a more effective change in the generation mix.

It is feasible for South Korea's total combined on-shore wind and solar capacity to reach more than 54 GW by 2028 – three years earlier than currently planned – with this achievable at a lower net cost to the power system than following the 9th Basic Plan renewables investment schedule.

At the same time, completing the phase out of coal plants by that same year could save the system $ 4 bn annually from 2028 through to 2050 compared to a scenario of carbon prices but no other phase out policies.

3.1 A stronger coal phase out policy and more ambitious renewable policies will mitigate the dispatch of coal plants

3.1.1 Carbon Tracker's dispatch model

Our model[5] allows a least-cost optimisation of power plants and storage dispatch within the constraint of a power network.

We assumed that South Korea's power system is composed by one single transmission zone. Different types of technical constraints are considered to determine which generator needs to be switched on or off on an hourly basis. The most important inputs relating to the South Korean power system are those related to the flexibility of generators:

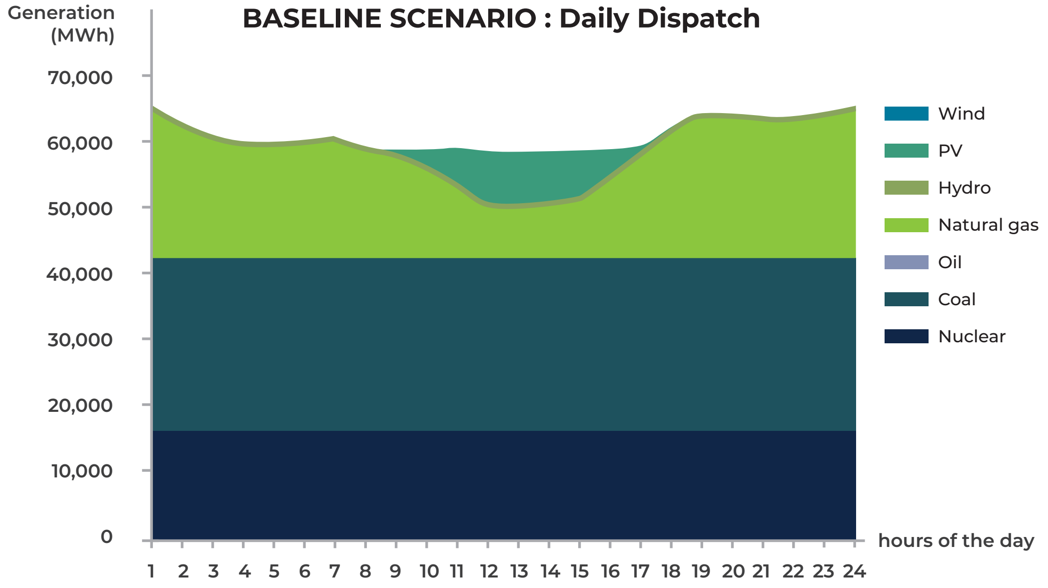
1. ramping limits: a measure of the responsiveness to short-time fluctuations in demand,
2. minimum up and down times: the number of hours a generator must stay in a status (on or off) once it is in such status.

3.1.2 Carbon price-adjusted dispatch: A strong carbon price should be combined with additional measures for the most effective coal phase-out

South Korea's merit order, based on operating marginal costs only, benefits coal as a fuel with low marginal cost compared to LNG fuelled gas, against very high upfront capital expenditures. There is an ongoing discussion regarding the possibility of introducing a carbon price for emitting power plants, which has contributed to the delay of the publication of the 9th Power Plan by the Ministry of Trade, Industry and Energy (MOTIE).

In line with the above, the first step of our analysis aims to highlight the differences between the current merit-order and a carbon price-adjusted merit order i.e., dispatch reflecting a carbon price. Figure 2 shows the daily dispatch profile of the Korean market: installed capacity and technical parameters are representative of the actual scenario, with the exception of regulatory constraints that are not included. Coal and nuclear form the majority of dispatch.

FIGURE 2 – DAILY GENERATION DISPATCH UNDER CURRENT SCENARIO



Source: Carbon Tracker analysis through PyPSA

5. The model is developed through PyPSA, an open source software tool used by power system analysts.
T. Brown, J. Hörsch, D. Schlachtberger, PyPSA: Python for Power System Analysis, 2018, Journal of Open Research Software, 6(1), arXiv:1707.09913, DOI:10.5334/jors.188.
For further details on the technicalities of the model please refer to PyPSA manual, available at: https://pypsa.org/

Running a year-long simulation, we obtain the annual dispatched power mix under the current market scenario: 43% of coal, followed by 27% nuclear and 24% of natural gas (LNG). Renewables – solar, on-shore wind and hydro - reach altogether a 6% share of the total dispatch, while oil accounts for less than 1%.

We included a carbon price in the model to test how the merit order would change. The carbon prices used for this analysis are calculated starting from emission intensities for different technologies and an emission allowance of 36 USD/tCO_2, a conservative choice relative to the latest prices of European emission allowances - as reported by Bloomberg New Energy Finance (BNEF)[6]. These are compared with the average carbon price of 5.8 USD/MWh derived from the ETS scheme currently in place in South Korea, estimated at the unit-level by Carbon Tracker previous research[7].

The daily generation profile does not change significantly under an EU-like carbon price-adjusted dispatch assumption, showing only a minimal switch from coal to gas. Consequently, as represented in Figure 3, the annual power mix does not change significantly either. Introducing a carbon price leads to a decrease in coal dispatch from 43% to 37%, and a 5% increase in natural gas dispatch - nevertheless accounting for more than 30 million tonnes of CO_2 emissions avoided annually.

This is mainly due to the fact that gas is the fuel that sets marginal prices in South Korea's power system. Given that power generation is fueled by very high costs of LNG, a carbon price wouldn't affect the share of coal in the power mix significantly.

6. BNEF (2021), BNEF Research - Why the EU ETS Does Not Need Holding Limits (unavailable without subscription)
7. Carbon Tracker analysis

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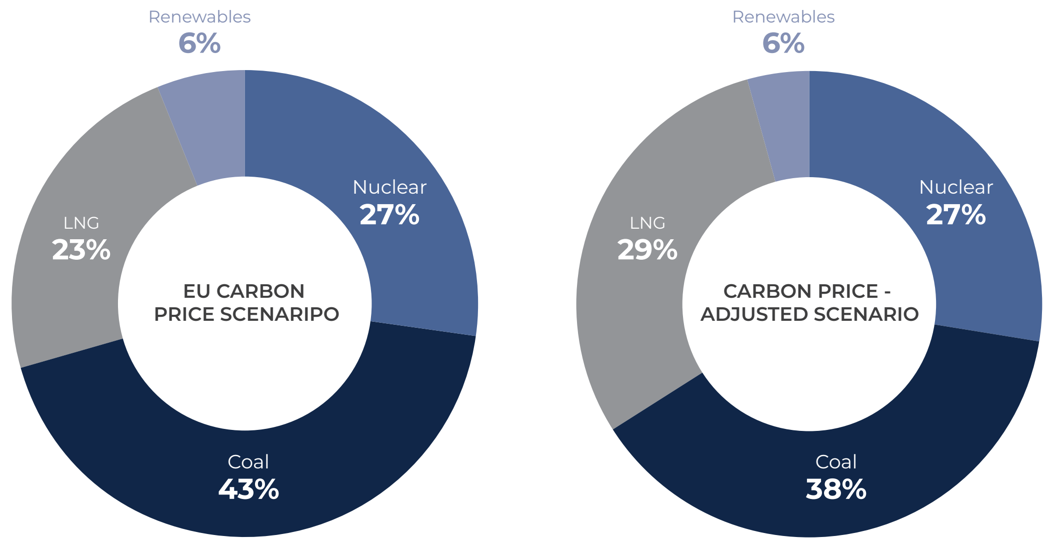
FIGURE 3– YEARLY POWER GENERATION MIX UNDER CURRENT MARKET AND CARBON PRICE-ADJUSTED SCENARIO



Source: Carbon Tracker analysis through PyPSA

Carbon prices will need to be supplemented with other measures to drive wider change. Renewable energy will need to be able to directly compete with fossil fuel generation sources by allowing more long-term power purchase agreements and reforming the current spot only market structure.

The implementation of a carbon price, as it is in place in many western countries, would serve as part of a suite of policy measures to lower emissions. Without relying on scenario compliance analysis, it highlights and strengthens the advantages of switching to a renewable oriented power generation from an economic perspective.

3.2 An accelerated renewables investment schedule will help to phase out coal earlier

Due to the structural and technical constraints described above, a carbon price alone will not be sufficient to phase out coal power. Assuming that this spot dominated market structure resumes, in order to phase out coal in a more cost effective manner, the South Korean Government will need to enhance its renewable energy targets.

With the 9th Basic Plan for Electricity Demand and Supply and the 5th Basic Plan for Renewables, MOTIE set its year-by-year renewable investment targets (reported below and in Table 12 in the Appendix B). Targets for the next 10 years are already approved and in the pipeline, while the projects from 2030 to 2050 are still in a preliminary phase.

TABLE 2 – RENEWABLES TARGET IN MW FROM 2030 TO 2050

	2020	2025	2030	2035	2040	2045	2050
PV (MW)	9,330	19,530	33,530	51,235	68,937	121,282	173,630
Wind (MW)	2,724	8,474	17,674	26,964	36,254	63,724	91,193

Source: 2030, 2040, and 2050 targets are taken respectively from the 9th Electricity Plan, the 3rd Basic Energy Plan, and the 2050 Long-term low greenhouse gas Emission Development Strategies. 2020, 2025, 2035, 2045 are inferred by Chungnam National University.

3.2.1 Meeting the 2030 RES target while phasing out coal will save more than $ 4 bn annually

Several analyses[8] have suggested that South Korea should phase out coal, at least by 80% compared to the current power mix share, by 2030.

We evaluated the savings which would arise for the generation sector from the implementation of the 2030 renewables target as it is, while implementing a carbon price scenario. While this is not the current status quo, we consider it very likely that carbon prices will come into the system. We therefore make it a baseline in order to assess savings of the additional measures that we consider are required. Therefore, we have considered operational and investment costs, compared to a baseline scenario including a carbon price.

For this analysis, we needed a renewable generation profile specific to the South Korean region. We used two different types of profiles, as reported in the assumptions table (Table 9) in the Appendix B: a smoothed profile, obtained through an approximation of the historical load, and an unprocessed one. The additional use of an unprocessed profile further supports the results, confirming the reliability of the grid even under volatile circumstances.

Taking the conservative band of learning rates for solar and on-shore wind as it is projected in IEA World Energy Outlook[9] for Europe, the overall investment necessary to hit the 2030 renewables target amounts to more than $ 50 bn, undiscounted. Against this stands annual savings obtained with increasing renewables capacity that will bring down the net present value of the investment. These savings are estimated at $ 3.4 bn rising to $ 4 bn and flat from 2032, bringing the cost of the overall investment down to a $ 8.9 bn net present value, as shown in 3.2.2.

8. Climate Analytics (2020), Transitioning towards a coal-free society: Science-based coal pathway for South Korea under the Paris Agreement. https://climateanalytics.org/latest/south-korea-must-exit-coal-by-2029-to-be-inline-with-the-paris-agreement/
9. IEA (2018), World Energy Outlook 2018. https://www.iea.org/reports/world-energy-outlook-2018

The annual planned investment according to the renewables target under the 9th Basic Plan is described in Table 13 in the Appendix B.

3.2.2 Accelerated and earlier coal phase out allow for to $ 5.5 bn savings

Our model optimizes the investment schedule for renewables on a least-cost basis, simultaneously considering the system marginal costs and the capex of different technologies. We then evaluated the savings arising from the implementation of this advanced renewable target, considering both operational and investment costs, compared to our baseline scenario.

The feasibility of the investment schedule is constrained by the rate at which onshore wind and solar panels can be deployed. We assumed a maximum y-o-y capacity growth rate of 32%[10] for solar, as it was registered globally and reported by IRENA in 2017 – before further increasing in 2018 and 2019. For wind, we assumed 27%[11] growth each year, as registered in 2019. The use of the 2017 figure for solar allowed more conservative growth projections for PV, leaving room to wind for which a greater growth rate is expected in the coming years. According to these limit growth rates, an achievable investment schedule for South Korea will lead to 40 GW of solar and 14 GW of on--shore wind installed by 2028, with an overall renewable installed capacity of more than 54 GW. Under the 9th Basic Plan, the same target would be reached in 2031 – three years later.

This advanced investment schedule will support an early coal-phase out in 2028, allowing the whole system to save $ 4 bn yearly compared to a non-phase-out scenario under our baseline scenario. These savings arise from the marginal cost of operating renewables, being close to zero. Therefore, the higher the capacity of renewables installed, the more likely a country – in this case, South Korea - is to rely on cheaper electricity at certain times.

Discounting the cashflows with the same assumptions as above, including the higher annual investments necessary to meet the 54 GW of installed renewable capacity target, the cost of the investment, on a net present value basis, amounts to $ 3.4 bn. The earlier 2028 coal phase out therefore implies more than $ 5.5 bn of savings, representing an opportunity to lower costs for ratepayers.

10. IRENA (2018), Global Renewable Generation Continues its strong Growth, https://www.irena.org/newsroom/pressreleases/2018/Apr/Global-Renewable-Generation-Continues-its-Strong-Growth-New-IRENA-Capacity-Data-Shows
11. Renewables Now (2019), Europe adds 15.4 GW of wind in 2019, https://renewablesnow.com/news/europe-adds-154-gw-of-wind-in-2019-687534/

TABLE 3 - UMMARY OF NPV CALCULATION UNDER DIFFERENT COAL PHASE OUT SCENARIO

Renewables investment schedule	Coal Phase Out Year	Renewables installed (GW)	Undiscounted initial	PV initial investment ($bn)	PV savings ($bn)	Overall NPV ($bn)
9th Basic Plan	2030	54 in 2031	(-)54.9	(-)41.7	32.8	(-)8.9
Accelerated, CTI	2028	54 in 2028	(-)52.0	(-)41.7	38.4	(-)3.4
Difference	-	-	2.9	(-)0.0	5.6	5.5

Source: Carbon Tracker analysis

Note: Annual savings are calculated against a non-coal phase out scenario under a carbon price regime. Savings are kept flat at $ 4 bn after the 54 GW is reached in both scenarios. The lower undiscounted initial investments under the accelerated scenario are due to a different optimized composition of the renewable fleet, to which specific learning rates are applied.

An efficient implementation and integration of storage units in the power system would support the transition to a zero-coal power mix.

A coal to gas switching, as announced by MOTIE, will simply lead to a change in the source of a stranded assets risk, as addressed in Carbon Tracker report "Whack-a-mole: Will South Korea's coal power transition be undermined by overcompensated gas?".[12]

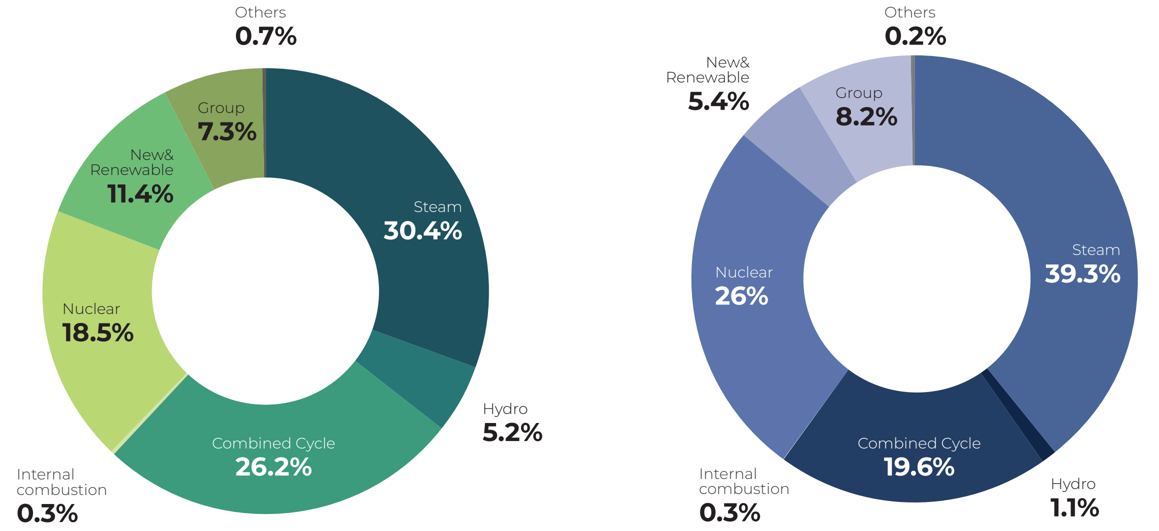
The full list of operating storage units and the coal-to-gas switching plan for South Korea are available in the Appendix B, respectively in Table 10 and Table 11.

12. Carbon Tracker et al. (2020), Whack-A-Mole: Will South Korea's coal power transition be undermined by overcompensated gas? https://carbontracker.org/reports/whack-a-mole

4. Why a coal phase-out is essential

In October 2020, President Moon Jae-in pledged to have South Korea achieve carbon neutrality by 2050. However, the country's carbon-intensive power sector, with coal power accounting for approximately 40% of total electricity generation and nearly a third of national emissions, remains a major obstacle to achieving this goal and enhancing South Korea's NDC to be Paris Agreement-compliant. According to a joint analysis by Climate Analytics and Solutions for Our Climate, South Korea must phase out coal power by 2029 in order to do its fair share under the Paris Agreement.[13]

FIGURE 4 – INSTALLED CAPACITY AND GENERATION POWER MIX OF KOREAN POWER SYSTEM IN 2019[14]



Source: Electric Power Statistics Information System of South Korea (2019?)

While there are still over 7 GW of coal power units under construction, there are indications of coal phase-out in Korea. In November 2020, the National Council on Climate & Air Quality (NCCA), a presidential advisory body led by former UN Secretary General Ban Ki-Moon, recommended the Korean government adopt a coal phase-out year of "2045 or earlier" and consider a "2040 or earlier" coal phase-out year given the recent 2050 carbon neutrality announcement. President Moon also committed to enhancing Korea's NDC by the end of his administration in May 2022. In December 2020, the Ministry of Trade, Industry and Energy (MOTIE) presented the 9th Basic Plan for Electricity Supply and

13. Climate Analytics (2020), Transitioning towards a coal-free society: Science-based coal pathway for South Korea under the Paris Agreement. https://climateanalytics.org/latest/south-korea-must-exit-coal-by-2029-to-be-inline-with-the-paris-agreement/
14. Korea Power Exchange (2020), Electric Power Statistics Information System of South Korea. http://epsis.kpx.or.kr/epsisnew/selectEKpoBftChart.do?menuid=020400

Demand (2020-2034) (9th Electricity Plan), which would close 30 coal power units (15.3GW) – approximately half of Korea's coal power fleet – by 2034. This is the first official coal phase-out policy but remains inadequate if Korea is to enhance its NDC, which has been assessed as "highly insufficient" by the Climate Action Tracker.

Carbon Tracker Initiative, Chungnam National University, and Solutions for Our Climate have prepared this analysis to assess how a more expedited coal phase out and more ambition in renewable investments is a reasonable choice for the Korean power sector. In this report, Chungnam National University analysed how new coal power plants are already unprofitable even based on Korean power market tailored modelling results rendered with figures provided by relevant utilities.

Meanwhile, Carbon Tracker Initiative, with a Pypsa model replicating a generic electricity market, analysed how a more aggressive renewable investment scheme would reduce the cost of a coal phase out in Korea and how Korean power market regulations have been excessively subsidizing coal power plants.

4.1 Coal phase-out: an effective way for carbon reduction

With the recent 2050 net zero announcement, the South Korean Government has been trying to align its energy and environmental policies with that goal. The power sector contributes to more than half of the nation's greenhouse gas emissions. In 2019, coal power plants alone contributed to approximately 25% of the nation's greenhouse gas emissions and approximately 40% of the total electricity generation in the country. [15,16]

Considering its high emission coefficient, phasing out coal power plants appears to be the most effective way to reduce greenhouse gas emissions in South Korea.

TABLE 4 - EMISSION COEFFICIENTS OF EACH CONVENTIONAL POWER PLANT (COAL, AND NATURAL GAS)

	Coal Power Generation	Natural Gas Power Generation (Combined Cycle)
CO2 emission coefficient [kgCO2e/kWh]	0.8229	0.3487
PM25 emission coefficient [g/kWh]	0.137	0.0232

Source: Greenhouse Gas Inventory and Research Centre of Korea (2019)

15. Ministry of Environment (2020), Greenhouse gas emissions increased by 2.5% in 2018, decreased by 3.4% in 2019, http://www.me.go.kr/home/web/board/read.do?menuId=286&boardMasterId=1&boardCategoryId=39&boardId=1400930
16. Greenhouse gas emissions data of coal power plants was collected in 2020 by Korea Federation for Environmental Movements from five GENCOs and GS Donghae Electric Power Corporation upon an information disclosure request.

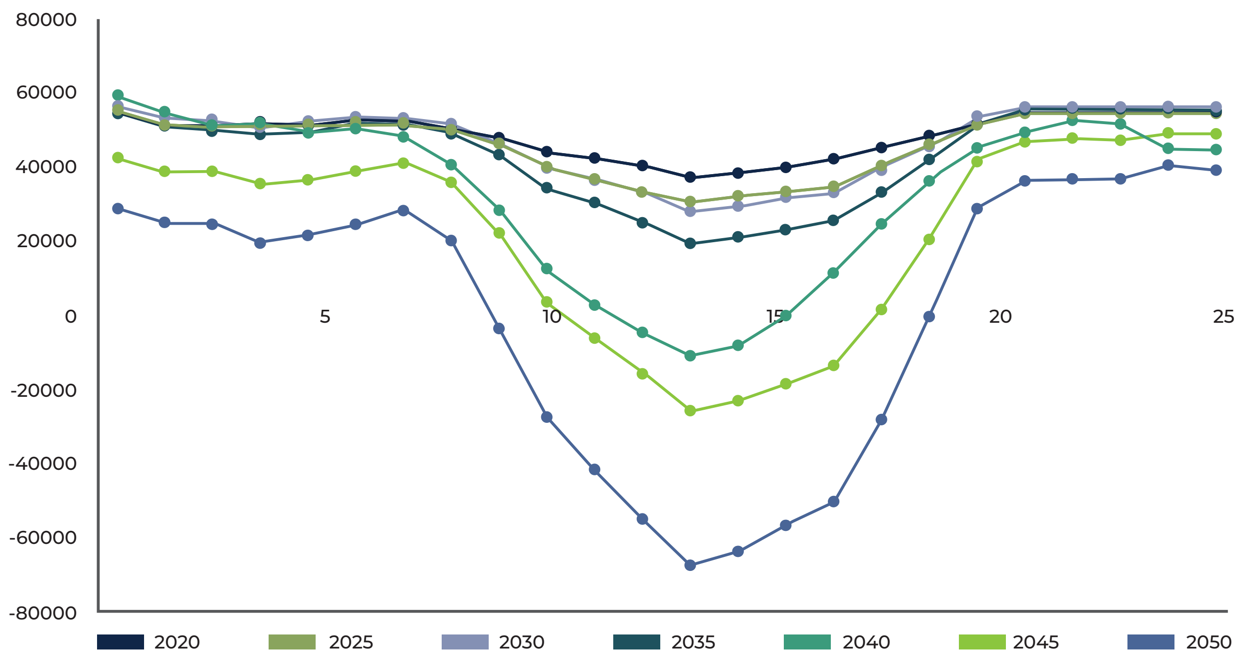
4.2 System reliability: no longer a matter of coal

Balancing the supply and demand is a crucial mission of power system operation. In addition, maintaining the voltage and frequency of each point of the grid within the prescribed range is a key task necessary for ensuring the security of the system. These parameters need to be satisfied at any given time, even during emergency events such as generation or other equipment failure. The Korea Power Exchange (KPX), the Korean system operator, is charged with these tasks. The KPX fulfils such obligations by dispatching power plants and network equipment in the most economical way.

4.2.1 Less room for base-load power plants

Figure 5 is Chungnam National University's analysis of how the daily net demand for power will develop between 2020 and 2050 in South Korea due to increased solar penetration. Unfortunately, conventional baseload power plants are not designed to flexibly follow the so-called "duck curve"[17]. Table 4 below shows the technical specification of conventional baseload plants in the South Korean power system.

FIGURE 5 – CHUNGNAM UNIVERSITY ANALYSIS OF NET DEMAND BETWEEN 2020 AND 2050 (APRIL 20TH OF EACH YEAR) (PREPARED BY CHUNGNAM UNIVERSITY)



Source: Chungnam University analysis
Note: Renewable energy generation assumed to constitute 60% of total generation in 2050.

17. See Figure 10 of Appendix B

As reported in Table 4, baseload power plants (e.g., nuclear or coal power plants) have low ramping capability, high minimum generation requirements, and long minimum up and down times. This means that these sources are not able to provide the flexibility needed to respond to the variation in renewable generations represented in the duck curves.

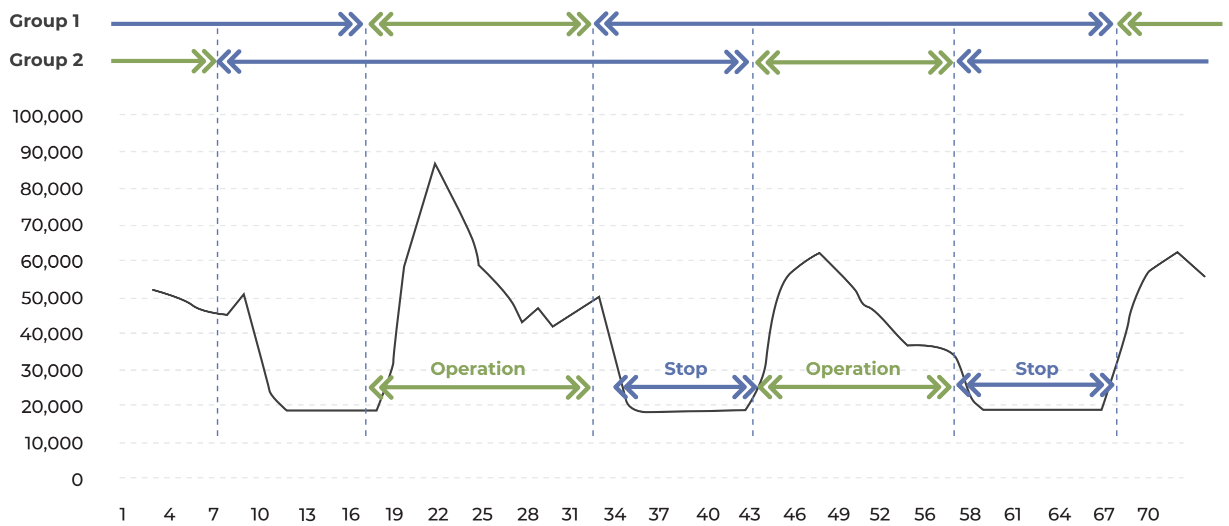
TABLE 5 - RAMPING CAPABILITY, MINIMUM UP/DOWN TIME, AND MINIMUM GENERATION OF COAL POWER PLANTS[18]

Technical Specifications		Ramping capability (MW/min]	Minimum up time (hours)	Minimum down time (hours]	Minimum generation (% of nominal capacity)
Coal	Range	0~31.5	5.5~12.5	12~20.8	47%~69%

Source: Song at al. (2018)

Figure 6 shows how coal power plants may need to operate in 2050 and how difficult it will become for them to survive in a renewable-oriented power system. With low ramping capability and long minimum up and down times, coal power plants cannot respond to load changes in such a system which will practically require a “two shifts per day” for these plants.

FIGURE 6 - EXAMPLE OF “TWO SHIFTS PER DAY” OPERATION OF COAL POWER PLANTS IN 2050.



Source: Chungnam National University analysis

Note: The flattened parts of the net load graph are attributable to curtailment of renewable energy sources implemented to stabilize the operation of nuclear power plants.

18. Song et al. (2018), How to find a reasonable energy transition strategy in Korea?: Quantitative analysis based on power market simulation, Energy Policy 119, p. 396-409. DOI: 10.1016/ j.enpol.2018.05.002

4.2.2 Plenty of alternatives as grid-stabilizing assets[19]

A typical concern of power system operators is that renewable energy sources and the phase-out of base-load power plants may negatively affect power system reliability. South Korean authorities plan to respond to the phase-out of coal power by introducing new gas power plants through the 9th Electricity Plan. The following two points may also be an issue in terms of frequency and voltage stability: (i) the increase of frequency fluctuation due to low system inertia and lack of controllable sources; and (ii) the absence of base-load plants for local voltage support in contingency events. It is true that these will be challenges in the future, but they are manageable problems with emerging technology, as outlined below.

Traditional thermal synchronous generators (i.e., steam and gas turbines) can automatically respond to frequency and voltage variations. In contrast, inverter-based sources such as photovoltaic and wind turbines act as grid following sources and relying on the frequency and voltage set by synchronous sources. Until now, it has been difficult to maintain voltage and frequency during system disturbances with grid-following sources.

Fortunately, various ways of securing voltage and frequency even under those conditions using wind turbines or grid-forming sources with energy storage systems are under development.[20] Major wind turbine manufacturers, including GE, Siemens and Vestas already provide synthetic inertia technology at a commercial level.

In addition, synchronous condensers, well-known control devices using motors, can replace the local voltage support function of base-load plants. For example, in Scotland, synchronous condensers have already been introduced to STATCOM operations[21]. Oberottomarshauser uses synchronous condensers to manage low system inertia and voltage instability caused by the shutdown of a nuclear power plant in Gundremmingen, Germany. In Jeju, South Korea, synchronous condensers are used to maintain system stability by supplying reactive power[22].

These alternatives are providing promising solutions for replacing traditional synchronous generators in ensuring grid stability, voltage levels and frequency control. Thus, showing that a grid can be safely operated and managed without the need of traditional solutions

19. All technical terms in this section are explained in Table 16 of Appendix B.
20. Lin et al. (2020), Research Roadmap on Grid-Forming Inverters. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-73476. https://www.nrel.gov/docs/fy21osti/73476.pdf.
21. ENTSO-e, Synchronous condenser, https://www.entsoe.eu/Technopedia/techsheets/synchronous-condenser
22. P.E. Marken (2012), New Synchronous Condensers for Jeju Island, IEEE Power and Energy Society General Meeting, DOI: 10.1109/PESGM.2012.6344607

5. How coal power plants will become unprofitable even under current regulations

This section analyses the unit level financial feasibility of coal power plants using a power market simulation tool replicating Korean power market and current environmental regulations. The analysis shows that even under current power market environmental regulations, the future of coal power plants in Korean is bleak.

Until the late 1990's KEPCO was a fully vertically integrated monopoly, with most of Korea's generation units, transmission and distribution network inside one corporate body. After the Asian financial crisis, the Korean government tried to restructure its power market, but this restructuring process was suspended in 2004 amidst labour union opposition. Due to this incomplete restructuring process, KEPCO's generation assets were spun off to become six generation companies (GENCOs) but not privatized and are still fully owned by KEPCO. The Korea Power Exchange (KPX) was established for system and market operation and KEPCO still owns most of the transmission and distribution network in Korea. KEPCO also still enjoys a virtual monopoly in the retail sale of electricity[23]. KEPCO owns 70% of operating generation capacity through the six GENCOs.[24] Please refer to Solutions for Our Climate's 2020 report for more information on the structure of the South Korean power market[25]. Please refer to Table 17 of Appendix B for more information of the new coal power plants under construction in South Korea.

5.1 Simulation of capacity factors of coal power plants

5.11 Scenarios

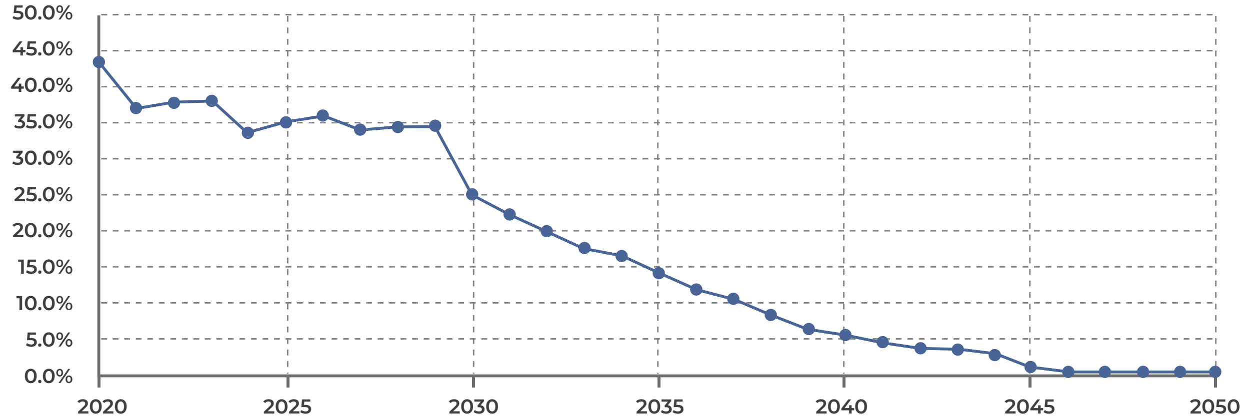
We relied on current policies when conducting the analysis. Our simulation result shows that even under current policies, which have already been criticized for not being consistent with Paris Agreement targets, the future of coal power plants is dim.

This **"current policy scenario"** assumes that (a) the national power mix set out in the 9th Electricity Supply and Demand Plan is implemented[26]; (b) the seven new coal power plants under construction are all completed; and (c) the coal power generation cap system, which the government should introduce by 2022 is implemented as planned. The details of this scenario are presented in Table 18 in the Appendix B.

As a means to meet emission caps, the Korean Government will implement a coal power generation cap system, which will set a cap for coal based generation consistent with the power sector's greenhouse gas emission cap to be at 193MtCO2e per year by 2030[27]. MOTIE and KPX are currently preparing the details of this regulation.[28]

With (i) the trajectory of the power sector GHG emissions cap; (ii) total power generation, nuclear generation, new and renewable generation volumes made available in the 9th Electricity Supply and Demand Plan; (iii) the average GHG emission coefficients applied to coal and gas power generation, the maximum volume of coal power generation can be inferred. In conducting the aforementioned analysis, we assumed that it is only coal and gas power generation that emit greenhouse gases in the power system and that the volume of oil generation is zero, since the ratio thereof is already quite nominal in the Korean power mix.[29] Since the KPM-2 model only provides hourly outputs, when reflecting the annual emission cap to the model, we converted the annual emission cap into a maximum ratio of coal power generation which can be applied to each hour, as described in Figure 7. The formula reflecting the logic for converting annual emission cap into a maximum ratio of coal power generation is reported in Table 7 in the Appendix B.

FIGURE 7 - MAXIMUM RATIO OF COAL GENERATION PER TOTAL GENERATION VOLUME



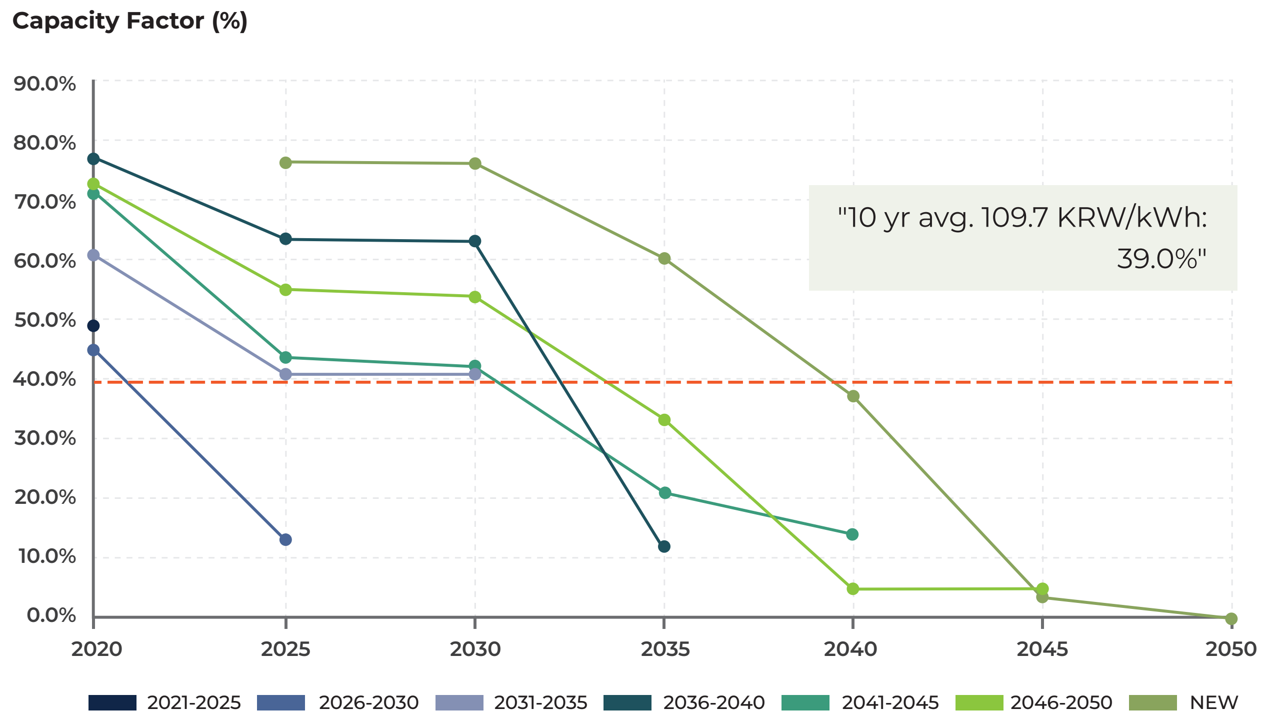
Source: Chungnam National University analysis.

23. For example, KPX forecasts electricity demand for each trading day and receives bids from generation companies for available capacity one day in advance. Based on this, the wholesale market price is determined by KPX in accordance with a pricing mechanism under its Electricity Market Operation Rules, rather than the short-run marginal cost like Western European markets.
24. Carbon Tracker Initiative et al. (2020), Whack-A-Mole: Will South Korea's coal power transition be undermined by overcompensated gas?, https://carbontracker.org/reports/whack-a-mole/
25. Solutions for Our Climate (2020), Renewables Go To Jail in Monopoly http://www.forourclimate.org/sub/data/view.html?idx=28&curpage=1
26. The official schedules for phase-out of coal power plants and their replacement with LNG plants presented in the 9th basic plan of MOTIE
27. In the 9th Electricity Plan, the government set a target to limit power sector emissions to a level below 193MtCO2e per year by 2030
28. Sangbok Lee (2021), Newly introduced policy expected to put a cap on the total coal generation and allow the units to bid in the auction to drive down the cost, E2NEWS http://www.e2news.com/news/articleView.html?idxno=229956
29. Only 1% of Korean power generation came from oil in 2019 (KEPCO 2020, Statistics of Electric Power in Korea, https://home.kepco.co.kr/kepco/KO/ntcob/ntcobView.do?pageIndex=1&boardSeq=21047466&boardCd=BRD_000099&menuCd=FN05030103&parnScrpSeq=0&categoryCdGroup=&regDateGroup2=)

5.1.2 Simulation results

The results of the simulation described in Figure 8 reveal coal power plants to be on borrowed time. Even under a current policy scenario and assuming that the SMP level stays as high as it was during the past 10 years, most coal power projects will not be commercially viable after 2030, despite being paid at the spot price. In this scenario, capacity factors of coal power plant will dramatically drop due to stronger renewable targets and greenhouse gas emission caps imposed on coal power generation, making most coal power plants uneconomic between 2030 and 2035. The plants expected to be shut down between 2031 and 2035, will start to be unprofitable earlier, specifically from 2025. The seven new coal power plants under construction will become unprofitable in the same way between 2035 and 2040. This result will deteriorate now faster with spot power market prices at lower levels, given that the recent five-year average SMP was KRW 82.7 per kWh. Thus, our analysis shows an upper bound scenario, with new coal projects likely to be unprofitable well ahead of 2035/2040 on less conservative assumptions. This analysis does not assume a 2030 power sector emission cap consistent with a 2050 net zero emission target. The future of coal power plants will be even worse if such a target is reflected in the analysis.

FIGURE 8 – EXPECTED CAPACITY FACTORS OF COAL POWER PLANTS IN A CURRENT POLICY SCENARIO BY RETIREMENT DATE



Source: Chungnam National University analysis.
Note: The red line in the chart above is the minimum capacity factor that a plant should meet to be profitable assuming SMPs are at its ten year average of KRW 109.7/kWh. All the different lines, such as "2021-2025" represent the year range the relevant coal power plants are planned to be decommissioned.

The significant decrease of coal power plant capacity factors is attributable to two forces: (i) the increase in renewable energy, which means that dispatch opportunities corresponding to coal power plants' ramp up and ramp down features are less frequent (a steeper duck curve)[30] and (ii) the newly introduced coal generation cap system. This figure also reveals that it will be difficult for new coal power plants to be financially afloat for more than 15 years after their commissioning dates, which will significantly undermine the possibility of investment recovery.

30. The explanation of the "duck curve" can be found in Figure 10 in Appendix B.

6. Conclusions & Recommendations

As the South Korean government has declared its 2050 net zero commitment, it is crucial to define an effective roadmap that leads to the earliest possible coal phase out.

To align the country's power system with the carbon neutrality goal, greater renewables penetration is required and earlier than currently planned. It is economically feasible under a cost-optimized analysis for renewables investment schedule for combined on-shore wind and solar capacity to reach more than 54 GW by 2028 – three years earlier than when achievable according to the 9th Basic Plan. This milestone can also coincide with the phase out of coal, the deadline for which must be brought forward.

The implementation of a carbon price could serve as a first trigger to support coal phase out, with simulation testing showing that its introduction can begin to slow coal dispatch. The efficient integration of storage units in the power system meanwhile will be necessary to secure the stability of the grid and reliability of supply as intermittent renewables increase their share of overall generation capacity.

Chungnam National University's analysis explicitly reveals that even under current regulations, almost all coal power plants will soon not be able to recover costs even if they receive spot power prices. Phasing out coal as early as 2028 is not only necessary and cost-effective, but also feasible.

Finally, addressing the distortions currently existing in South Korea's power market plays a substantial role in managing the energy transition, in order to avoid a mere switching from coal to gas. Subsidies should be redirected. Instead of supporting the profitability of coal units through the limited or capped cost-plus price system, these should incentivize the implementation of an accelerated renewables and storage fleet and cover the initial extra costs that would derive from the implementation of a carbon price-adjusted dispatch.

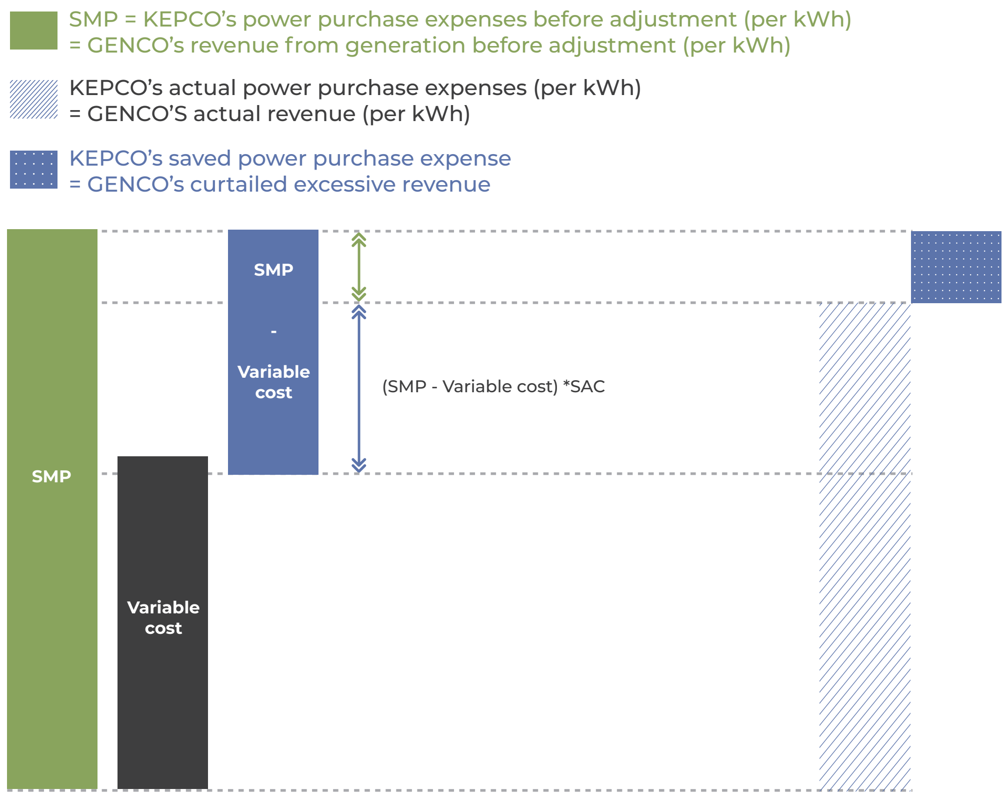
7. Appendix A

7.1 Regulatory structure of coal power plants in Korean electricity market: how South Korean coal power plant operators are compensated

According to the South Korean Utility Business Act, power must be traded through the spot-based power market operated by the KPX and generators are not allowed to directly sell power to consumers.[31] More than 90% of power traded is traded on a spot basis and long-term power purchase agreements with KEPCO barely exist.

The hourly day-ahead price of power traded in the South Korean power system is called the "System Marginal Price" or "SMP", which determines the tariff paid to power generators. The difference between SMP and variable costs becomes profit. For coal power plants, since the SMP is usually higher than the true variable costs paid by GENCOs, the final settlement prices paid to utilities are adjusted. The KPX adjusts the settlement price paid to the utility by applying a "settlement adjustment coefficient (SAC)" to the difference between the SMP and the variable costs of plants.

FIGURE 9 – CONCEPT OF SETTLEMENT ADJUSTMENT AND PROFIT GUARANTEE LOGIC



31. Solutions for Our Climate (2020), Renewables 'Go to Jail' in Monopoly. http://www.forourclimate.org/sub/data/view.html?idx=28&curpage=1

KEPCO: Korea Electric Power Corporation
GENCO: KEPCO's subsidiary generation company
SMP: System Marginal Price

Source: Chungnam National University analysis

The SAC is a figure between zero and one. According to the Electricity Market Operation Rules referred to above, the SAC should not exceed "1", since, in such a case, the settlement paid to the GENCOs[32] will exceed the spot market price (SMP). The settlement adjustment scheme can be represented in this simple equation:

Unit-level profits = (SMP – Variable cost) * SAC

This settlement adjustment scheme applies only to KEPCO GENCOs and private company owned coal power plants. In other words, all of South Korea's nuclear (there are no private company owned nuclear units in South Korea), coal power plants, KEPCO owned gas and oil plants are subject to this scheme. Renewable power plants and private company owned gas and oil power plants are not subject to this scheme – most private company owned gas and oil power plants are merchant power plants.

Not many know how the SAC is calculated, except that the SACs applied to each GENCO are set to provide a guaranteed level of profit to the utilities. The sub-regulations to the Electricity Market Operation Rules, merely states principles such as that the SAC should be determined to maintain appropriate level of investment return or that the GENCOs should maintain a net profit above zero. One important feature known about this settlement adjustment is that it is made at company level and not unit level. Details of the formula calculating the SAC are unknown to the public.

As each GENCO is guaranteed a limited/capped cost plus-markup through the settlement adjustment scheme described above, coal power generating companies usually do not have the motivation to reduce capital investments. This is one of the reasons banks, in the past, have been willing to finance new coal power plants.

Why was such a scheme introduced? The settlement adjustment scheme was introduced as a temporary means to balance cashflow between KEPCO and the subsidiary GENCOs, before the GENCOs were planned to be privatized. This privatization process abruptly stopped in 2004 amidst labor union opposition and that temporary measure still remains even though seventeen years have passed since that suspension. During those seventeen years, technology and the market structure

32. GENCOs refers to five generation companies in Korea, i.e., Korea South-East Power Corporation, Korea Midland Power Corporation, Korea Western Power Corporation, Korea Southern Power Corporation, and Korea East-West Power Corporation, which are all KEPCO's subsidiaries.

7.2 Simulation of capacity factors of coal power plants: methodology

The Korean Power Market model – 2 (KPM-2) which is an extended version of the KPM model[33], was used to project future capacity factors of coal power plants assuming current power market and environmental regulations. The KPM-2 model elaborately replicates the unit commitment, pricing and settlement scheme operated by the KPX. As a result of this model, we can obtain the hourly dispatch results of each plant for a simulated time span between 2020 and 2050. This result can be converted to annual capacity factors of each power plant.

The credibility of the KPM-2 has been proven by comparing actual market results with simulation results for 2020 which can be found below in Table 5:

TABLE 6 - COMPARISON OF ACTUAL KOREAN POWER MARKET DATA AND KPM-2 SIMULATION RESULTS.

	Annual SMP [KRW/kWh]	Share of Generation [%]				
		Nuclear	Coal	LNG	New & Renew.	ETC
Real	68.87	29.0	35.6	26.4	6.8	2.1
KPM-2	69.7	29.6	37.5	24.1	7.2	1.6
Difference	0.83	0.6	1.9	-2.3	0.3	-0.6

Source: Chungnam National University
Note: The difference between real data and the KPM can be explained by the following three points – 1) The results neglect the efficient LNG fuel price of direct procurement of some private generation companies. Some LNG plants procuring the fuel in this way currently has a dispatch priority on several old coal power plants. It can lead to the overestimated coal generation and underestimated LNG generation; 2) Differences in the New & Renewable and ETC are from the gap between the estimated values in the 9th Basic Plan and the real value; 3) Slight difference in the Nuclear results from the assumed maintenance schedule and emergency operation with curtailment in the simulation. It is inevitable error in the simulation model.

For the convenience of research, we grouped existing and developing coal power plants into seven groups depending on when the coal power plant is expected to close under current policy as presented in Table 8 of Appendix B. The Korean Government has presented years when coal power plants that have been commissioned up to 2004 will be closed under the 9th Power Plan announced in December 2020. For coal power plants that have been commissioned after 2004, thirty years is the operation period Korean

33. Song et al. (2018), How to find a reasonable energy transition strategy in Korea?: Quantitative analysis based on power market simulation Energy Policy, 119, p. 396-409. DOI: 10.1016/ j.enpol.2018.05.002, https://www.sciencedirect.com/science/article/pii/S030142151830294

regulators commonly refer to as how long a coal power plant should operate, although there is no regulation on coal power plant operation period supporting this practice.

7.3 Relationship between SAC and capacity factor of plants

It is difficult to infer the exact relationship between the SAC of KEPCO and each GENCO and the factors (e.g., residual lifetime, capacity factor, fixed cost and variable cost of each unit) that are used to calculate the entity's SAC. This is because SACs are not applied at a unit-by-unit level but at company level. More specifically, when calculating the SAC, the overall cashflow and profitability of the GENCO, including its gas power business is all considered.

However, when it comes to private companies which only own two units of coal power plants, finding out the relationship between the SAC and the various factors that determine it is a less complicated task. In this analysis we have used data available for one of such private coal fired power plants to find out this relationship. Data in the Investment Memorandum of the 2,100 MW Samcheok Bluepower coal power project, made available by Korea Development Bank in March 2018 to present to potential syndicate project finance lenders, was mainly relied on.

With the unit level fixed cost, variable cost and regulated rate of return provided in the Information Memorandum referred to above, and with power market model-based projections of annual average SMPs and annual average capacity factors, we can determine where the SAC will be at in the future, using the mechanism described in Table 6 below. This Formula was inferred from the Information Memorandum referred to above and general understanding of logic related to the cost-of-service regulation. The profit analysis of Samcheock Information Memorandum is also based on this logic.

TABLE 7 – FORMULA FOR CALCULATING SAC

<table>
<tr><td rowspan="5">R + ACP – F – V = a</td><td>PR: unit-level profits [KRW/kWh]
= (SMP - V) * SAC
* V: unit-level variable cost [KRW/kWh]</td></tr>
<tr><td>ACP: adjusted capacity payment [KRW/kWh] [34]
= Capacity payment [KRW/kW]/ Capacity Factor *80%
*80%: Projected capacity factor for coal-fired power plants in the Investment Memorandum of the Samcheok Blue Power</td></tr>
<tr><td>F: unit level fixed cost [KRW/kWh]
= Fixed cost / Generation Volume
= Fixed cost / {(Max. of Generation Volume) *Capacity Factor}
= B/u*
* B: Fixed cost / Max. of Generation Volume
* u: Capacity Factor of each plant in future</td></tr>
<tr><td>V: unit level variable cost [KRW/kWh]</td></tr>
<tr><td>a: regulated rate of return [KRW/kWh]</td></tr>
<tr><td colspan="2">SAC = (F + a – ACP) / (SMP – V) = (B/u + a – ACP) / (SMP – V)</td></tr>
</table>

Note: This formula is inferred by Chungnam National University through the profit analysis results in the Investment Memorandum of Samcheok Blue Power coal power project. Unit level variable cost are assumed to be the same for each plant.

As discussed above, the SAC should not exceed "one (1)" since, if so, the compensation paid to the utility will exceed the weighted spot price of electricity. With the mechanism described above, assumptions made available in the aforementioned Information Memorandum and the SAC cap of "1", we can find out at least how high the capacity factor of coal power plants unit should be during a certain period for that plant to be commercially viable. We compared such minimum capacity factor with capacity factor calculations derived through the power market modelling described below.

The minimum capacity factor the coal power unit should meet to be commercially viable may vary depending on spot power market price levels. In this analysis we conservatively assumed future spot prices (SMP) will be at the past ten-year average price which is KRW 109.7 per kWh (0.10 USD/kWh). The recent five-year average SMP of KRW 82.7 per kWh (0.074 USD/kWh), may imply higher capacity factors as required for plant to be commercially viable. This of course is constrained by environmental policy which imposes emission limits and thereby caps out, as highlighted above.

34. Pursuant to the Power Market Operation Rules, promulgated by KPX, power plants subject to dispatch orders of KPX are eligible to receive capacity payments of approximately KRW 10 per kW (USD 0.95 cent per kW) for making their units available for dispatch.

8. Appendix B

TABLE 8 - LOGIC FOR CONVERTING ANNUAL EMISSION CAP INTO A MAXIMUM RATIO OF COAL POWER GENERATION.

$COAL \times GHG_{coal} + (FOSSIL - COAL) \times GHG_{LNG} \leq G$

Max (COAL) [%] = $(G - FOSSIL \times GHG_{LNG}) / GHG_{coal} - GHG_{LNG}$

- G [kg CO2]: Annual power sector GHG emission cap
- FOSSIL [kWh]: Generation from fossil fuels
- COAL [kWh]: Generation from coal
- GHG_{coal} [kgCO2/kWh]: Average GHG emission coefficient of coal power generation (0.823)
- GHG_{LNG} [kgCO2/kWh]: Average GHG emission coefficient of LNG power generation (0.3625)

TABLE 9 - CATEGORIZATION OF COAL POWER PLANTS BY PHASE-OUT YEAR

Phase-out period used for KPM2 modelling	Unit Name	Commissioning Year	Decommissioning Year	Source of Decommissioning Year
2020~2025 group	Boryeong 1	1995	2020	8th Electricity Plan
	Boryeong 2	1995	2020	8th Electricity Plan
	Samcheonpo 1	1983	2021	8th Electricity Plan
	Samcheonpo 2	1983	2021	8th Electricity Plan
	Honam 1	1973	2021	8th Electricity Plan
	Honam 2	1973	2021	8th Electricity Plan
	Boryeong 5	1993	2023	9th Electricity Plan
	Boryeong 6	1994	2024	9th Electricity Plan
	Samcheonpo 3	1993	2024	8th Electricity Plan
	Samcheonpo 4	1994	2024	8th Electricity Plan
	Taean 1	1995	2025	8th Electricity Plan
	Taean 2	1995	2025	8th Electricity Plan
2026~2030 group	Samcheonpo 5	1997	2027	9th Electricity Plan
	Taean 3	1997	2027	9th Electricity Plan
	Taean 4	1997	2027	9th Electricity Plan
	Hadong 1	1997	2027	9th Electricity Plan
	Hadong 2	1997	2027	9th Electricity Plan
	Samcheonpo 6	1998	2028	9th Electricity Plan
	Hadong 3	1998	2028	9th Electricity Plan
	Donghae 1	1998	2028	9th Electricity Plan
	Dangjin 1	1999	2029	9th Electricity Plan
	Dangjin 2	1999	2029	9th Electricity Plan
2026~2030 group	Hadong 4	1999	2029	9th Electricity Plan
	Donghae 2	1999	2029	9th Electricity Plan
	Dangjin 3	2000	2030	9th Electricity Plan
	Hadong 5	2000	2030	9th Electricity Plan
2031~2035 group	Dangjin 4	2001	2031	9th Electricity Plan
	Taean 5	2001	2031	9th Electricity Plan
	Hadong 6	2001	2031	9th Electricity Plan
	Taean 6	2002	2032	9th Electricity Plan
	Yeongheung 1	2004	2034	9th Electricity Plan
	Yeongheung 2	2004	2034	9th Electricity Plan
	Dangjin 5	2005	2035	Assuming an average lifetime of 30 years
2036~2040 group	Dangjin 6	2006	2036	Assuming an average lifetime of 30 years
	Dangjin 7	2007	2037	Assuming an average lifetime of 30 years
	Dangjin 8	2007	2037	Assuming an average lifetime of 30 years
	Taean 7	2007	2037	Assuming an average lifetime of 30 years
	Taean 8	2007	2037	Assuming an average lifetime of 30 years
	Boryeong 7	2008	2038	Assuming an average lifetime of 30 years
	Boryeong 8	2008	2038	Assuming an average lifetime of 30 years
	Yeongheung 3	2008	2038	Assuming an average lifetime of 30 years
	Yeongheung 4	2008	2038	Assuming an average lifetime of 30 years
	Hadong 7	2008	2038	Assuming an average lifetime of 30 years
	Hadong 8	2009	2039	Assuming an average lifetime of 30 years
2041~2045 group	Yeosu 2	2011	2041	Assuming an average lifetime of 30 years
	Boryeong 3	1993	2043	Environment Impact Assessment of retrofitting
	Boryeong 4	1993	2043	Environment Impact Assessment of retrofitting
	Yeongheung 5	2014	2044	Assuming an average lifetime of 30 years
	Yeongheung 6	2014	2044	Assuming an average lifetime of 30 years

2046~2050 group	Dangjin 9	2016	2046	Assuming an average lifetime of 30 years
	Dangjin 10	2016	2046	Assuming an average lifetime of 30 years
	Samcheok Greenpower 1	2016	2046	Assuming an average lifetime of 30 years
	Yeosu 1	2016	2046	Assuming an average lifetime of 30 years
	Taean 9	2016	2046	Assuming an average lifetime of 30 years
	Samcheok Greenpower 2	2017	2047	Assuming an average lifetime of 30 years
	Shin-Boryeong 1	2017	2047	Assuming an average lifetime of 30 years
	Shin-Boryeong 2	2017	2047	Assuming an average lifetime of 30 years
	Taean 10	2017	2047	Assuming an average lifetime of 30 years
	Bukpyeong 1	2017	2047	Assuming an average lifetime of 30 years
	Bukpyeong 2	2017	2047	Assuming an average lifetime of 30 years
New	Shin-Seocheon	2021	2051	Assuming an average lifetime of 30 years
	Gosung Hai 1	2021	2051	Assuming an average lifetime of 30 years
	Gosung Hai 2	2021	2051	Assuming an average lifetime of 30 years
	Gangneung Anin 1	2023	2053	Assuming an average lifetime of 30 years
	Gangneung Anin 2	2023	2053	Assuming an average lifetime of 30 years
	Samcheok Blue Power 1	2024	2054	Assuming an average lifetime of 30 years
	Samcheok Blue Power 2	2024	2054	Assuming an average lifetime of 30 years

DYING EMBERS: WHY COAL IS BURNING OUT 21 / 04 / 2021

TABLE 10 - DATA AND ASSUMPTIONS

DATA	DESCRIPTION	SOURCE
Generators inventory	List of all the power generating units in South Korea. Each generator is qualitatively classified by type of fuel, capacity (MW), city and region.	Korea Power Exchange (2020a)
Country load (MW)	Load profile, representing South Korea electricity demand, is provided by CNU, according to historical data.	Korea Power Exchange (2020b)
Fuel cost (USD/MWh)	Historical 2019 fuel costs for nuclear, coal, oil and natural gas. Data were provided in USD/GCal, converted to USD/MBtu.	Korea Power Exchange (2020a)
Marginal cost (USD/MWh)	Marginal cost (USD/MWh) for each generator are based on marginal fuel costs, considering the type of technology of each generator and its efficiency.	Korea Power Exchange (2020a)
Efficiency (%)	Efficiencies (%) are taken from IEA World Energy Outlook 2018. 60% for combined cycle gas turbines, 55% for nuclear power plants, 45% for oil plants, 43% for supercritical coal plants, 39% for subcritical ones and 47% for ultrasupercritical coal units.	IEA World Energy Outlook (2018)
Carbon price (USD/MWh)	A carbon price is added according to the different scenarios on top of fuel cost/MWh. Carbon costs per MWh are calculated from emission intensities of 426 gCO2/kWh for natural gas and 874 gCO2/kWh for coal, taken from the Parliamentary House of Science and Technology, and the 40 USD/tCO2 carbon price from BNEF.	BNEF 2021 Parliamentary House of Science and Technology
Start-up costs (USD)	Start-up costs, i.e. the extra costs incurred when a generator needs to be switched on rapidly, are provided from historical data.	Song et al. (2018)
Capital cost (USD/MW)	Investment costs for the different generating technologies are taken from IEA World Energy Outlook 2018. Specifically, we used a curve starting from 1,300 USD/kW in 2017 for coal reaching 860 USD/kW in 2030, and from 1,820 USD/kW for wind reaching 1,740 USD/kW in 2030.	IEA World Energy Outlook (2018)
Minimum up/down times (h)	Minimum up and down times are provided by CNU, taken from their technical historical database. These indicate the minimum amount of hours that a generator is required to stay on or off once it is in such status.	Song et al. (2018)

Ramp limit up/down (%/hr)	Ramping limits are provided by CNU, taken from their technical historical database. These indicate the flexibility potential of each generator, i.e. how quick it can ramp up or down when needed. They were originally provided in MW/min, converted to % of nominal capacity/hr.	Song et al. (2018)
Ramp limit start up (%/hr)	Ramping limits are provided by CNU, taken from their technical historical database. These indicate the flexibility potential of each generator, i.e. how quick it can ramp up during the start-up period. They were originally provided in MW/min, converted to % of nominal capacity/hr.	Song et al. (2018)
Ramp limit shut down (%/hr)	Ramping limits are provided by CNU, taken from their technical historical database. These indicate the flexibility potential of each generator, i.e. how quick it can ramp up during the shut-down period. They were originally provided in MW/min, converted to % of nominal capacity/hr.	Song et al. (2018)
Maximum/ minimum power (%)	Maximum power is assumed as 100% of installed capacity. Minimum power is assumed as 0% of installed capacity. These inputs can be potentially modified from 0 to 1 when some specific type of power profiles need to be implemented.	-
Maintenance rate (%)	Maintenance rates are provided by CNU at the fuel level, taken from their technical historical database. These indicate the amount of time that a generator is required to stay off for maintenance.	Korea Power Exchange (2020b)
Outages rate (%)	Outages rates are provided by CNU at the fuel level, taken from their technical historical database. These indicate the amount of time that a generator is assumed to be off for any kind of unexpected contingencies.	KPX (2011), Report on Outages of Electric Equipment in Korea,[35]
Renewables profiles (MWh)	Generation profiles for solar and wind are provided by CNU, according to historical generation data of two renewables installation in South Korea. Specifically, a 20 MW wind farm and a 1 MW photovoltaic field. From the historical profiles, characterized by an high hourly volatility, we derived a smoothed profiles, that homogenized the yearly solar and wind generation.	Public Data Portal (2020)
WACC	Weighted average cost of capital, which is the rate that a company is expected to pay to finance its assets, is assumed at 4.50 %.	Chungnam National University

35. Korea Power Exchange (2011), Report on Outages of Electric Equipment in Korea. https://kpx.or.kr/www/downloadBbsFile.do?atchmnflNo=16226

TABLE 11 - OPERATING HYDRO PUMPED STORAGE UNITS

Unit name	Capacity (MW)
Muju	600
Yecheon	800
Samrangjin	600
Cheongpyeong	400
Yangyang	1000
Sancheong	700
Cheongsong	600

TABLE 12 - COAL UNITS THAT ARE PLANNED TO BE SWITCHED TO GAS

Unit name	Capacity (MW)	Switching date
Samcheonpo 3, 4	1,120 x2	2024
Samcheonpo 5, 6	500 x2	2027, 2028
Hadong 1, 2	500 x2	2026, 2027
Hadong 3, 4	1,000 x2	2028
Hadong 5, 6	1,000 x2	2031
Taean 1, 2	1,000 x2	2024, 2025
Taean 3, 4	500 x2	2028, 2029
Taean 5, 6	1,000 x2	2032
Boryeong 5 and 6	1,000 x2	2025
Dangjin 1, 2	1,000 x2	2029
Dangjin 3, 4	1,000 x2	2030
Yeongheung 1	1,000	2034

TABLE 13 - RENEWABLES TARGET IN MW FROM 2030 TO 2050

	2020	2025	2030	2035	2040	2045	2050
PV (MW)	9,330	19,530	33,530	51,235	68,937	121,282	173,630
Wind (MW)	2,724	8,474	17,674	26,964	36,254	63,724	91,193

TABLE 14 - INVESTMENT SCHEDULE AS PER 9TH BASIC PLAN

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Mln USD capex	3,442	3,735	4,024	4,950	5,214	5,124	5,505	6,102	5,995	6,319

TABLE 15 - INVESTMENT SCHEDULE SUGGESTED

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Mln USD capex	3,519	3,978	5,396	6,728	7,970	8,055	9,450	6,863	4,882	4,913
PV (MW)	11,196	13,211	16,118	19,986	24,983	29,979	35,975	40,048	42,519	45,305
Wind (MW)	3,474	4,424	5,663	7,135	8,732	10,479	12,574	14,335	15,866	17,313

TABLE 16 - NEW TECHNOLOGIES TO BE IMPLEMENTED BY 2028

Technology	MW installed by 2028	Capex required $
SOLAR	40,048	31 bn
ON-SHORE WIND	14,335	21 bn
COAL TO GAS SWITCH	20,000	-
HYDRO PUMPED STORAGE	4,700	-

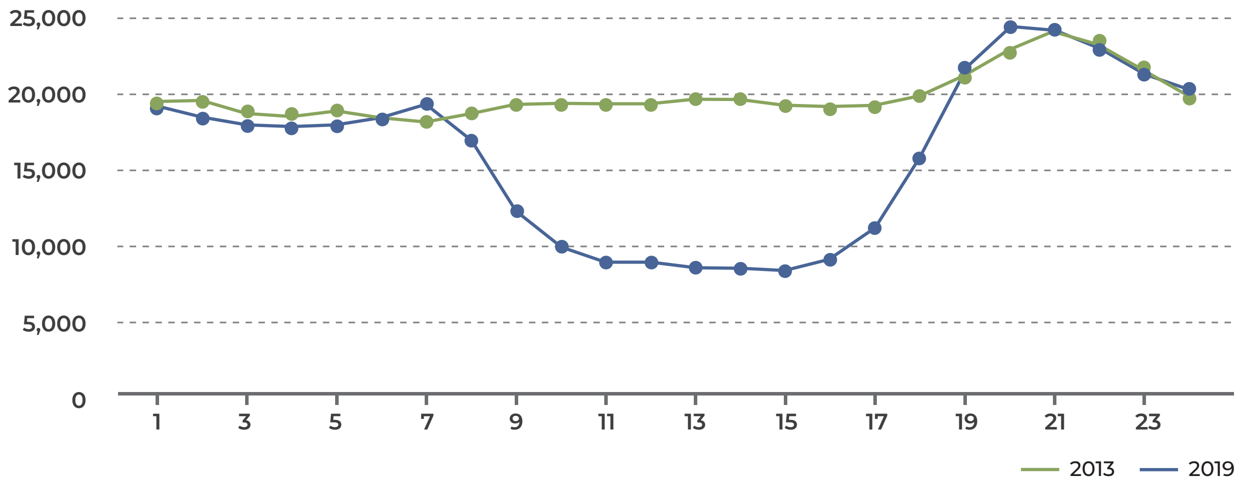
TABLE 17 – LIST OF TECHNICAL TERMS[36]

Technical Terms	MW installed by 2028
Capacity payment	Some electricity market uses capacity payment pricing for compensating capital costs of peak power plants in the marginal cost-based electricity market. This payment is capacity basis (per kW) considering reliability contribution of peak power plants to whole power system. It is similarly applied to base-load power plants in South Korea, but not given to carbon-intensive plants in Europe.
Frequency fluctuation	Frequency is the real-time index of balance between supply and demand in a power system. When the system loses its balance in supply and demand, the frequency may go beyond the prescribed range of frequency deviation. Generally, uncertainty and variability of renewable generation can intensify the fluctuation of frequency.
Generator excitation	In conventional generator, electricity is generated by rotating magnetic powered by turbine. Generator excitation system supplies electrical current for magnetizing the rotating part, and it can also control the voltages by adjusting the level of the current.
Minimum Up Time	Minimum time required after black start for stabilization of a thermal attribute of conventional power plants. When a plant is turn on, this plant cannot be shut down during the minimum up time.
Minimum Down Time	Minimum time required after shutdown for stabilization of a thermal attribute of conventional power plants. When a plant is turn off, this plant cannot be start again during the minimum down time.
Phase-locked loops	Phase-locked loop is a control scheme that makes an output signal refer to an input signal. In the inverter-based renewable energy sources (non-synchronous machine), the frequency and voltage of the source are virtually made from the system frequency and voltage at the interface. If every source in the power system use this phase-locked loop control scheme, there is no source for making stable reference signal anymore. It makes the system vulnerable for any disturbance.

36. Bergen and Vittal (2000), Power Systems Analysis (second edition)

Ramping capability	Ramping capability means capability of plants to increase or decrease its power output per minute.
Rotational inertia	Conventional power plants generate electricity using rotational mechanical turbine powered by steam. It naturally creates an inertia for instantly storing energy. The inertia from rotating machine contribute to a power system being robust against some disturbances.
System inertia	System inertia can be calculated from the sum of all rotating System inertia can be calculated from the sum of all rotating
Synchronous condenser	Synchronous condenser is a synchronous motor based on rotating machine, but whose shaft is not connected to anything but spins at system frequency. Its purpose is not to convert electrical energy to mechanical energy, but to control the voltages or other state variables of a power system.
Synchronous generator	Conventional generator which is operated by rotating machine
Terminal voltage	Voltage at interface between a generator and whole power system. Generator excitation controls this voltage being at the pre-set value.
Turbine-governor control	Against sudden disturbance in a power system, conventional generators are designed to instantly respond without centralized dispatch from system operator. Turbine-governor control scheme simply implement the function by increasing/decreasing the power output of plant corresponding to decrease/increase in power system frequency.

FIGURE 10 – "DUCK CURVE"



Note: Demand curve of California's traditional power system in 2013 (green), and net demand curve of renewable-oriented power system (blue) in 2019 [37]

The duck curve is the shape of the net load[38] of a power system with significant shares of renewable energy generation. The term was first used in 2021 by the California Independent System Operator.

In a conventional power system, which would have a small portion of renewable energy, the daily demand curve generally would look like the red – line in Figure 10. The development of cheap renewables, promoted by intensifying climate change, is changing the situation. With the widescale deployment of renewables, the net demand curve is changing into the shape of the green line in Figure 10.

37. IEA (2019), The California Duck Curve. https://www.iea.org/data-and-statistics/charts/the-california-duck-curve
38. Net load = Load – Non-dispatchable renewable energy

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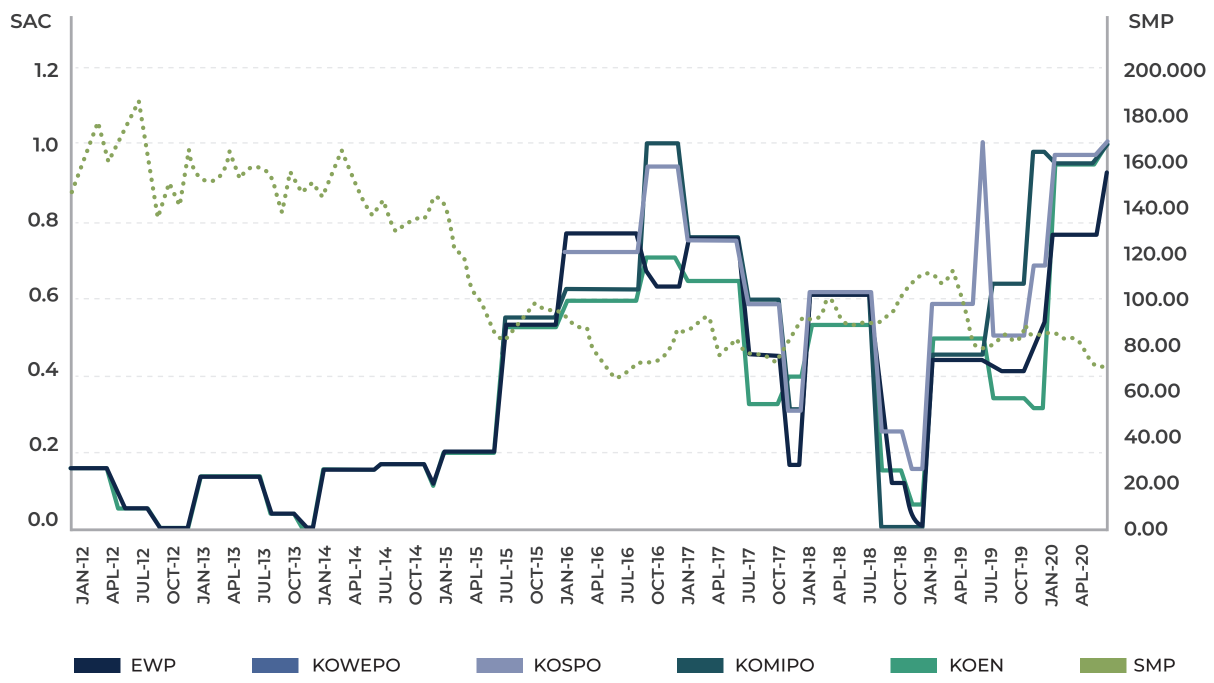
TABLE 18 - LISTS OF NEW COAL POWER PLANT UNDER CONSTRUCTION

Unit name	company	capacity	Operation Date	Progress in construction (October 7, 2020)
Sinseocheon	Korea Midland Power Corporation	1,000MW	2021.3.	90.32%
Gosung-Hai Unit 1	Gosung Green Power (Korea East West Power Corporation, SK E&C, SK Gas)	1,040MW	2021.4	92.63%
Gosung-Hai Unit 2		1,040MW	2021.10	
Gangreung-Ahnin Unit 1	Gangreung-Eco Power (Korea East West Power Corporation, Samsung C&T)	1,040MW	2022.9	50.16%
Gangreung-Ahnin Unit 2		1,040MW	2023.3	
Samcheok Unit 1	Samcheok Blue Power (Posco Energy, Posco E&C, Doosan Heavy Industries & Construction)	1,050MW	2023.10	27.11%
Samcheok Unit 2		1,050MW	2024.4	

FIGURE 11– HISTORICAL DATA OF SAC FOR FIVE GENCOS HAVING COAL POWER



PLANTS AND SMP TABLE 19 - DETAILS OF SIMULATION SETTINGS FOR KPM-2

Item		Setting or Reference
Demand	Pattern	Demand pattern of 2019
	Annual Consumption	9th Electricity Plan + 2050 LEDS Scenario
Renewable (Solar and Wind)	Share of Generation [%]	9th Electricity Plan + 20% (2030), 35% (2040), 60% (2050)
	Capacity Factor [%]	9th Electricity Plan
	Capacity [MW]	Corresponding capacity for supplying target generation volume with the fixed capacity factor
	Pattern	Historical data in South Korea (2013-2018)
Curtailment Criteria	When	Net load is under the sume of scheduled nuclear generation and 10GW operating reserve
	Target	Wind and Solar
Reserve Requirement	Frequency Control	700MW
	Frequency Restoration (Primary)	1000MW
	Frequency Restoration (Secondary)	1400MW
	Frequency Restoration (Tertiary)	1400MW
Capacity Planning Criteria for Future	Capacity Reserve	22%
	New Plant	Schedule in 9th Electricity Plan
	Back-up Plant	Natural Gas Plant
Capacity Planning Criteria for Future	Retirement	Schedule in 9th Electricity Plan and Lifetime
	Lifetime of Nuclear Plant	40 or 60 yrs
	Lifetime of Coal Plant	30 yrs
	Lifetime of Combined-cycled Gas Plant	30 yrs
	Lifetime of Solar and Wind	25 yrs
Maintenance Schedule	Scheduling Method	Applying fair schedule based on average maintenance rate and period of historical data (2018 ~ 2019)
	Average Maintenance Rate	Coal Plant 20%
		Nuclear Plant 15%
		Natural Gas Plant 10%
		Oil Plant 5%
Fuel Price	Heat Price	Median Value of Past 20 Years (2001-2020)

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