Executive Summary

2050 Climate Neutrality Roadmap for Korea

K-Map Scenario

Implementing an ambitious decarbonization pathway
for the benefit of future generations and the Korean economy

GESI Green Energy Strategy Institute

Institute for Green Transformation

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2050 Climate Neutrality Roadmap for Korea – K-Map Scenario : Implementing an ambitious decarbonization pathway for the benefit of future generations and the Korean economy

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Explanatory notes

- The definition of **carbon neutral** in Korea is equivalent to climate neutral, as it includes all greenhouse gas emissions as estimated in metric tons of carbon dioxide equivalents (CO_2e). This covers emissions from carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrochlorofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). All sectors of the economy are taken into account (power, industry, buildings, transport, agriculture, as well as carbon sinks).

- The **Gov-Scenario** refers to the plans of the Korean government, as outlined in the ***2050 Carbon Neutrality Scenario*** (which sets greenhouse gas emissions targets for 2050) and the ***2030 National Emissions Reduction Target*** (the Korean NDC, which sets targets for 2030). The Korean government announced both plans in October 2021 by increasing the ambition of its NDC.

- The **K-Map Scenario** refers to the **research findings** of three leading Korean climate and energy think tanks for establishing a more ambitious net-zero roadmap.

- In this study, the **industrial sector** includes the **industrial processes** defined by the National Inventory Report of Korea, which excludes electricity and heat utilization in the industrial sector, since they are already included in the power sector. In addition, in the absence of further specification, **hydrogen** refers to **green hydrogen produced with renewable electricity.**

- The term **renewable energy** is based on the **OECD definition** (see https://data.oecd.org/energy/renewable-energy.htm). It does not include by-product gases from steel or petrochemical processes – a point of divergence from official Korean government statistics (in 2019, by-product gases from industry represented some 35% of total "renewable electricity generation" in these statistics). Thus, the figures on renewable energy in this study may differ from those of the Korean government.

Abbreviations

- BAU: business as usual
- BEV: battery electric vehicles
- BF-BOF: blast furnace-basic oxygen furnace
- CAPEX: capital expenditure
- CAT: Climate Action Tracker
- CCfD: carbon contracts for difference
- CCU: carbon capture and utilization
- CCUS: carbon capture, utilization and storage
- CO_2: carbon dioxide
- COP26: the 26th UN Climate Change Conference of the Parties (COP26) held in Glasgow in 2021
- DRI: direct reduced iron
- EAF: electric arc furnaces
- EBRD: European Bank for Reconstruction and Development
- EU: European Union
- GDP: Gross Domestic Product
- GESI: Green Energy Strategy Institute
- GHG: greenhouse gases
- IEA: International Energy Agency
- IGT: Institute for Green Transformation
- IPCC: Intergovernmental Panel on Climate Change
- KMA: Korea Meteorological Administration
- LNG: Liquefied natural gas
- LULUCF: Land Use, Land-use Change and Forestry
- NDC: Nationally Determined Contribution
- NGFS: Network for Greening the Financial System
- NPV: net present value
- OECD: Organisation for Economic Co-operation and Development
- OPEX: operating expenditure
- PV: photovoltaics
- TFA: total floor area
- UNFCCC: United Nations Framework Convention on Climate Change
- V2G: vehicle to grid
- ZEB: zero energy building

Units

- GW: gigawatt
- KRW: Korean won (₩)
  1 US dollar equals 1 120.30 KRW in this report;
  1 trillion KRW is equivalent to 892 million USD
- kWh: kilowatt-hour
- $MtCO_2e$: million tons of carbon dioxide equivalent
- MW: megawatt
- MWh: megawatt-hour
- TOE: ton of oil equivalent
- TWh: terawatt-hour

Preface

The global race to net zero is speeding up. The US has rejoined the Paris Agreement while the EU has laid out its European Green Deal, which aims to mobilize at least €1 trillion up to 2030 for climate mitigation measures. As of February 2022, more than 120 nations had increased their NDC targets for 2030, while countries emitting about 70% of global greenhouse emissions have avowed to achieve net zero by 2050 or soon after. Just three years after Greta Thunberg's *School Strike* in September 2018, powerful momentum for change has developed in international climate policy.

South Korea (hereinafter *Korea*) has also joined the race. In October 2020 Korea pledged to achieve climate neutrality by 2050, backing up this commitment in October 2021 by announcing its *2050 Carbon Neutrality Scenario* and revised NDC for 2030. This is remarkable progress, especially considering the country had been criticized in the past as a climate villain by the international community.

However, Korean commentators and international organizations have noted that the Korean NDC target for 2030 – which relies on international carbon credits, as well as CCUS – is insufficient and incompatible with the 1.5°C target set forth by the Paris Agreement. In addition, while targets are important, a concrete implementation pathway for Korea that is undergirded by sound policy instruments has been lacking to date.

Against this backdrop, three leading Korean climate and energy think-tanks – the Green Energy Strategy Institute, Institute for Green Transformation, and NEXT Group – have developed a detailed and ambitious climate neutrality roadmap for Korea – the so-called K-Map. The research for this roadmap was performed in partnership with Agora Energiewende and in close consultation with various expert organizations in Germany, in order to incorporate the most recent lessons learned from Europe.

This research finds that Korea can avoid more than 1.6 gigatons of additional emissions cumulatively by 2050 compared to the government plan with domestic endeavours alone. In doing so, Korea would not only honour its international obligations to protect the climate, but also avoid *passing the buck* to future generations.

With less than eight years to 2030, the next Korean administration that takes office in spring 2022 has a journey of great importance to undertake. We hope this study will help Korean policymakers successfully navigate the challenges ahead.

Key Findings at a Glance

1 **Korea can achieve net zero by 2050 with a significant increase in renewables deployment, improved energy efficiency, the gradual electrification of end-use sectors, and reliance on green hydrogen where direct electrification is not possible.** An interim target of at least 53% renewables in power generation is required in 2030 to transition to an 84% share by 2050. Coal power plants must be phased out by 2035; natural gas power plants by 2045. The gradual electrification of heat, transport, and industry, as well as various flexibility options (such as storage and demand-side flexibility) will facilitate the deployment of renewables while reducing emissions to net zero by 2050.

2 **On the road to climate neutrality by 2050, Korea should adopt a more ambitious 2030 target and accelerate its domestic efforts while avoiding reliance on international carbon credits. It should also focus on domestic renewables expansion, rather than on CCUS.** This would better align with the Paris Agreement's 1.5°C target while also enabling a smoother path to climate neutrality by 2050.

3 **Korea has to kick-start enhanced climate action as soon as possible.** The new administration needs to focus on key strategic action areas, including the rapid expansion of renewable energy (such that wind and solar power are expanded by 18 GW annually); the promotion of electric vehicles (such that 10 million EVs are on the road by 2030); the accelerated energy refurbishment of buildings, including a heating fuel switch (with 1.4 million heat pumps installed by 2030); the development of a hydrogen infrastructure where direct electrification is not possible; the rapid deployment of livestock manure fermentation facilities; and a strengthening of the Emissions Trading Scheme in the power and industrial sectors.

4 **The path to climate neutrality will require a comprehensive investment program similar to the Miracle on the Han River period.** Investing a total of 1 300 trillion KRW by 2050, or 45 trillion KRW annually (2.5% of Korea's real 2020 GDP), will not only substantially reduce emissions, but also provide a strong boost to the national economy and, last but not least, improve quality of life for Korea's citizens by reducing noise and air pollution.

Contents

1. Introduction

In October 2020, Korea – the world's eleventh largest greenhouse gas emitter in 2018 – pledged to become climate neutral by 2050, thus proudly joining the *climate neutrality club*. This was followed just a year later by the Korean government's adoption of an enhanced NDC target for 2030 – that is, to achieve a 40% reduction in relation to 2018. While the Korean NDC is subject to controversy,[1] this is undoubtedly a tremendous step forward for a country previously dubbed a *climate villain* due to its international development of coal power.

Korea's existing commitments are highly laudable. Nevertheless, greater mitigation efforts are still required to avert the further intensification of the climate crisis, which has already caused more frequent tropical typhoons, unprecedented heat waves, and massive wildfires.[2] Indeed, the international community has expressed criticism of Korea's revised target, pointing out that it falls far short of the 1.5°C goal of the Paris Agreement.[3] Furthermore, at the recent COP26 in Glasgow, UNFCCC asked all member countries to *revisit and strengthen* their 2030 NDC targets by the end of 2022. Accordingly, there is a clear need for Korea to further augment its climate ambition – not only by adopting new targets, but also by developing detailed policies to achieve them.

Immediately following the October 2020 announcements, conservative parties as well as some industrial actors in Korea criticized the government plans, arguing that climate neutrality is a premature goal for Korea. Dissenting voices have focused on the enormous costs associated with such a transition. However, the naysayers typically ignore the opportunity costs that will arise from business as usual. No one can calculate with precision the exact amount of investment that will be required for Korea to become climate neutral. There is a risk that Korean policymakers, embroiled in debate, will miss a historic opportunity to kick-start the transition, and thus fail to keep pace with the rest of the world.

Against this backdrop, three independent Korean think tanks joined forces: the Green Energy Strategy Institute (GESI), Institute for Green Transformation (IGT), and the NEXT Group. In April of 2021, they began to develop an ambitious and concrete emissions reduction scenario tailored to circumstances in Korea. This research was crucially supported with analytical work undertaken by German partners.[4]

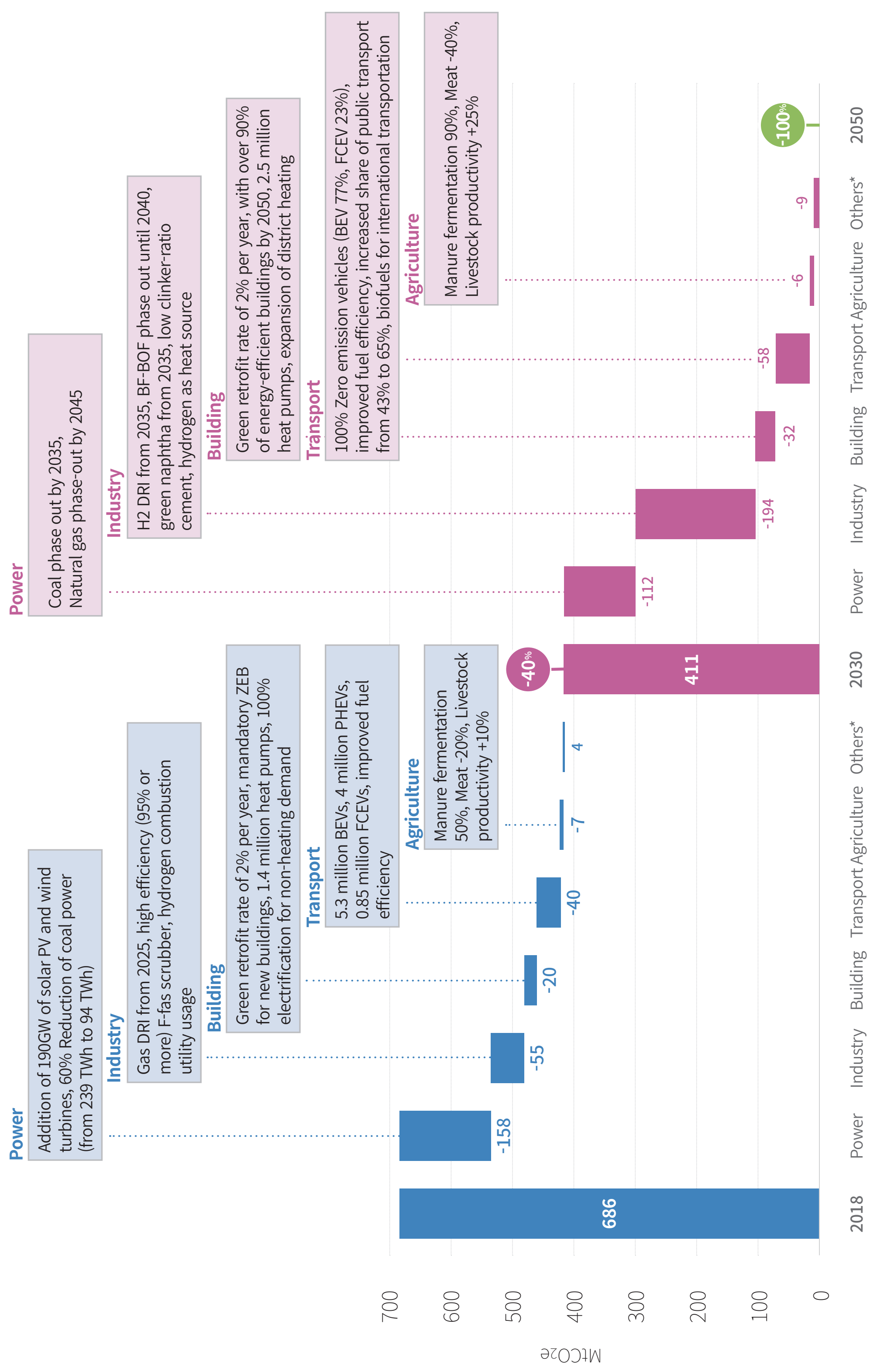
1 The government's announcement of a 40% reduction target may be misleading, as it compares gross and net emissions. The Korean government's set its 2030 reduction target by comparing expected net 2030 emissions (436.6 $MtCO_2e$, including sinks) with gross 2018 emissions (727.6 $MtCO_2e$, excluding sinks), for a 40% reduction between 2018 and 2030. Comparing the net 2030 target with net 2018 emissions (686.3 $MtCO_2e$) reduces the size of the reduction to 36.4%. In addition to this point of controversy, the 2030 NDC includes two problematic carbon sinks: international carbon credits, which contributes 33.5 $MtCO_2e$ to 2030 reductions, and CCUS, which contributes an additional reduction of 10.3 $MtCO_2e$ (an unrealistic level of reduction by 2030). If these two measures are excluded from the calculations, then net 2030 emissions under the government plan increase to 480.4 $MtCO_2e$. This would represent an NDC reduction of just 30%, as opposed to the 40% communicated by the government. See Table 1.

2 Heat waves and tropical nights have increased markedly in the summer, and the Korea Meteorological Administration attributes them to anthropogenic greenhouse gas emissions (KMA, 2020). Weather extremes will become more frequent as global warming accelerates (IPCC, 2018).

3 For example, the Climate Action Tracker, an NGO that monitors international climate policy, still assesses Korea's climate policies as being *highly insufficient*, despite the recent NDC revision. The organization points out that Korea must achieve a 59% emissions reduction by 2030 (compared to 2018) to be in alignment with the 1.5°C target (CAT, 2021).

4 The study *Klimaneutrales Deutschland 2045* (Towards a Climate-Neutral Germany by 2045) was conducted by Prognos, Öko-Institut and Wuppertal Institut on behalf of Agora Energiewende. It helped to strengthen the energy transition objectives adopted by the Scholz administration at the end of 2021 – including increasing renewable energy to 80% of electricity consumption in 2030, and a faster coal phase-out, ideally by 2030.

[Figure 1] K-Map Scenario for Korean carbon neutrality by 2050



* Others refers to waste, fugitive emissions and carbon sinks.

The aim of the study was to investigate the optimal path for Korean emission reductions and to calculate associated investment requirements. The study takes into account the characteristics of each individual sector (power, industry, buildings, transport, and agriculture) while also considering population and GDP forecasts. Based on the assumption of certain policy measures and related conditions (including in particular adoption rates for climate protection technologies), the analysis estimates cumulative emissions, energy consumption, required investment, and the quantitative benefits of avoiding greenhouse gas emissions up to 2050.

The results of the study are clear: with domestic efforts alone, Korea can achieve a 40% emissions reduction by 2030 (compared to 2018; see Figure 1), and Korea can avoid an additional 1.6 gigatons of greenhouse gas emissions up to 2050 compared to current government plans (hereinafter, the Gov-Scenario). Doing so would require additional investment of an estimated 1 300 trillion KRW (830 trillion KRW in 2022 net present value) up to 2050 (compared to a scenario without an accelerated energy transition, referred to as the business-as-usual or BAU scenario[5]). This means that additional annual investment of 45 trillion KRW would avert 8.3 gigatons of GHG emissions compared to the BAU scenario. This corresponds to an economic benefit of about 1 400 to 3 100 trillion KRW (50 to 110 trillion KRW annually) based on NGFS carbon price projections.[6] Such investment would not only allow Korea to achieve climate neutrality, but also give rise to virtuous economic activity dedicated to green transition. This promises to advance Korea as a leader in clean technologies, ameliorate youth unemployment, and also improve quality of life overall for the Korean people. By implementing cutting-edge policy support measures that relieve the private sector of initial investment burdens, such as *Carbon Contracts for Difference* (CCfD)[7], Korea can surmount the economic policy challenges that complicate the transition to climate neutrality.

5 The BAU scenario, which is required for comparative analysis, assumes that energy consumption and GHG emissions in each sector will follow the trends expected before the adoption of the net zero carbon objectives and the reinforcement of the 2030 NDC target announced in October 2021. A more accurate comparison of total required investment, benefits, and cumulative emissions will be available once the government presents its decarbonization pathway in more detail.

6 This amount is calculated as: (forecasted carbon price) * (BAU emissions – K-Map emissions) with carbon price forecasts based on the “Below 2°C” and “Net Zero 2050” carbon price projections for Korea presented by the Network for Greening the Financial System (NGFS, 2020). (See price projections at the end of this executive summary.)

7 A policy mechanism in which the government provides companies with advance financial support in an amount proportional to the production cost increases attributable to the investment in climate-friendly technologies. Companies receiving support pay back the subsidy to the government at a later date, when surplus profits arise from the sale of relevant products. For details, see *5-2. Intelligent policies to support climate neutrality*.

2. More ambitious 2030 climate commitment only through domestic efforts

According to our analysis, Korea can reach 411 $MtCO_2e$ of emissions in 2030, a 40% decline from 2018 (with net emissions of 686 $MtCO_2e$).[8] Importantly, this target can be reached without CCUS and without emissions reductions outside the country. Compared to the Gov-Scenario, this means an additional reduction of 69 $MtCO_2e$ in 2030.[9]

One key to achieving greater reductions up to 2030 will be the accelerated transformation of the **power sector**. Renewable electricity, in particular wind and solar, should be rapidly increased to reach about 380 TWh in 2030, more than double the government plan (185 TWh). At the same time, electricity generation from fossil-fuel power plants (i.e., coal, natural gas, heavy fuel oil) needs to be sharply decreased by more than 50% between 2018 (399 TWh) and 2030 (194 TWh). This will result in a reduction of 158 $MtCO_2e$ greenhouse gas emissions in 2030, 38 $MtCO_2e$ more than in the Gov-Scenario.

In the **industrial sector**, emissions can be reduced by 55 $MtCO_2e$ in 2030 compared to 2018, which is 16 $MtCO_2e$ more than the reductions foreseen by the Gov-Scenario. Developing new climate-friendly technologies and establishing new infrastructure and supply chains for hydrogen will be key drivers in this early stage. Important steps include improving overall energy efficiency, a fuel transition in combustion facilities from fossil fuels to hydrogen, a switch to *Direct Reduced Iron* (DRI) processes in the steel industries (initially based on natural gas, and later on hydrogen), the application of physical and chemical recycling in synthetic resins production in the petrochemical industry, as well the energy efficiency improvement of fluorinated gas (F-gas) scrubbers in the semiconductor and display industries.

In the **buildings sector**, a reduction of 20 $MtCO_2e$ can be achieved in 2030 compared to 2018, which is 3 $MtCO_2e$ more ambitious than the Gov-Scenario. This reduction is based on lower fossil fuel use in heating, broad deployment of heat pumps (1 million units), a strengthening of district heating (currently 2 million TOE to 38 million TOE), the green retrofit of the existing building stock at a rate of 2% per year, and a mandatory *Zero Energy Building* (ZEB) standard for new buildings.

Substantial reductions can also be made in the **transport sector**, with emissions reduced by more than 40% (41 $MtCO_2e$) between 2018 (98 $MtCO_2e$) and 2030 (57 $MtCO_2e$). This drastic reduction (which is 3 $MtCO_2e$ more ambitious than the Gov-Scenario) is driven by the rapid adoption of around 10 million climate-friendly vehicles in road transport.

The **agricultural sector** can reduce its annual emissions by around 7 $MtCO_2e$ in 2030 compared to 2018. Key measures for this transformation include the rapid deployment of livestock manure fermentation facilities to cover 50% of all manure treatment facilities (thus achieving a reduction of 3.1 $MtCO_2e$), and greater reliance on decarbonized energy sources including green electricity (enabling a reduction of 2.2 $MtCO_2e$).

8 While our K-Map scenario still implies a large gap to the level of reduction recommended by CAT, our scenario has the advantage of retaining the macroeconomic assumptions (e.g., population and GDP) used by the Gov-Scenario. Changes to these underlying assumptions produce corresponding divergence in emissions projections.

9 A simple comparison with the 2030 government target (436.6 $MtCO_2e$) only implies an additional reduction of 25.6 $MtCO_2e$. However, the governmental target includes international carbon credits (33.5 $MtCO_2e$), which are problematic, and an unrealistic level of CCUS abatement (10.3 $MtCO_2e$). Given additional domestic efforts to make up for the removal of these two items, net 2030 reductions in excess of the government target equal to 69.4 $MtCO_2e$. This additional reduction corresponds to 10 percent of 2018 emissions.

[Table 1] Comparison of emissions reduction targets for 2030 and 2050

		2018	2030 Targets		2050 Targets	
			Gov-Scenario	K-Map	Gov-Scenario	K-Map
Net Emissions		686.3	436.6	411.4	0	0
Emissions	Power	269.6	149.9	112.0	0	0
	Industry	260.5	222.6	205.8	51.1	11.3
	Buildings	52.1	35.0	32.3	6.2	0
	Transport	98.1	61.0	57.6	2.8	0
	Agriculture	24.7	18.0	17.9	15.4	12.3
	Waste	17.1	9.1	9.1	4.4	4.4
	Hydrogen	-	7.6		0	0
	Fugitive emissions, etc.	5.6	3.9	3.9	0.5	0.5
Sinks	LULUCF	-41.3	-26.7	-27.2	-25.3	-28.5
	CCUS	-	-10.3		-55.1	*
	International carbon credits	-	-33.5		-	

* In the K-Map Scenario, CCUS is included in the industrial sector, with only 23.4 $MtCO_2e$ of reductions through CCU in 2050.

While the K-Map and Gov-Scenario follow similar trend lines up to 2030 in the transport, agricultural and industrial sectors, they diverge significantly in the power and building sectors (see table 1).

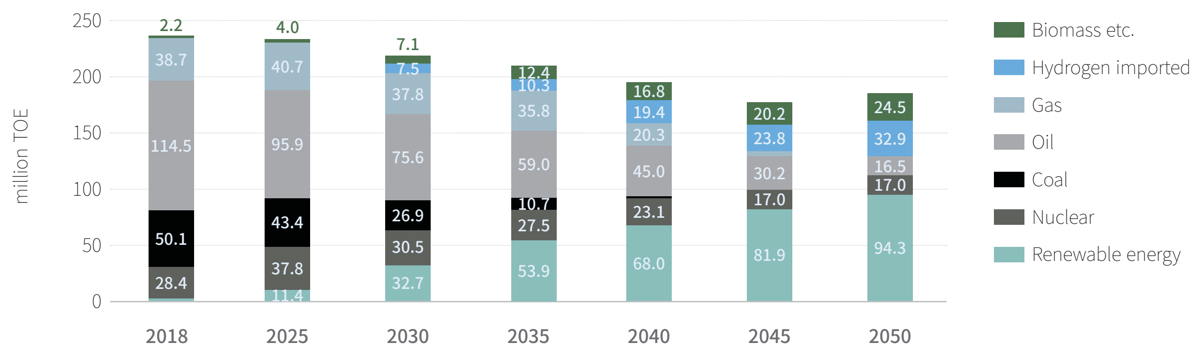
3. The road beyond 2030 – how to achieve net zero in 2050

On the road to net zero by 2050, large efforts will be needed after 2030, especially in the industry and power sectors, where the reductions will become more difficult and costly if not planned properly. In order to ensure the technologies necessary for deep decarbonization are available at the lowest possible cost, proper early planning is required. Coal-fired power plants need to be totally phased out by 2035, while oil- and natural gas-fired power plants will be phased out by 2045. Nuclear will be phased out according to government plans, and will only make a marginal contribution to decarbonization efforts by 2050 (8.1% of total primary energy supply). Efficiency improvements will remain important to help reduce emissions in all economic sectors. Electrification will continue across all sectors, directly where possible and indirectly using sustainable hydrogen and other synthetic fuels, where direct electrification is not possible. Green hydrogen will also be increasingly used as a raw material in the industrial sector. CCUS will remain a marginal technology, only used where CO_2 emissions cannot be avoided by other means, and mostly used in the cement and oil refining/ petrochemical industries. By 2050, electrification and decarbonization in tandem with a decrease in final energy consumption (thanks to efficiency gains and population decline) will lead to a 22% decline in primary energy demand (compared to 2018 levels), as can be seen in Figure 2.

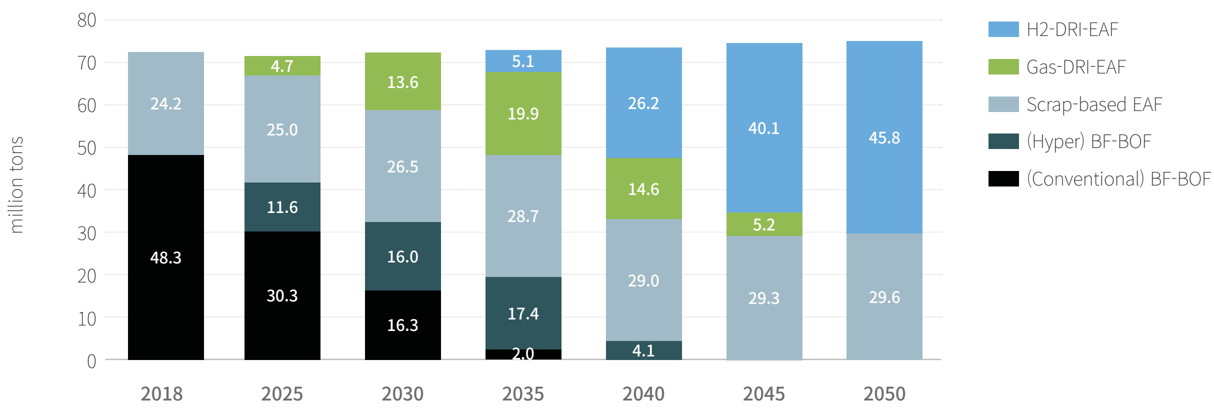
The **power sector** will continue to decarbonize on the back of accelerated renewables deployment (reaching 84% of power production in 2050), the phase-out of coal in 2035, and a switch from natural gas-fired power plants to hydrogen turbine power plants.

In the **industrial sector**, emissions will need to decrease from 200 $MtCO_2e$ in 2030 to 11 $MtCO_2e$ in 2050, thus entailing a fundamental transformation over a period of twenty years. Direct emissions reductions – that rely very marginally on CCUS – represent the largest difference between our roadmap and the Gov-Scenario (which still foresees more than 50 $MtCO_2e$ of emissions in the sector in 2050, which will be offset by CCUS and carbon sinks). This transformation of Korean industry will drive demand for green hydrogen, which is expected to reach 18.2 million tons in 2050, of which the industrial sector will account for 13.5 million tons.

[Figure 2] Primary energy demand, 2018–2050



[Figure 3] Forecasted steel production by process



In the steel industry, the hydrogen-based DRI and electric arc furnace (EAF) routes will replace the emission-intensive blast furnace-basic oxygen furnace (BF-BOF) route, leading to a 90 $MtCO_2e$ reduction in GHG emissions in 2050 compared to 2030 levels. This transition must take place during the next reinvestment cycle in the steel sector, considering an average blast-furnace relining lifespan of 10 to 15 years. The BF-BOF route, which accounts for 65.7% of total steel production, will be completely replaced by DRI by 2040. While DRI will be based on natural gas as a reducing agent from 2025 onward and serve as a bridging technology for about 10 years, it will then be substituted by hydrogen DRI in 2035.

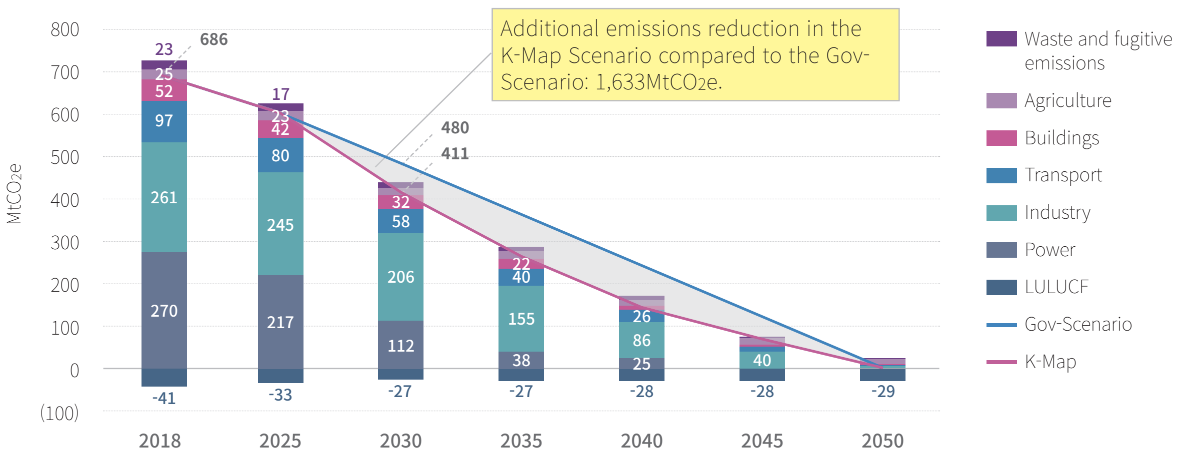
In the petrochemical industry, crude oil consumption will decrease, despite a slight 0.6% annual growth in the demand for petrochemical goods. This will be enabled by the expansion of green plastic production through recycling and the use of organic feedstock. Furthermore, input materials will be manufactured using green naphtha processes that synthesize hydrogen with captured CO_2. The phase out of conventional combustion vehicles will facilitate a rapid decline in demand for petroleum products, allowing the oil refining and petrochemical industry to achieve net negative emissions of 5 $MtCO_2e$ in 2050, thanks to CCU-based green naphtha processes.

The **buildings and transport sectors**, which will already see considerable reductions up to 2030, will more easily reach net zero by 2050, thanks to the path dependencies created by climate policy beyond 2030. In the Gov-Scenario, by contrast, residual emissions are still foreseen in those sectors in 2050.

In terms of cumulative emissions since 2018, the K-Map Scenario projects total cumulative emissions of 10 587 $MtCO_2e$ up to 2050, 1 633 $MtCO_2e$ lower than the Gov-Scenario (12 220 $MtCO_2e$).[10] This augmented level of reduction up to 2030 would not only contribute to intergenerational climate justice. It would also show that Korea is shouldering its fair share of the burden to achieve the 1.5°C.

10 The Gov-Scenario does not provide the reduction path from 2018 to 2050. Thus, it is assumed that the emissions reduction in the Gov-Scenario takes place: (1) up to 2025 as same as the K-Map since it is the best reduction path for the nearest time; (2) from 2025 linearly toward the NDC target of 480 $MtCO_2e$; (3) from 2030 linearly toward the 2050 net-zero target.

[Figure 4] Comparison of emissions trends and cumulative emissions



4. Key strategies for Korea to kick-start climate action now

The transformation of the Korean economy towards net zero over the next three decades represents a tremendous opportunity for industry and society. The key to accelerating the transition lies in choosing the right policies and focusing on the best technologies. Renewable power is going to be the backbone of the transition. Renewables are a mature technology and today have lower generation costs than nuclear or thermal power in many countries around the world. The gradual electrification of heat, transport and industry along with various flexibility options (such as storage and demand-side flexibility) will facilitate the large-scale deployment of renewables while bringing down emissions to net zero by 2050.

Strategy 1 – Use renewables to drive power-sector transformation

Korea is the 8th largest consumer of electricity per capita among the OECD countries, with a total power consumption of about 525 TWh per year, including 56% consumed in the industrial sector alone. While energy efficiency measures will be crucial for minimizing consumptions levels, the importance of electricity and especially renewable power will grow during the transition. For many applications, especially in transport, low-temperature heating, cooling, and hot water, the use of electricity is the most efficient solution, especially compared with combustion engines and boilers.

Against this backdrop, and despite energy efficiency measures, total power demand, especially in the industry and transport sectors, is expected to increase by about 40% in 2030 (from 526 TWh in 2018 to 723 TWh) and more than double in 2050 (1 258 TWh).

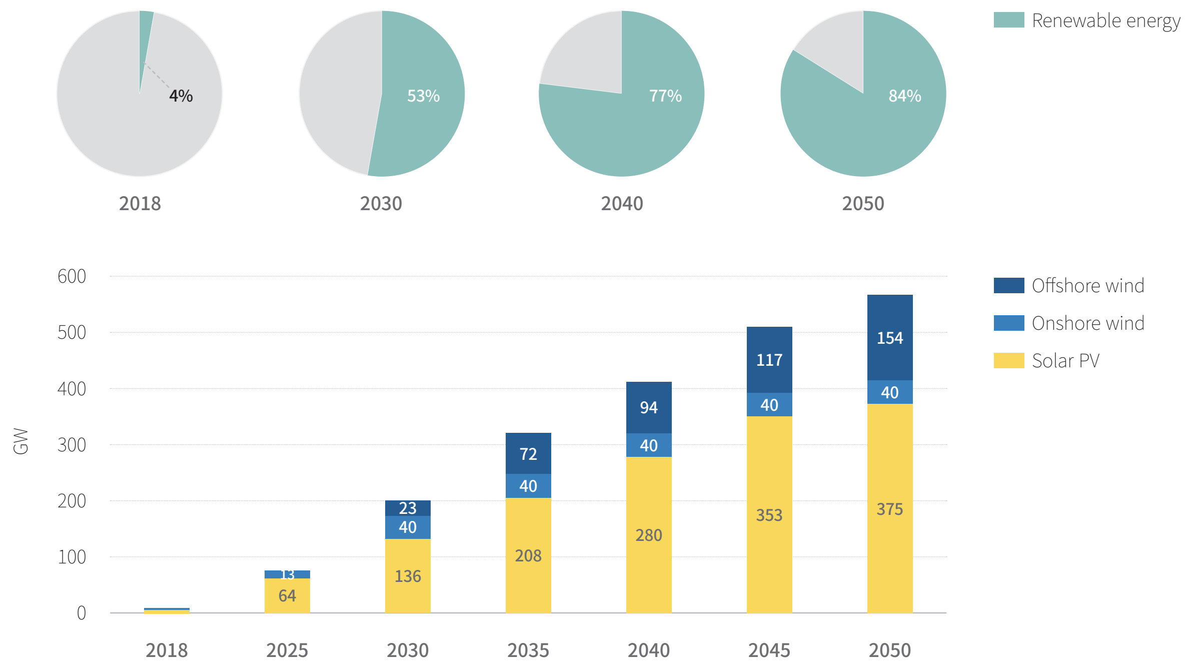
In order to achieve climate neutrality, this demand has to be met as soon as possible by renewable power generation. By 2030, renewable power will have to supply 53% of Korea's energy; by 2050, the figure will have to have increased to 84%. Coal power will need to be phased out by 2035 (a reduction of 37 GW against current levels), and natural-gas power plants will have to switch to green hydrogen turbines by 2045 (for a total of 40 GW installed capacity). According to the government plan, nuclear capacity will be slowly reduced over three decades, from 22 GW in 2018 and 20 GW in 2030 down to 11 GW in 2050.

The significant growth of renewable power implies the installation of about 18 GW of variable renewables pro year up to 2030 (11.7 GW of solar PV, 3.8 GW of onshore wind, and 2.7 GW of offshore wind). This represents a significant increase compared to current installation rates. Due to limited land availability, onshore wind power will reach a maximum potential of 40 GW in 2030, while offshore wind will continue to increase after 2030 with over 6.3 GW installed annually, for a total of 154 GW of installed capacity by 2050. The potential for solar PV is very large, leading to 375 GW of installed capacity by 2050, with a growth rate of about 14.5 GW over 2030–2040 and 10 GW beyond that. In total, onshore wind, offshore wind, and solar power will cover about 10%, 37%, and 38% of total power production in 2050, respectively. Renewable electricity generation in 2050 will reach a total of 1 093 TWh, making up 84% of the country's total generation of 1 296 TWh.[11] As a result, the power sector, today's largest emitter, will reach zero emissions by 2050.

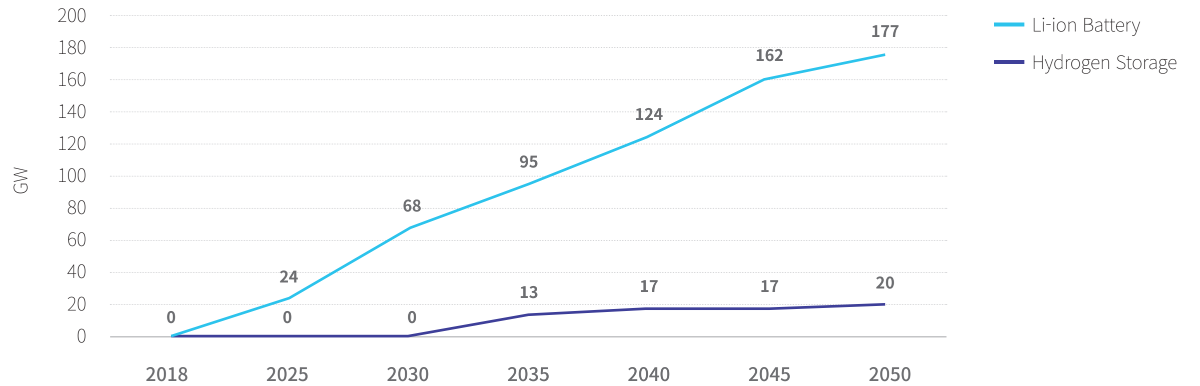
Korea's electricity grid is isolated due to its geographical location, which means that the variability of renewable electricity supply needs to be counterbalanced by domestic flexibility options

11 The difference between total power demand (1 258 TWh) and total generation (1 296 TWh) results from grid losses.

[Figure 5] Share of renewable electricity generation and renewable capacity growth, 2018–2050



[Figure 6] Outlook for electricity storage capacity of battery and hydrogen, 2018–2050



to keep the grid stable at all times. Hydropower will play a role but it cannot be expanded over a certain level due to geographical constraints. The lion's share of flexibility will be provided by lithium-ion (Li-ion) batteries, heat pumps, electric vehicles, and hydrogen storage for green hydrogen produced by surplus renewable generation. Batteries, which offer short-term electricity storage for a daily or weekly period, need to expand rapidly starting in 2025, when renewables penetration will reach about 20%. Hydrogen storage, which can offer longer-term storage across seasons, will have to be deployed in earnest starting around 2030. At that point, offshore wind power, the main energy source for producing green hydrogen, will be at full-scale operation. Hydrogen storage capacity will reach 20 GW by 2050.

Strategy 2 – Support the ramping up of green hydrogen

Because of Korea's energy-intensive industry, green hydrogen will have to play a crucial role in replacing fossil fuels in the country's transition to climate neutrality. Note that blue hydrogen – hydrogen reformed from natural gas using carbon capture – is not considered in the K-Map Scenario. For one, blue hydrogen will not be perfectly carbon-free: future carbon capture rates currently under discussion go up to only about 98%. Moreover, there will likely be fugitive upstream methane emissions from natural gas. Any remaining residual emissions would need to be compensated through negative emissions in a climate-neutral world. And finally, producing blue hydrogen will require new infrastructure for gas reforming and carbon capture, which could ultimately impede the transition to green hydrogen through technological lock-in.

Climate neutrality in the steel and petrochemical industries will only be achievable through the use of green hydrogen in industrial processes. Green hydrogen must also be used in the power sector as long-term storage, compensating for the seasonal variability of renewables and maximizing renewable energy potential by lowering renewables curtailment. In the K-Map Scenario, green hydrogen demand in Korea reaches 18.2 million tons in 2050, of which the industrial sector accounts for 13.5 million tons, the transport sector for 2.8 million tons, and the power sector for 1.8 million tons. This is 30% lower than the demand outlook in the Gov-Scenario for 2050 (27.4 million tons). The difference is attributable to the government's greater emphasis on fuel-cell power plants and hydrogen turbines in the power sector.

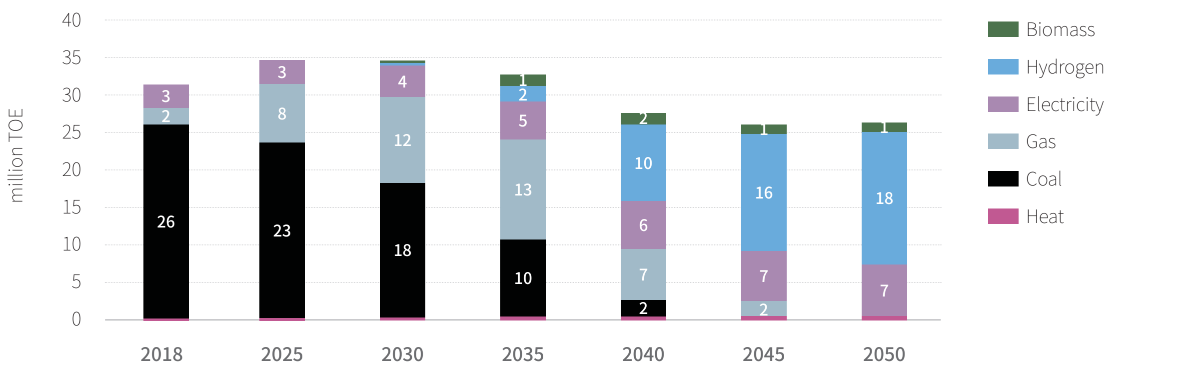
Green hydrogen demand in the industrial sector is about 1.9 million tons larger in the K-Map Scenario than in the Gov-Scenario. This difference is due to the early use of green hydrogen as a heat source and its greater role as a feedstock in various applications: as

[Table 2] Hydrogen demand outlook by year and sector (Unit: million tons)

	2030	2040	2050
K-Map Scenario	**2.65**	**10.55**	**18.19**
Power	-	0.79	1.84
Industry	1.99	8.04	13.53
Transport	0.66	1.72	2.82
Gov-Scenario (2021)	**1.9**	**N/A***	**27.4**
Power	1.6	N/A	14.2
Industry	-	N/A	10.6
Transport	0.4	N/A	1.5
CCUS**	-	N/A	1.0

* The Korean government's Hydrogen Economy Roadmap (2019) estimates that hydrogen demand in 2040 will amount to 5.3 million tons.
** In the K-Map Scenario, all CCUS is included in the industrial sector (i.e., petrochemical industry).

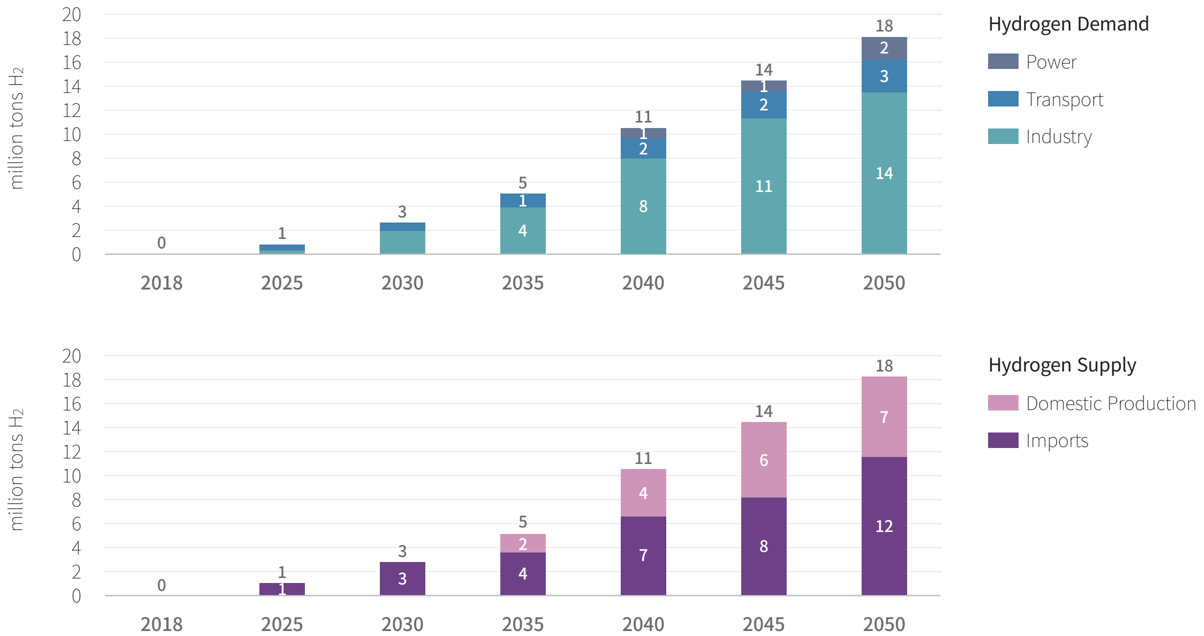
[Figure 7] Energy demand in the steel industry by energy sources, 2018–2050



the reducing agent in DRI facilities for steelmaking, as a precursor for green naphtha in petrochemical and oil refining, and as a major fuel in other industries. Its use is expected to become more widespread starting in 2025. By 2050, it is projected to be the second-largest energy source for the industrial sector, covering 26% of energy demand.

In the transport sector as well, the K-Map Scenario expects more hydrogen demand (about 1.3 extra million tons). This is because the K-Map Scenario assigns green hydrogen a key role in decarbonizing heavy vehicles that are difficult to electrify. It will also play a crucial role in decarbonizing long-haul transport, with the green

[Figure 8] Demand and supply outlook for hydrogen, 2018–2050



hydrogen consumption in aviation and shipping covering 60% of total hydrogen consumption in the transport sector.

Hydrogen plays an especially critical role in reaching climate neutrality in the steel industry. The steelmaking process using the BF-BOF route, which currently accounts for two-thirds of the total steel production, will be fully replaced by DRI process by 2040. As a result, green hydrogen will account for two-thirds of energy consumption in the steel industry in 2050.

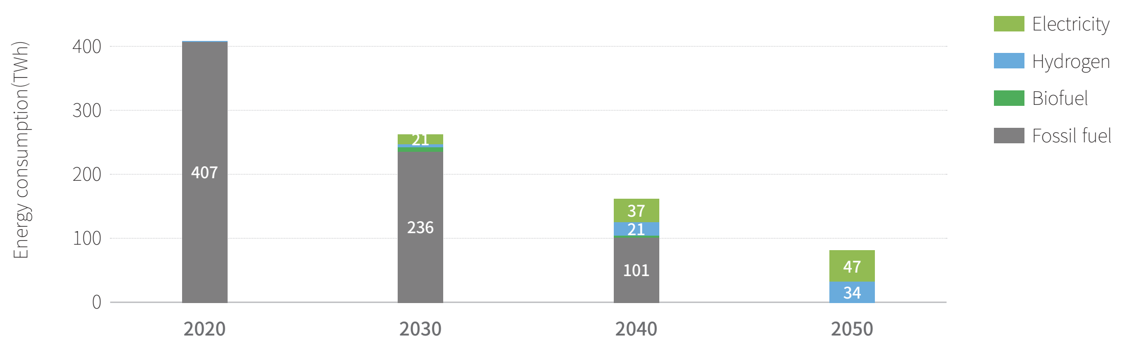
In the K-map scenario, one-third of hydrogen demand will be met through local production (6.7 million tons); the remaining two-thirds (18.2 million tons) will be met through imports.[12] The local production of green hydrogen will rely largely on floating offshore wind power, whose production is expected to begin in 2035 when off-grid offshore wind farms (i.e., not connected to the mainland) start operation.

Strategy 3 – Support the transition in the transport sector

The Korean government has provided financial support for clean vehicle deployment since 2013. However, targets need to be increased to reflect the fact that automobile manufacturers operating in the Korean market have already started to increase their production capacities and are aiming to roll out 800 thousand clean vehicles per year by 2030.

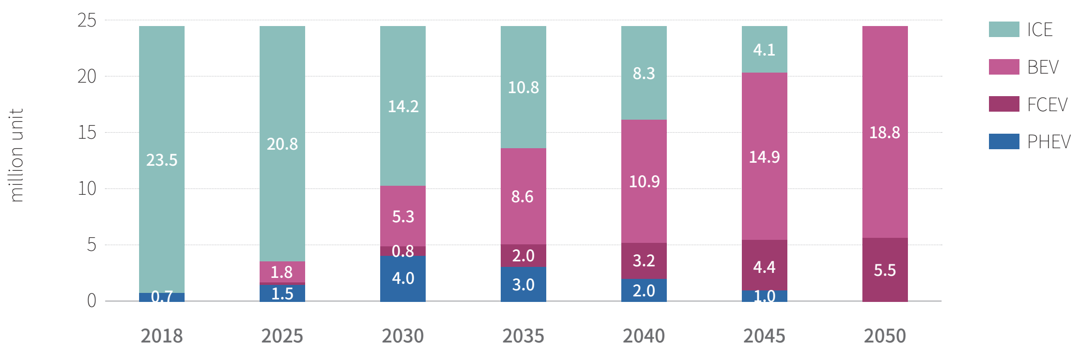
In the K-Map Scenario, the clean vehicle fleet expands to 10 million vehicles by 2030 (5.3 million BEVs; 4 million plug-in hybrids, or PHEVs; and 850 thousand hydrogen fuel-cell electric vehicles). By 2050, this fleet would reach a total of 24.3 million vehicles (18.8 million BEVs and 5.5 million other clean vehicle types). In addition, new combustion-engine vehicles will be banned after 2040. The gradual electrification of the fleet and the associated efficiency gains will reduce fossil-fuel consumption in road transport by 171 TWh (14.7 million TOE) in 2030 and by 407 TWh (35.0 million TOE) in 2050 (in relation to 2020 levels). This, in turn, will avoid 29 $MtCO_2e$ of emissions by

[Figure 9] Outlook for energy consumption in road transport, 2018–2050



12 To this end, hydrogen use must be focused on the industrial sector rather than on the power and transport sectors, where alternatives exist.

[Figure 10] Outlook for clean vehicle expansion for road transport, 2020–2050



2030 and 78 $MtCO_2e$ of emissions by 2050, resulting in an 80% reduction of greenhouse gas emissions in the transport sector by 2050.

The rapid transition to clean vehicles will create a positive ripple effect across the entire society. It will enable a direct reduction of greenhouse gases in the transport sector and will accelerate the transformation of the oil-refining industry by reducing the demand for internal combustion fuels. Furthermore, it will enhance the competitiveness of the Korean automobile industry in the global market, while also providing a suitable environment for the introduction of technologies such as V2G (Vehicle to Grid), reducing variability in the power generation system. Lastly, it will contribute to energy security by reducing oil imports.

In order to support this transition, stronger policy measures and support are required from the government. This includes increased subsidies for clean vehicles, better public transport systems for an accelerated modal shift, the reinforcement of fuel efficiency control systems, and regulations on biofuels and e-fuels for long-haul transport.

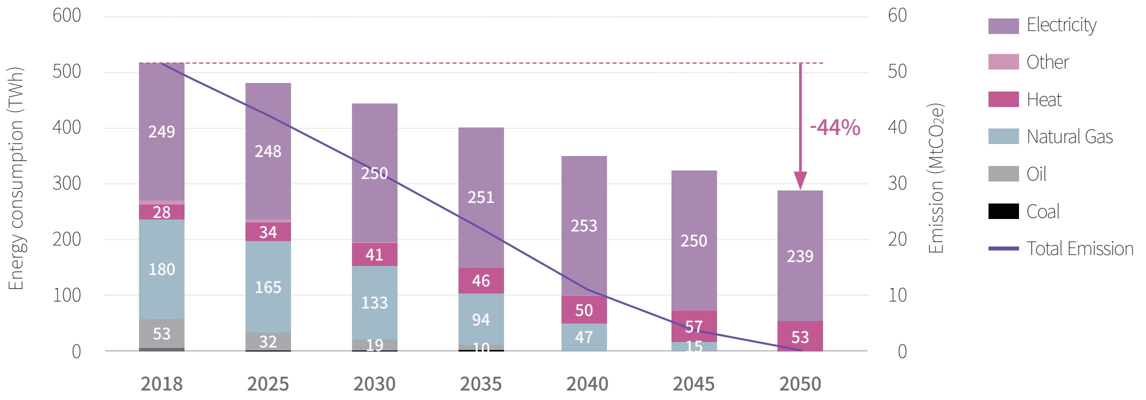
Strategy 4 – Speed up energy retrofits for buildings and the switch to decarbonized heating

The key measures for reducing emissions in the building sector are improved insulation and the switch to decarbonized heating fuel (heating fuel consumption represents more than half of total energy consumption in the sector).

The first priority is to accelerate energy retrofits for existing buildings. This is particularly important for buildings constructed before 2010, i.e., prior to the introduction of improved insulation standards. A toolbox of policy measures (minimum standards, tax exemptions, and/or direct subsidies for retrofits) is needed to reach an annual retrofit rate of 2%.[13]

13 In the Renovation Wave Strategy (2020) and the Fit for 55 package (2021), the EU has announced plans to raise the retrofit rate of existing private buildings from 1% to 2% per year and from 1% to 3% per year for public buildings. IEA (2021) has found that the retrofitting of all existing buildings needs to take place at 2.5% per year through 2030 if the world is to reach climate neutrality by 2050.

[Figure 11] Outlook for energy consumption and GHGs emission of the building sector, 2018–2050



The second priority is to reinforce ZEB requirements for new buildings in order to increase the energy efficiency grade in the ZEB certification system.[14] Thanks to the retrofit program, the total floor area (TFA) of old buildings will gradually decrease, while the proportion of energy-efficient buildings will rise. By 2050, around 70% of the TFA of buildings will either have been retrofitted or have been built after 2019. By then, only 7.8% of existing buildings will have been constructed prior to 2010, without enhanced insulation standards.

The third priority is to prohibit the installation of new gas boilers starting in 2025 and to promote a gradual switch to decarbonized heating fuels through heat pumps (3.6 million units) and district heating (124 million TOE). This will reduce the energy demand for heating by 55 TWh by 2030 and by 155 TWh by 2050 relative to 2018 levels. This, in turn, will cut emissions by 17 $MtCO_2e$ by 2030 and by 42 $MtCO_2e$ by 2050 relative to 2018 levels.

Combined, these three priorities (retrofitting; increasing ZEB requirements; and switching to decarbonized heating fuels) will decrease energy consumption in the building sector by 44% by 2050 (from 521 TWh in 2018 to 292 TWh in 2050). The gradual switch to heat pumps and district heating will allow the sector to reach net zero by 2050.

14 According to the K-Map Scenario, all residential buildings need to meet the ZEB certification standard of below 90kWh/m^2 in annual energy consumption (grade 1++ in the current building energy efficiency rating system). Their energy efficiency should gradually improve to below 60kWh/m^2 (1+++ grade) starting in 2041. Non-residential buildings should have an annual energy consumption of below 200kWh/m^2 (grade 1+) and below 100kWh/m^2 (grade 1++) by 2036.

5. A supportive policy framework for reaching climate neutrality

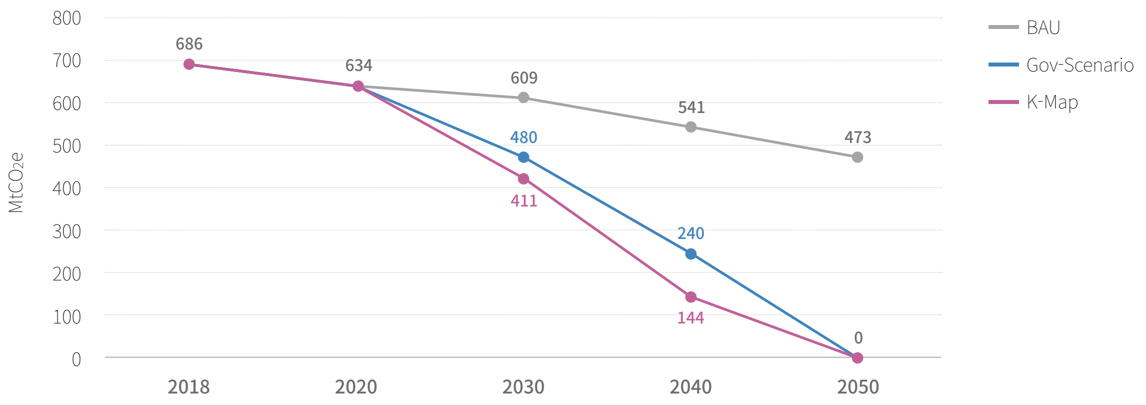
1) A comprehensive investment program comparable in scope to the *Miracle on the Han River* [15]

The transition to net zero will require massive investment estimated at KRW 1 330 trillion KRW (830 trillion KRW in 2022 NPV) up to 2050 compared to a scenario without accelerated energy transition (referred to as the BAU scenario, as shown in Figure 12). For the deployment of renewables, a total of 483 trillion KRW – or 16.7 trillion KRW annually – has to be invested by 2050. For the decarbonization of the industrial sector, the full introduction of innovative technologies such as hydrogen DRI, including their operating expenditures, will require an additional 659 trillion KRW.

More investment is required at an early stage when technologies are still immature. For example, floating offshore wind turbines, which currently cost 180 KRW/kWh, are expected to experience a cost decline to 126 KRW/kWh after 2030, when relevant technologies are commercialized and competition intensifies in the global market. At a glance, significant investment in rudimentary or unproven technologies might seem unreasonable or misguided.

However, in Korea, which has a strong manufacturing base, such investment will greatly facilitate the development of innovative technologies – while also reaping the environmental and economic benefits of emissions avoidance.[16] Investment in advanced green manufacturing technologies could allow Korean companies to become global leaders in important niche markets. At the same time, such investment will save some 8.3 gigatons of GHG emissions compared to the BAU scenario. This corresponds to an economic benefit of about 1 400 to 3 100 trillion KRW (50 to 110 trillion KRW annually) based on the carbon price projections by NGFS. If the economic benefits of reduced petroleum and LNG imports are taken into account, the advantages associated with the climate neutral transition grow even larger.

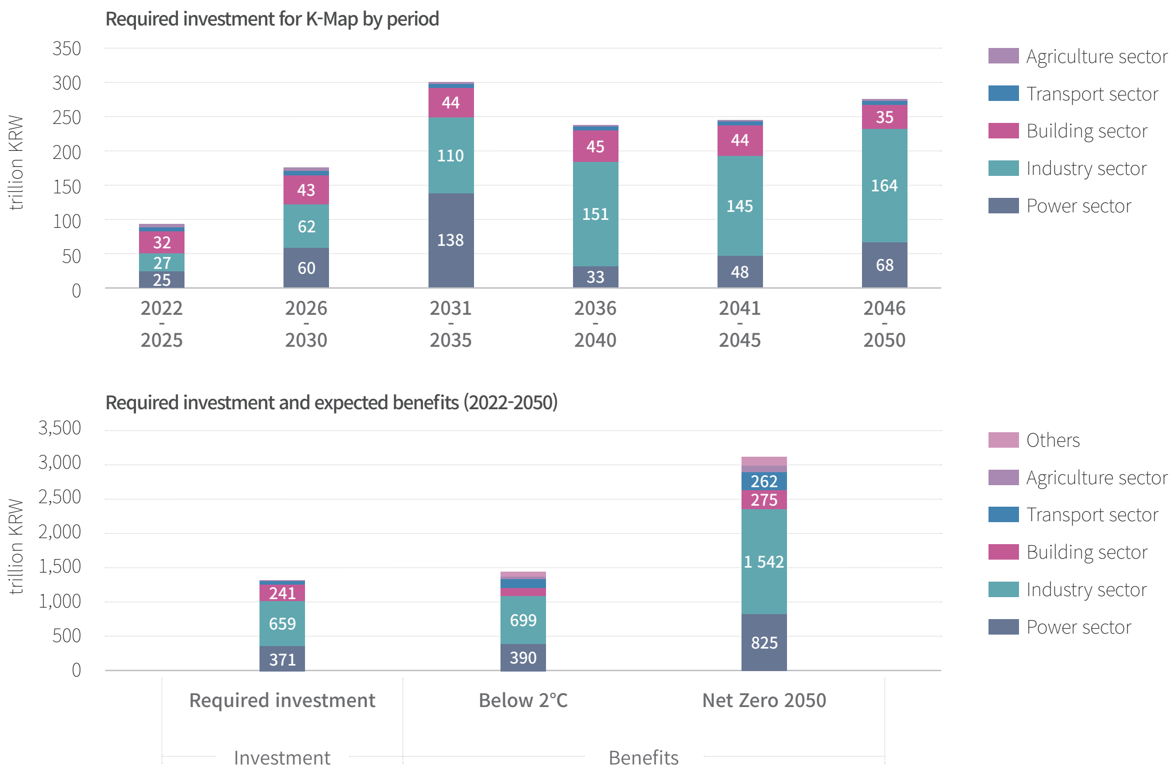
[Figure 12] GHG emissions outlook in each scenario



15 Miracle on Han River (or Hangang River) refers to Korea's economic growth from one of the poorest countries just after the Korean War (1950-1953) to a developed nation at an unprecedented speed.

16 Leading markets and international organizations are already implementing or recommending the introduction of carbon tax, thus making greenhouse gas emissions an economic cost.

[Figure 13] Required investment and expected benefits from the K-Map Scenario



[Table 3] Required investment under the K-Map Scenario (compared to BAU) (Unit: trillion KRW)

	2022 - 2025	2026 - 2030	2031 - 2035	2036 - 2040	2041 - 2045	2046 - 2050	Total	Total (NPV)	Annual average
Power sector	25	60	138	33	58	57	371	244	12.8
Industry sector	27	62	110	151	145	164	659	385	22.7
Building sector	32	43	44	45	44	35	241	160	8.3
Transport sector	6	6	5	6	6	5	33	22	1.1
Agriculture sector	5	7	3	2	2	2	21	16	0.7
K-Map Scenario Total	94	178	300	237	254	262	1 326	827	45.7

[Table 4] Expected benefits from the K-Map Scenario (compared to BAU)

	GHG Emissions Reductions from 2022 to 2050 ($MtCO_2e$)	Benefits from GHG Emissions Reductions* (trillion KRW)		Average Annual Benefit (trillion KRW)
		Below 2°C Scenario	Net Zero 2050 Scenario	
Power sector	2 493	409	869	12-26
Industry sector	3 766	699	1 542	24-53
Building sector	743	126	275	4-9
Transport sector	744	122	262	4-9
Agriculture sector	259	42	91	1-3
Other (LULUCF, waste, leakage)	375	62	136	2-5
K-Map Scenario Total	8 380	1 460	3 176	50-110

* Calculations according to the Below 2°C and Net Zero 2050 carbon price projections for Korea (NGFS, 2020).

However, the investment required for climate neutrality could lead to negative socioeconomic impacts because the burden will be borne by individual consumers through increasing energy prices and economy-wide cost-push inflation.[17]

Ultimately, government policy will be decisive for kick-starting the green transition and enabling rapid emissions reductions. To this end, the government should take full advantage of its fiscal and regulatory policy discretion.

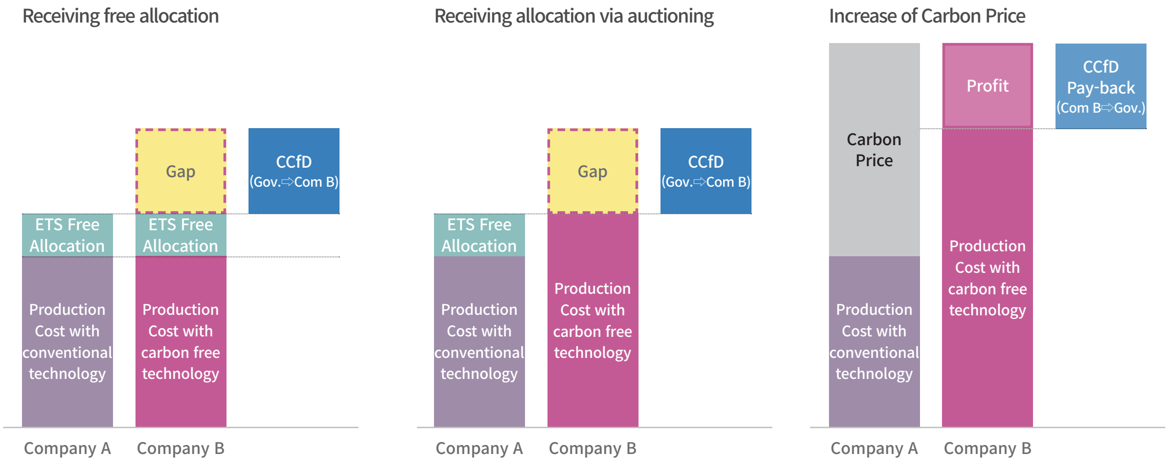
2) Intelligent policies to support climate neutrality

The rapid adoption of climate-friendly technologies and processes in each sector will be essential for an accelerated transition to climate neutrality. However, most climate-friendly technologies entail higher costs than their traditional counterparts. As a result, private-sector actors have little incentive to adopt them. To overcome this hurdle, various policy instruments are required, not only to increase the price of fossil fuels, but also to support investment in low-carbon solutions. In this connection, key policy instruments include: a well-functioning Emissions Trading Scheme in the power and industrial sectors; a strengthened ZEB standard; greater subsidies for clean vehicles in the transport sector; green financing for post-carbon technologies; direct financial support for green industries; tax incentives; auction mechanisms for the development of renewable energy, and the public procurement of sustainable products.

The adoption of a broad toolbox of policy measures can rapidly accelerate the deployment of green technologies. In the industry sector, for instance, the introduction of *Carbon Contracts for Difference* (CCfD) could be an important and suitable tool to promote investment in low carbon technologies. Under a CCfD, the government covers initial investment in climate-friendly technologies required by a company in whole or in part. The company later pays the government

17 According to Bank of Korea (2020), implementing measures toward net zero by 2050 will lead to a 0.25 to 0.32 percentage point decrease in annual GDP and 0.09 percentage point increase of annual customer prices from 2021 to 2050 due to various risks and cost factors. In order to minimize negative economic impacts, the Bank of Korea has asked the government undertake earlier implementation of measures to reduce the emissions, including investment in green industries.

[Figure 14] Cost allocation under Carbon Contracts for Difference



* Agora Energiewende (2020)

back when surplus profits are generated by the technologies, either by selling emissions permits or by competing with other emission-intensive products as the carbon price increases. Ultimately, CCfDs allow companies to minimize their exposure to the risk of fluctuating production and carbon emissions costs when they invest in climate-friendly technologies. They can reduce initial capital expenditures (CAPEX) as well as operating expenditures (OPEX).

The Korean government already has a variety of funding programs it could use to support the transition to climate neutrality in each sector. These programs can be used to establish a Korean version of CCfD or introduce other support mechanisms. In the power sector, for example, the *Electric Power Industry Foundation Fund* and *Energy Efficiency Fund* can be used to support the just transition in the area of renewables expansion and the early phase-out of coal and gas power.[18] In the industrial sector, the *Industrial Promotion Fund* (industrial technology and commercialization promotion fund) and *Energy Special Accounting* (special accounting for energy and resource businesses) can be used to support the research, development, and demonstration of climate-friendly industrial processes and technologies. In the building sector, the *National Housing Fund* can support ZEB construction and green retrofitting; the *Climate Counteract Fund* can promote clean vehicle deployment in transport; and *Direct Payment Program for Promoting Public Functions of Agriculture and Rural Communities* can augment the carbon-sink role of rice paddies, among other measures.

18 While there is no firm definition for the term of just transition, such a transition seeks "to ensure that the substantial benefits of a green economy transition are shared widely, while also supporting those who stand to lose economically – be they countries, regions, industries, communities, workers or consumers." (EBRD, n.d.)

[Table 5] Key indicators in the K-Map Scenario

	2018	2030	2040	2050	2018 ~ 2030 p. a. net	2030 ~ 2050 p. a. net
Greenhouse Gas Emissions (MtCO2e)	686	411	144	0	-23	-21
Power sector	270	112	25	0	-13	-6
Industry	261	206	86	11	-5	-10
Buildings	52	32	10	0	-2	-2
Transport	97	58	26	0	-3	-3
Agriculture	25	18	15	12	-1	-0.3
LULUCF, Waste, and Others	-19	-14	-19	-24	0.4	0.5
Fossil Fuel's Primary Energy Consumption						
Oil (million TOE)	114	76	45	16	-3	-3
Coal (million TOE)	50	27	2	0	-2	-1
Natural Gas (million TOE)	39	38	20	0.03	-0.1	-2
Power						
Electricity Generation (TWh)	571	726	1 024	1 296	13	29
Share of renewables in gross electricity consumption (%)	4	53	77	84	4	1.6
Photovoltaics (GW)	7	136	280	375	11	12
Onshore wind (GW)	1	40	40	40	3	-
Offshore wind (GW)	0	23	94	154	2	7
Electrical Energy Storage (GW/GWh)	2/19	68/332	141/2 023	197/6 035	6/26	6/285
Industry						
Steel production with gas DRI (million tons)	0	13.5	14.6	0	1.0	-0.6
Steel production with hydrogen DRI (million tons)	0	0	26	46	-	2.0
CO_2 absorption with CCUS (million tons)	0	0	9.0	23.4	-	1.1
Buildings						
Total floor area of newly constructed/green retrofitted buildings (million m^2)	0	813	1 369	1 895	68	54
Energy demand for new residential buildings (kWh/m^2a)	123	85	70	60	-3.2	-1.3
Energy demand for new non-residential buildings (kWh/m^2a)	300	200	140	100	-8.3	-8.3
Number of heat pumps (thousands of units)	0	1 052	2 412	3 572	88	126
District heat supply (million TOE)	2	38	78	124	3	4
Transport						
Number of electric vehicles (thousands of units)	0.13	5	11	19	0.4	0.7
Fossil energy demand in the transport sector (million TOE)	43	27	13	0	-1.3	-1.3
Agriculture and LULUCF						
Livestock manure fermentation (% share of all livestock manure)	1.7	50	70	90	-	-
LULUCF absorption (MtCO2e)	-41.3	-26.7	-26.0	-25.3	1.2	-
Hydrogen						
Hydrogen turbines (GW)	0	0	20	40	0	2
Hydrogen demand (million tons)	0	3	11	18	0.3	0.8
Domestic green hydrogen production (million tons)	0	0	4	7	-	0.4
Imported green hydrogen (million tons)	0	3	7	12	0.3	0.5
Green hydrogen storage (GW)	0	0	17	20	-	1
Macroeconomic Indicators						
GDP growth (annual %)	1.9	1.9	1.9	1.0	-	-0.05
Population (millions)	51.6	51.9	50.9	47.7	-	-0.2
Carbon price projection according to NGFS "Below 2°C Scenario" (US$2010/t CO2e)	20	109	135	266	7	8
Carbon price projection according to NGFS "Net Zero 2050 Scenario" (US$2010/t CO2e)	20	140	260	718	10	29

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