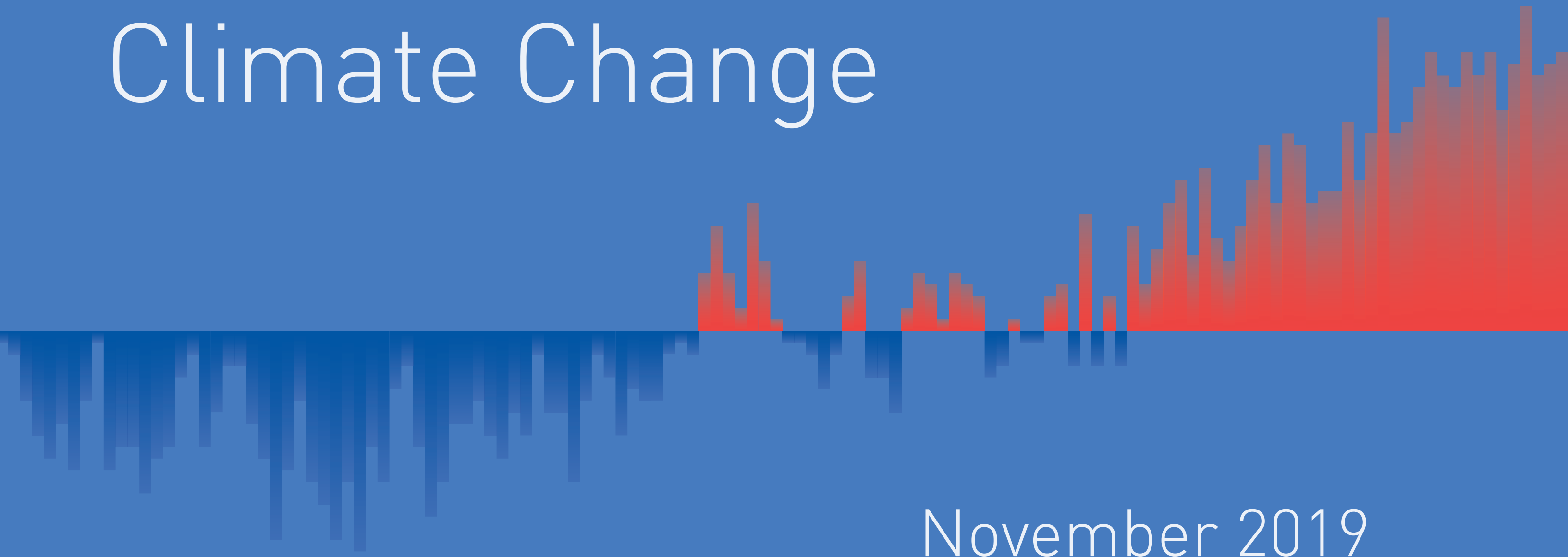
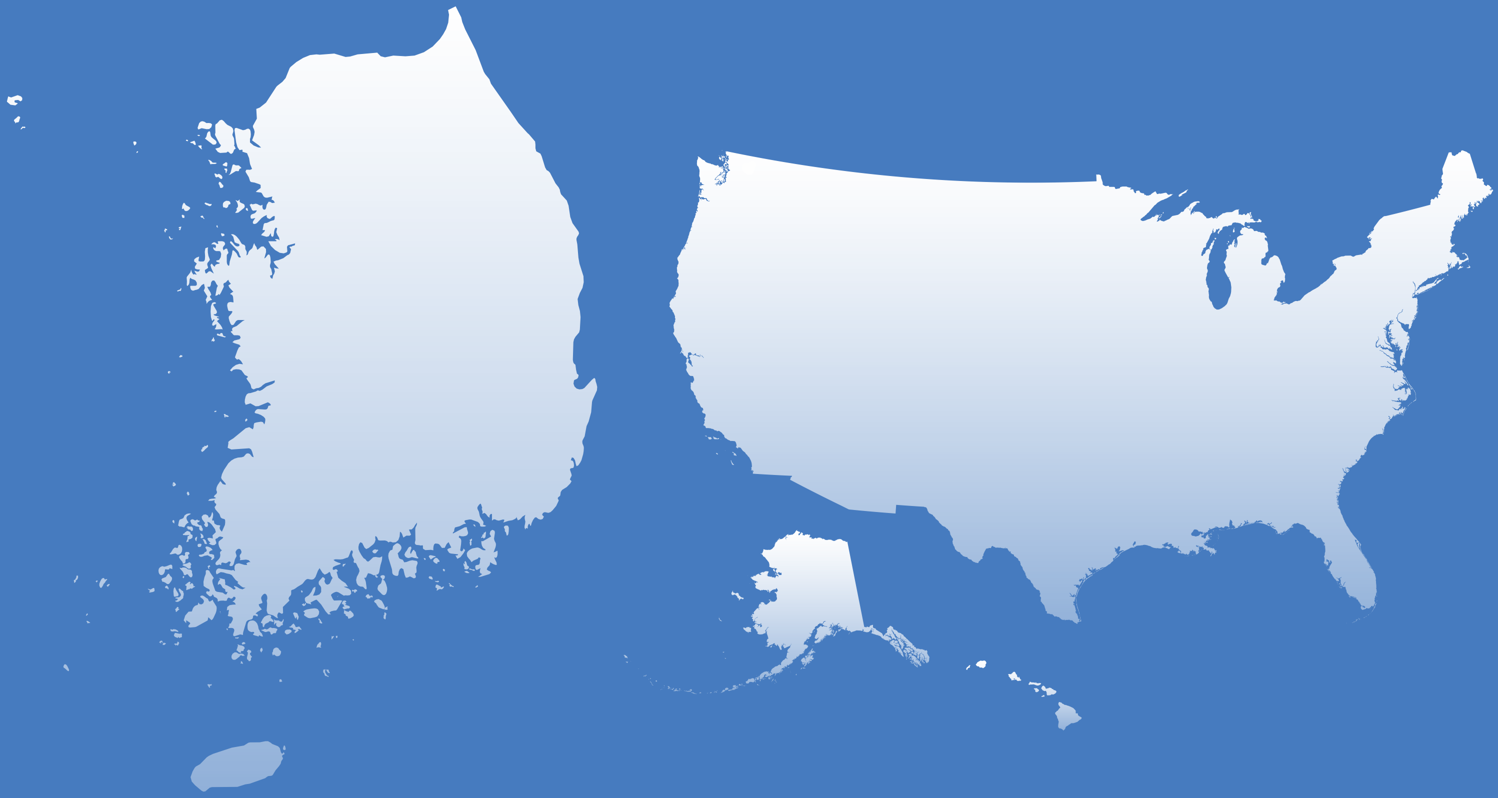
U.S.-ROK Cooperation on Nuclear Energy to Address Climate Change



November 2019

A Report by the
Nuclear Innovation Alliance



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LEAD AUTHOR
Matt Bowen, Ph.D.

TECHNICAL CONTRIBUTORS
Stephen Brick, Max Luke

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DESIGN
David Gerratt/*NonProfitDesign.com*

COVER
Julia Steketee

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DISCLAIMER

Reviewers and discussants were not asked to concur with the judgments or opinions in this report. All remaining errors are the author’s responsibility alone.

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EXECUTIVE SUMMARY

Mounting scientific evidence concerning the risks posed by climate change support an urgent effort to reduce worldwide carbon emissions. Deep decarbonization (80% or greater) of world economies by mid-century may be necessary in order to avoid the worst impacts associated with greenhouse gas accumulation in the atmosphere. In general, nations are not reducing their emissions fast enough to meet this goal, and global emissions rose in 2018. The United States and the Republic of Korea (ROK) possess the financial resources and technical capabilities to decarbonize their power grids if they choose to do so and, as global powers, are positioned to help the rest of the world meet the same challenge.

Both the United States and the ROK consume most of their energy from fossil fuels: oil, coal, and natural gas account for greater than 80% of energy use in each country. In recent years the United States has been slightly decreasing carbon dioxide emissions from its power sector—in part by displacing coal generation with greater natural gas use in a flat electricity demand context. But given that gas plants still emit around 50% the carbon dioxide of coal plants, this approach will ultimately fail to produce deep decarbonization. Greenhouse gas emissions in the ROK, meanwhile, have increased in recent years, due to rising energy consumption and a reliance on fossil fuels.

Nuclear power represents more than half of each country's zero-carbon electricity supply, and in the ROK it is around 84%. Reactors in both countries are aging and licensed to operate for finite periods of time. While extending operating licenses is possible, it is also possible that some reactors will shut down at the end of their current license periods or earlier. If existing U.S. and ROK reactor operation licenses are not extended, nearly 9,000 MW of nuclear power in each country would retire before 2030. In the United States, more than 70,000 MW of nuclear energy capacity would be gone by 2045 if every existing power plant retired at the end of its current operating license term. The zero-carbon energy losses resulting from these nuclear power plant retirements would more than offset gains from renewable energy growth in the past decade.

Nuclear power represents more than half of each country's zero-carbon electricity supply, and in the ROK it is around 84%. Reactors in both countries are aging and licensed to operate for finite periods of time. While the possibilities of extending operating licenses exists, it is also possible that some reactors will shut down at the end of their current license periods or earlier.

The United States and the ROK have been debating energy policies that would facilitate greater decarbonization. The U.S. Congress has yet to settle on a national climate policy, but individual states have passed laws to reduce greenhouse gas emissions from the power sector. For example, California recently passed a clean energy standard which mandates that all of its electricity come from zero-carbon energy sources by 2045. A Clean Air Task Force (CATF) analysis had previously assessed that such a clean energy standard—which allows for all zero-carbon sources of energy, including nuclear power, to contribute to the electricity supply—would be less costly than a 100% renewables-and-storage approach.[1] Separate analyses for the United States and other countries have reached a similar conclusion: that a portfolio of zero-carbon energy sources is the optimal path forward, in part due to the variation in power output from wind and solar sources.[2]

The ROK's current policy towards its electricity supply is found in the 8th Basic Plan for Long-Term Electricity Supply and Demand. Analysis performed for this report estimates that the current ROK plan is expected to lead to small reductions in carbon emissions from the power sector: roughly a 5% reduction by 2030 from 2017 levels. This report assesses that the ROK could reach much deeper decarbonization of its power sector using four additional technical pathways beyond increased renewables and energy efficiency measures. Specifically, in addition to the measures described in the 8th Basic Plan, the ROK could completely eliminate coal generation by: 1) running its existing nuclear reactors more efficiently; 2) extending nuclear reactor operating lifetimes; 3) building new nuclear reactor projects that were previously planned (but subsequently cancelled); and 4) replacing remaining coal generation with additional natural gas use. Pursuing these four policy levers, and absent the need for any new energy technology breakthroughs, the ROK could achieve a roughly 77% decarbonization of its power sector from 2017 emission levels at a modest overall cost: $2.6/MWh on a total system basis. Pursuing only the first two pathways would still reduce power sector emissions by 40% and at a net cost savings to the ROK.

If the ROK did achieve deeper decarbonization in a relatively short period of time (e.g., by 2030), it would provide a valuable example to the rest of the world that decarbonization of the power sector is both possible and achievable at a cost and on a time scale relevant to addressing climate change. By contrast, Germany's approach to climate change in the past decade provides an example in the opposite direction: a wealthy, technologically advanced country that committed massive subsidies towards renewable energy but which, in part because of its policy decision to shut down German nuclear power plants, has fallen well short of its own climate goals. Germany has retained its dependence on coal generation and its overall carbon emissions have remained largely the same over the past decade.

The U.S. and ROK nuclear industries have a long history of cooperation. U.S. and ROK entities have supplied parts and expertise to the construction and operation of new nuclear power plants in the United States, the ROK, and other countries, such as the United Arab Emirates (UAE). The ROK has continued to build nuclear power plants and has demonstrated that it can build them on time and on budget. Enhanced U.S. and ROK cooperation on nuclear energy could also help to limit increasing Russian and Chinese domination of the international nuclear energy marketplace.

In addition to the existing nuclear energy cooperation between the two countries, there are additional opportunities for the United States and the ROK to cooperate on advancing nuclear power as an energy source capable of mitigating the risk of climate change. Cooperation to enable existing reactors to produce greater amounts of energy each year and to extend existing plant lifetimes are two cost-effective ways for both countries to reduce carbon emissions (or at least hold them steady). In terms of new nuclear power plant construction, the Massachusetts Institute of Technology (MIT) has identified several areas of R&D that would potentially help to bring down the cost of new nuclear plants, including: advanced concrete and construction, advanced power conversion, coatings and nano-textured surfaces, and instrumentation and control. The United States and the ROK could also collaborate on advanced reactor development, including projects such as the versatile test reactor—a sodium fast reactor project that the United States is investigating for potential construction, and which would provide a source of fast neutrons for materials testing. Finally, both countries could share experiences and research into waste management strategies for spent nuclear fuel.

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[1] Presentation by Clean Air Task Force to the California Public Utility Commission, "Deep Decarbonization of the Electricity Sector: The Challenge of Variability and Storage," April 4, 2018.

[2] Testimony of Karl Hausker, Senior Fellow, U.S. Climate Program, World Resources Institute to the U.S. House of Representatives, Energy and Commerce Committee, Subcommittee on Environment and Climate Change. Hearing on "Building America's Clean Future: Pathways to Decarbonize the Economy," July 24, 2019.

CHAPTER I

NATIONAL ENERGY USAGE AND THE CLIMATE CHANGE IMPERATIVE

THE INTERGOVERNMENTAL PANEL on Climate Change (IPCC) recently published a report ("Global warming of 1.5°C") which served as one more warning to the world's governments that the window to effectively respond to climate change is closing, and urgent action is needed.[3] Scientific organizations have for decades noted the risk posed by the accumulation of greenhouse gases in Earth's atmosphere, including the potential for global warming to threaten fresh water supplies, coastal infrastructure, and the lives of people living in low-lying areas. Higher temperatures, rising sea levels, ocean acidification, and other outcomes expected to follow from increased greenhouse gas emissions will be disruptive to the world's populations.[4]

To prevent the worst consequences, scientists have estimated that countries should target deep decarbonization levels (e.g., 80% or greater) in the next few decades or roughly by mid-century. However, global carbon emissions have been moving in the opposite direction, with an average increase of 1% each year from 2007 to 2017.[5]

The United States and the ROK possess both the financial resources and the technical capabilities to lead world efforts to decarbonize. The energy portfolios of both nations are diverse, with several zero-carbon options, including nuclear energy. The most recent IPCC report posits that a 50–500% increase in nuclear energy from present levels could be part of scenarios to limit warming to 1.5°C. Nuclear power is the largest source of zero-carbon energy in both the ROK and the United States—increasing its deployment could thus make a substantial dent in atmospheric-warming emissions. This report is focused on expanding the nuclear energy option, particularly opportunities for the United States and the ROK to collaborate further to enhance this technology's capability to reduce global greenhouse gas emissions.

The United States and the ROK possess both the financial resources and the technical capabilities to lead world efforts to decarbonize. The energy portfolios of both nations are diverse, with several zero-carbon options, including nuclear energy.

A. Energy Portfolios

Primary energy consumption by fuel in the ROK and the United States is illustrated in Figure 1. The ROK, with very little domestic fossil reserves available, imports about 98% of the fossil fuels it uses. The ROK was the fourth largest importer of coal and third largest importer of liquified natural gas in the world, according to a 2018 U.S. Department of Energy analysis.[6]

In contrast, the United States, with its substantial fossil energy resources, became the world's

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[3] Intergovernmental Panel on Climate Change, "Global Warming of 1.5°C," 2018. Available at *https://www.ipcc.ch/sr15*.

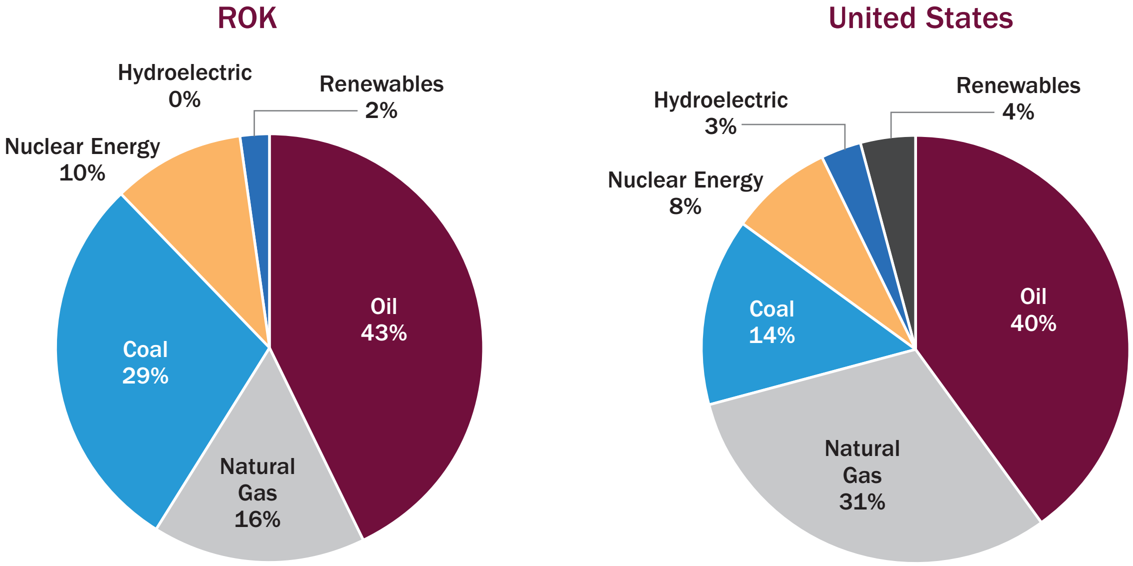
[4] See, for example, the Royal Society and U.S. National Academy of Sciences report, "Climate Change: Evidence and Causes," 2014.

[5] BP Statistical Review of World Energy 2019. Page 57.

[6] *https://www.eia.gov/beta/international/analysis_includes/countries_long/Korea_South/south_korea.pdf*; the report was updated in July of 2018.

FIGURE 1

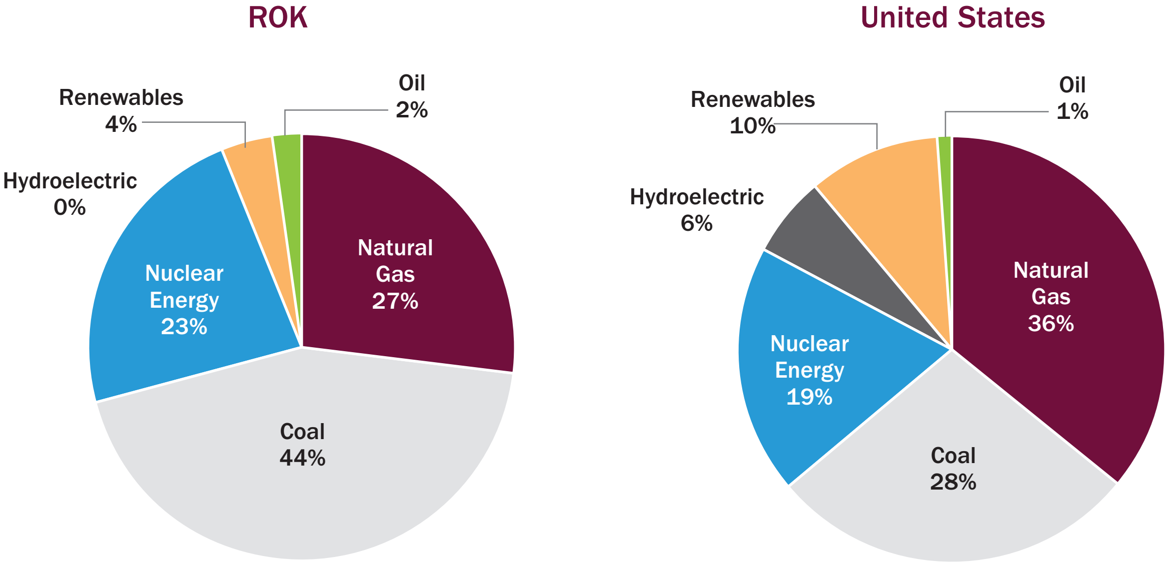
ROK and U.S. Total Primary Energy Consumption in 2018



Source: BP Statistical Review of World Energy 2019

FIGURE 2

ROK and U.S. Electricity Generation by Fuel in 2018



Source: BP Statistical Review of World Energy 2019

largest producer of petroleum in 2013 and the largest producer of natural gas in 2009.[7]

The sources of electricity generation in both countries are shown in Figure 2. In the ROK, coal is the largest source of electricity, followed by nuclear energy and natural gas. In the United States, natural gas has recently surpassed coal as the largest source of electricity generation, with nuclear energy as the third largest contributor.

As Figure 3 shows, while energy consumption in the United States has remained roughly the same in the past decade, energy demand in the ROK

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[7] *https://www.eia.gov/todayinenergy/detail.php?id=36292*

has continued to grow. From 2007 to 2017, energy demand in the ROK grew at an average annual rate of 2.3%, while in the United States it fell on average 0.4% annually. In 2018, U.S. energy consumption grew 3.5%.

B. Greenhouse Gas Emissions

Carbon dioxide emissions for the ROK over the past decade are shown in Figure 4. The ROK's greater dependence on coal and natural gas and rising energy consumption explain its rising greenhouse gas emissions.

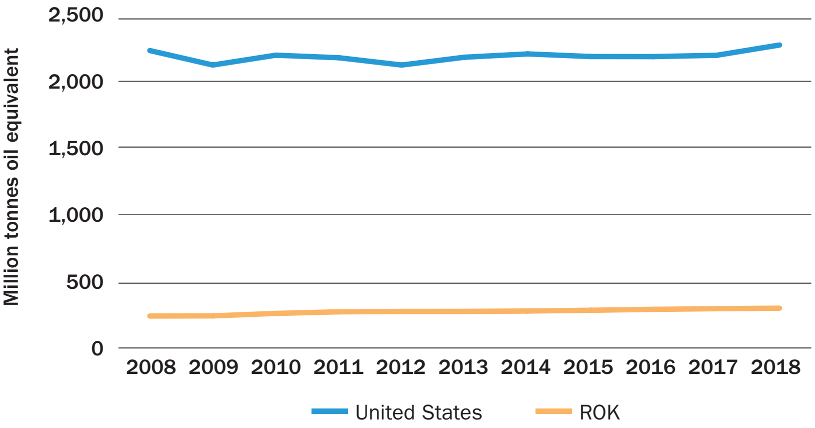
In the United States, declining energy demand, along with natural gas use displacing coal-fired generation, has contributed to slightly declining greenhouse gas emissions, as shown in Figure 5 (though emissions rose in 2018).

The U.S. Department of Energy's Energy Information Administration (EIA) projects in its 2016 International Energy Outlook that both the United States and the ROK will increase their energy consumption between now and 2040, with corresponding growth in greenhouse gas emissions. Total U.S. energy consumption is projected to grow 5% from 2020 to 2040, while during the same period ROK energy consumption is projected to jump 22%. As Table 1 shows, U.S. emissions are estimated to remain the same over the next two decades, with a greater contribution from natural gas, a slightly smaller contribution from coal generation, and a slightly smaller emissions profile from liquids (primarily petroleum). The greenhouse gas emissions projected by EIA, however, assume that nuclear energy use is greater in both countries in 2040 than it is in 2020. (This assumption is discussed in greater detail later in this chapter.)

EIA projects that in the ROK, carbon dioxide emissions in 2040 will be 16% greater than in 2020. This is driven primarily by an increased use of coal and natural gas.

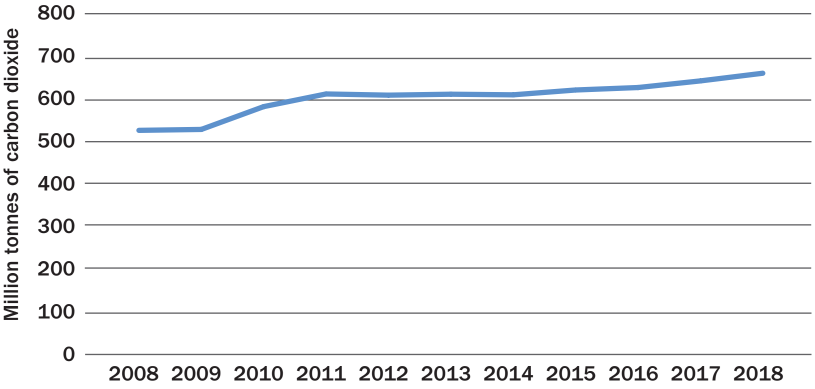
As Table 1 and Table 2 show, neither country is projected to even moderately decarbonize its economy by mid-century. In addition, while EIA estimates that each country will use more nuclear energy in 2040 than currently in use, most of the reactors operating in the United States and the ROK will reach the end of their current operating licenses before 2040, leaving this projection in question. Moreover, as Chapter II discusses, each country has unique economic and policy environments that affect the operation of existing plants and the potential for new builds.

FIGURE 3
Trends in ROK and U.S. Total Energy Consumption



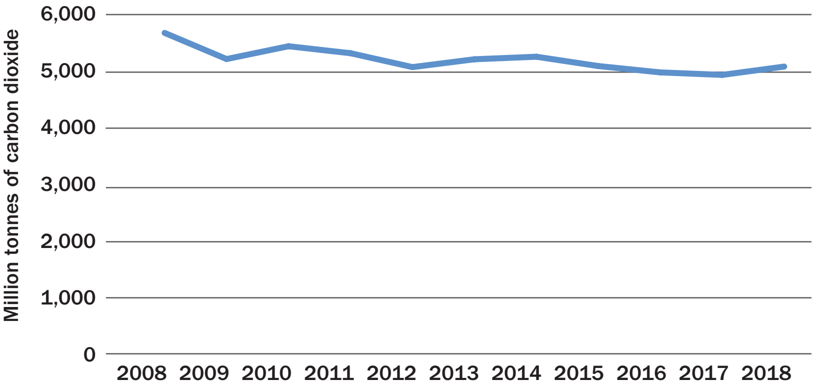
Source: BP Statistical Review of World Energy 2019

FIGURE 4
Rise in ROK Carbon Dioxide Emissions



Source: BP Statistical Review of World Energy 2019

FIGURE 5
Plateau of U.S. Carbon Dioxide Emissions



Source: BP Statistical Review of World Energy 2019

TABLE 1

Projected U.S. Carbon Dioxide Emissions Out to 2040

Year	2020	2025	2030	2035	2040
Liquids	2269	2227	2182	2163	2147
Coal	1824	1840	1822	1808	1804
Natural gas	1394	1432	1497	1538	1586
Total	5499	5511	5514	5521	5549

Emissions are in million metric tons carbon dioxide. Liquids are primarily petroleum.

Source: U.S. EIA 2016 International Energy Outlook. Tables A10, A11, A12, and A13.

TABLE 2

Projected ROK Carbon Dioxide Emissions Out to 2040

Year	2020	2025	2030	2035	2040
Liquids	263	264	267	272	280
Coal	345	347	355	371	394
Natural gas	126	131	140	160	177
Total	734	742	761	803	850

Emissions are in million metric tons carbon dioxide. Liquids are primarily petroleum.

Source: U.S. EIA 2016 International Energy Outlook. Tables A10, A11, A12, and A13.

C. Nuclear Power's Role

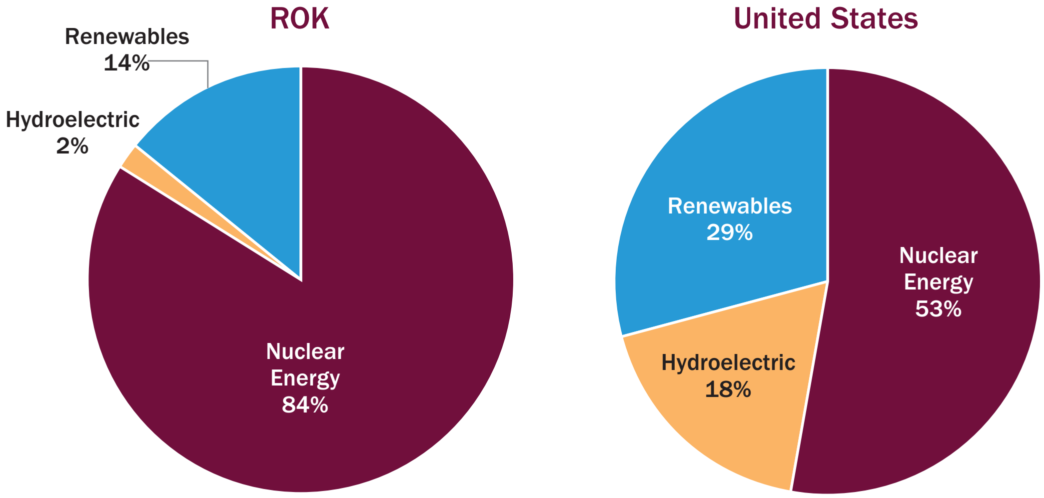
The United States currently has the largest nuclear reactor fleet in the world: 97 reactors at 59 sites with a total of nearly 100,000 MW of baseload capacity.[8] The ROK has the sixth largest nuclear fleet by capacity (behind also France, China, Japan, and Russia) with 24 operating reactors at four sites and a total of more than 23,000 MW of capacity.[9] As Figure 6 shows, nuclear power is the largest source of zero-carbon energy in each country.

The nuclear reactors in each country are approved to operate for fixed periods of time. In the United States, nuclear power plants were originally licensed to operate for a period of 40 years, and many of those original plants have since been approved to operate for an additional 20 years. As discussed in Chapter III, a small number of nuclear plant owners in the United States have begun efforts to license their nuclear reactors for a further 20 years, which would mean 80 years of operation for successful applications. The APR1400 reactors in the ROK were given initial licenses to operate for 60 years, while other pressurized water reactors were given initial licenses to operate for 40 years. The heavy water reactors in the ROK were initially licensed to operate for 30 years.

Table 3 shows the total amount of nuclear energy capacity that would retire over five-year

FIGURE 6

ROK and U.S. Zero-Carbon Electricity Generation by Fuel in 2018



Source: BP Statistical Review of World Energy 2019

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[8] *https://www.nei.org/resources/statistics/us-nuclear-generating-statistics*, as of June 2019.

[9] International Atomic Energy Agency: PRIS Database, as of August 2019.

increments if reactors in each country ceased operation at the end of their current licensed terms. Exactly when existing reactors in each country retire could have a great impact on each country's greenhouse gas emissions profile, as nuclear is currently the largest source of zero-carbon energy for both the United States and the ROK.

Table 3 also shows that a total of 76% of the ROK fleet would retire by 2044 if each reactor were shut down at the end of its current operating license term. In 2017, nuclear energy generated 148 TWh in the ROK, while renewable energy produced 16 TWh. Even with a five-fold increase in renewable energy generation, the loss of 76% of the nuclear fleet would negate those zero-carbon gains.

The United States faces a similarly striking potential loss: 75% of the U.S. reactor fleet would retire by 2044 if each reactor were shut down at the end of its current operating license term. U.S. nuclear energy generation in 2017 produced 847 TWh. A loss of 75% of that generation (or 635 TWh) would eliminate 1.5 times the zero-carbon energy generated from renewable sources (419 TWh) in 2017.

TABLE 3

Potential U.S. and ROK Nuclear Energy Capacity Retirements Out to 2044

Time Range	2020–24	2025–29	2030–34	2035–39	2040–44
ROK	2,279	6,850	1,000	3,000	4,000
United States	2,286	7,104	29,723	13,622	22,622

Capacity retirements if existing operating licenses are not renewed (in MW).

Source: NEI and KHNP

The EIA projections of greenhouse gas emissions shown in Table 1 and Table 2 assume that nuclear energy use in the United States and the ROK will be greater in 2040 than in 2020. However, if large portions of the existing fleet retire, that almost certainly will not be the case. The most likely outcome where nuclear reactors retire is that they will be replaced by a mix of energy generation technologies that include natural gas—resulting in an increase in greenhouse gas emissions and accelerated global warming.

The Hanul Nuclear Power Plant located in the ROK.

© Korea Hydro & Nuclear Power Co., Ltd

CHAPTER II

CHALLENGES WITH DECARBONIZING THE ELECTRICITY SECTOR

As chapter I illustrates, neither the United States nor the ROK are on a trajectory to reach decarbonization by mid-century. Both countries will face challenges in decarbonizing their power sectors but doing so could also help to reduce emissions from other sectors (e.g., in combination with electrifying some portion of transportation). Both countries currently derive over half of their electricity production from the traditional use of coal and natural gas (i.e., the carbon emissions are not captured and sequestered), which will have to be largely eliminated in order to achieve deep decarbonization. Each country generates about 30% of its electricity from nuclear power and renewable energy (non-hydroelectric), both of which could be expanded to replace traditional fossil energy use. This chapter looks at previous analyses in the United States, including for California, which has phased out in-state coal generation and passed a law mandating a zero-carbon electricity sector by 2045. California will face challenges connected with any efforts to pursue decarbonization using solely renewable energy, as will other states. This chapter also presents a new analysis of the ROK electricity grid, including some of the challenges associated with pursuing decarbonization by means of renewable energy alone. The analysis argues that the ROK could greatly reduce carbon emissions from its power sector through increased nuclear energy use and at a modest cost. Finally, this chapter examines Germany's continued use of coal and natural gas and the consequences of its decision to phase out nuclear power, despite its own climate goals.

Both countries currently derive over half of their electricity production from the traditional use of coal and natural gas (i.e., the carbon emissions are not captured and sequestered), which will have to be largely eliminated in order to achieve deep decarbonization.

A. United States

U.S. climate policy is in a state of flux. The United States signed the Paris Agreement in 2015 but announced in 2017 that it was withdrawing from the historic global accord on climate action. A similar reversal took place recently when the U.S. Environmental Protection Agency rescinded its own landmark regulation, adopted in 2015 (and known as the "Clean Power Plan"), to reduce greenhouse gas emissions and moved to replace it with a much weaker rule.[10]

The U.S. Congress has voted on legislation to reduce greenhouse gas emissions in the past, though no bill has passed into law that would decarbonize the electricity sector or any other sector of the U.S. economy. More recently, members of Congress have introduced a federal clean energy standard that would require increasing amounts of electricity to be generated from zero-carbon energy sources.[11]

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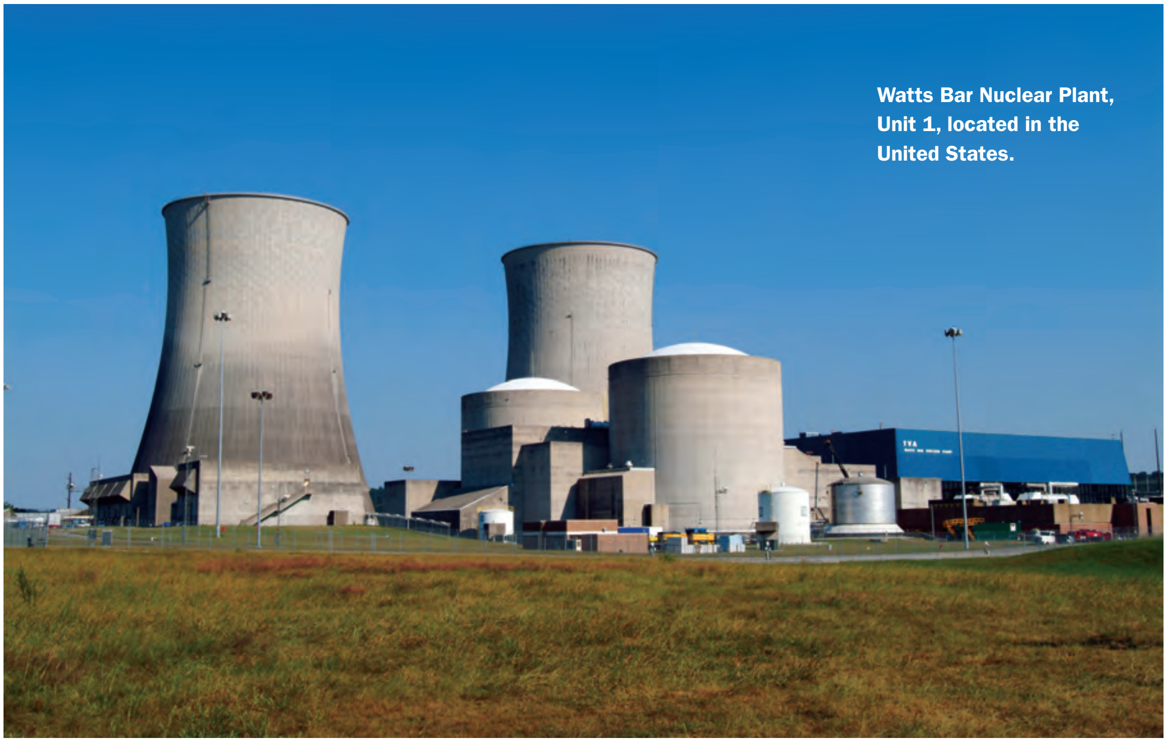
[10] *https://www.bloomberg.com/news/articles/2019-06-18/trump-to-swap-obama-s-clean-power-plan-for-modest-upgrades*

[11] See either S.1359 or HR.2597 in the 116th Congress for examples of a national clean energy standard; see S.1128 in the 116th Congress for an example of a bill that puts a price on carbon emissions.



Watts Bar Nuclear Plant, Unit 1, located in the United States.

© TVA

This federal legislative proposal follows a recent pattern of individual states adopting clean energy standards that require all of their electricity come from zero-carbon energy sources. As of August 2019, eight states have made commitments to decarbonize their electricity sectors by mid-century at latest.[12]

The United States is also dealing with health issues related to air pollution from fossil energy use. Clean Air Task Force (CATF) has published reports finding that thousands of U.S. deaths per year are attributable to fine particle pollution from U.S. power plants, principally coal plants. In 2018, CATF used updated 2016 emissions data to estimate that 3,000 deaths per year in the United States could be attributed to pollution from power plant emissions.[13] U.S. efforts to increase zero-carbon generation clearly offer the additional benefit of reducing air pollution and its associated impacts on public health. In 2019, CATF published a report which found that the loss of nuclear power plants in Illinois would lead to between 1,200 and 2,700 premature deaths, an additional 30,000 asthma attacks, 140,000 work days lost, and $10 to $24 billion in monetized damages—all due to increased air pollution.[14]

In a recent U.S. House of Representatives Energy and Commerce Committee Hearing, the challenges of reducing U.S. carbon emissions and air pollution using solely renewable energy were discussed. Karl Hausker, of the World Resources Institute, testified that:

> …one cannot conclude simplistically that wind and solar PV are "cheapest," period, end of story. Power system dynamics are much more complex . . . power systems that become highly dependent on solar and wind ("variable renewables") would be likely to face reliability and affordability challenges when their share of the total generation mix crosses certain thresholds… integration costs are likely to escalate as the share of solar PV and wind increases, and that is why one cannot simply conclude they are "cheapest" based on LCOE, and that we should commit to a 100% renewable grid.

As far as solar energy is concerned, beyond the daily and even minute-by-minute variance in solar radiation, the United States must contend with seasonal variation, as solar plants tend to generate more energy during the summer than in the winter, a trend which is depicted in Figure 7.

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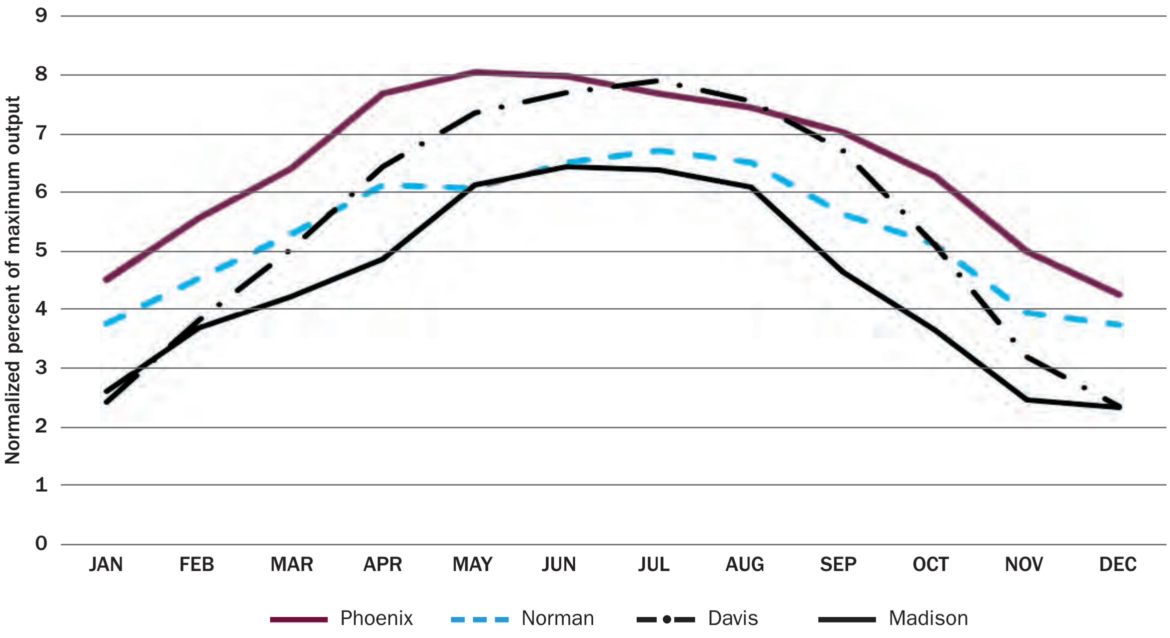
[12] *https://blog.ucsusa.org/jeff-deyette/states-march-toward-100-clean-energy-whos-next*

[13] *https://www.catf.us/educational/coal-plant-pollution*

[14] *https://www.catf.us/resource/retirement-of-nuclear-power-plants-in-illinois*

FIGURE 7

Monthly Solar Radiation for Four U.S. Locations



Source: Stephen Brick and Samuel Thernstrom, “Renewables and decarbonization: Studies of California, Wisconsin and Germany,” Electr. J. 29, 6-12 (2016).

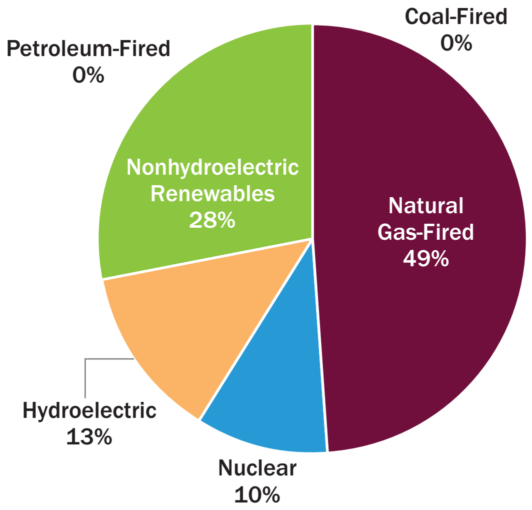
To take one specific example, California is one of the largest energy-consuming states, and in 2016 was responsible for 363 million metric tons of greenhouse gas emissions. Total electricity consumption in California was 285 TWh in 2018.[15] The state has managed to phase out in-state coal generation and its in-state electricity generation is now dominated by natural gas, renewable energy, and hydro-electric power, as shown in Figure 8.

As previous CATF analysis has pointed out, however, California will face challenges in trying to decarbonize its electricity grid using only renewable energy.[16] Apart from minute-by-minute or hour-by-hour variations in wind power, for example, there is also a broader seasonal variability to contend with, as shown in Figure 9. A greater amount of wind energy is generated in California between April and September than during other months, and this phenomenon has consequences for decarbonization efforts, in combination with the seasonal variability in solar radiation.

As the share of electricity derived from wind and solar power increases in California, the seasonal

FIGURE 8

Snapshot of California In-State Electricity Generation by Fuel



California electricity generation profile for the month of September in 2018.

Source: EIA

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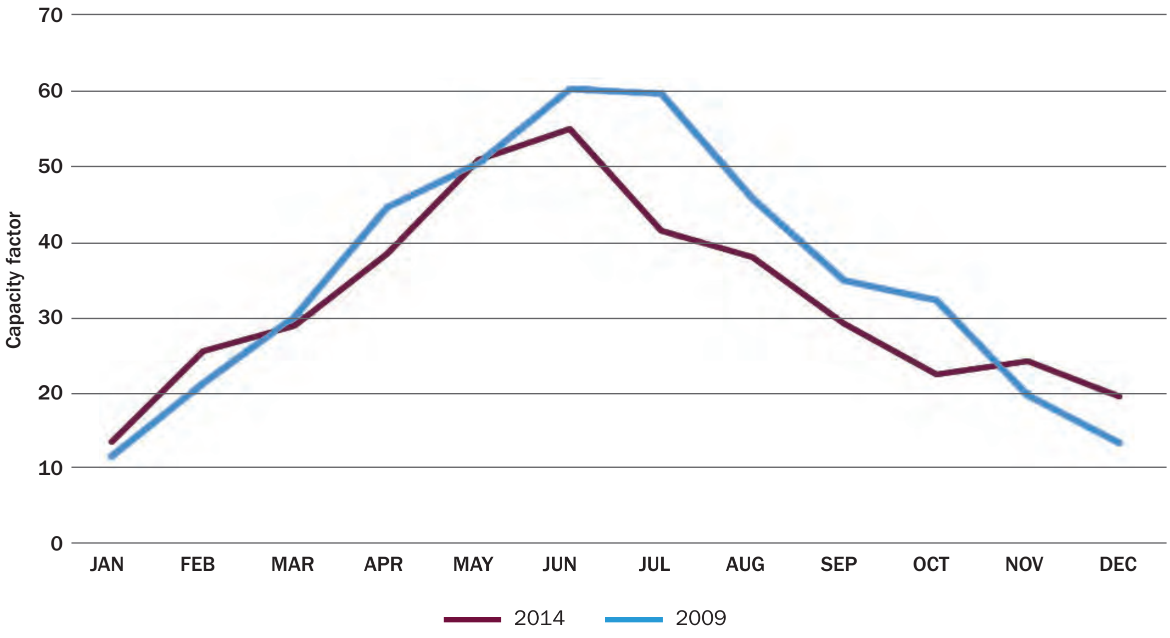
[15] *https://www.energy.ca.gov/almanac/electricity_data/total_system_power.html*

[16] Presentation by Clean Air Task Force to the California Public Utility Commission, “Deep Decarbonization of the Electricity Sector: The Challenge of Variability and Storage,” April 4, 2018.

FIGURE 9

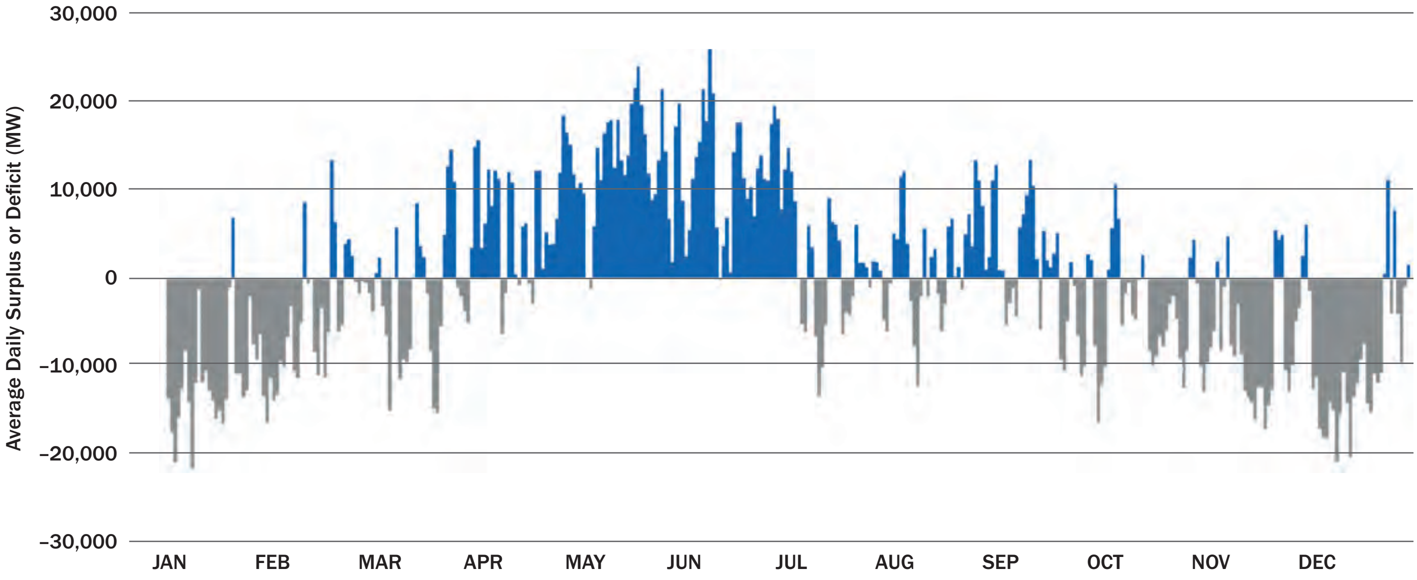
CAISO Wind Monthly Capacity Factor in 2009 and 2014



Source: Stephen Brick and Samuel Thernstrom, “Renewables and decarbonization: Studies of California, Wisconsin and Germany,” Electr. J. 29, 6-12 (2016).

FIGURE 10

Scaled Renewable Energy Generation and Comparison with Demand in California

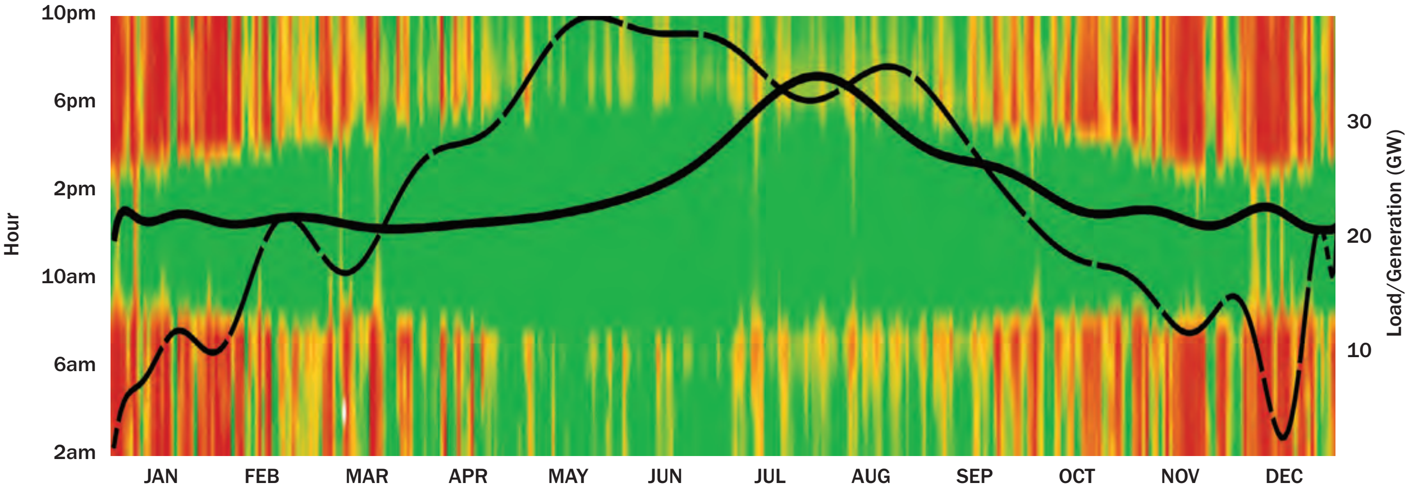


Daily surplus (blue) and deficits (grey) when scaling 2018 wind and solar generation in California to each meet 50% of total 2018 annual CAISO load.

Source: Clean Air Task Force

FIGURE 11

Hourly Comparison of Demand with Scaled Renewable Energy Generation in California



Scaling 2018 wind and solar generation in California to each meet 50% of total 2018 CAISO annual load. Red areas indicate nearly 0% load served, while green areas indicate 100% load served or more. The solid line is weekly electricity load (GW) and the dashed line is for weekly renewable energy generation (GW).

Source: Clean Air Task Force

Trying to meet 100% of California's total electricity demand during the year with an equal mix of solar and wind energy would be challenged by the daily and seasonal mismatch in generation and demand.

imbalance in wind and solar energy generation compared with electricity demand could ultimately create challenges. As shown in Figure 10 and Figure 11, trying to meet 100% of California's total electricity demand during the year with an equal mix of solar and wind energy would be challenged by the hourly, daily, and seasonal mismatch in generation and demand. Any surplus of renewable energy would have to be either wasted or stored, in turn increasing costs to the system. Energy deficits would also have to be addressed to maintain grid reliability.

The challenge associated with trying to reliably meet electricity demand and achieve deep decarbonization using only variable renewable energy generation helps explain why many studies have concluded that a diversified portfolio of zero-carbon technologies (e.g., including nuclear energy) would reduce the costs of such an effort in the United States.[17]

B. Republic of Korea

Similarly, the ROK would face challenges in trying to pursue deep decarbonization using only renewable energy. In late 2017, the ROK government adopted the 8th Basic Plan for Long-Term Electricity Supply and Demand 2017-2031, which contains a number of targets, including to reduce electricity demand in 2030 by 13% compared with the reference case (579.5 TWh versus 667 TWh). The plan also calls for utilities to obtain 20% of their electricity from "new" and "renewable" energy sources by 2030, a reduction in nuclear energy use, and an increase in natural gas use compared with the reference scenario.[18]

The analysis presented below estimates that the targets in the 8th Basic Plan will lead to a 5.3% reduction in carbon emissions from the ROK electricity sector by 2030 relative to 2017 (253 MMTCO$_2$ versus 267 MMTCO$_2$). Meeting these targets will be referred to as the "Target 2030" scenario. Several assumptions are made in this analysis, including:

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[17] See, for example, the 2019 presentation to the Colorado Public Utilities Commission by Vibrant Clean Energy, "Modeling Renewable Energy, Clean Technologies and Electrification for Deep Decarbonization Future." Also, MIT, "The Future of Nuclear Energy in a Carbon-Constrained World," 2018.

[18] "New" includes fuel cell and integrated gasification and combined cycle technologies.

- The targets in the 8th Basic Plan for renewables and "new energy" are met.
- 7,000 MW of APR1400 projects currently under construction are operational by 2030.[19]
- 9,129 MW of existing reactors are retired by 2030 according to government policy.[20]
- On account of the targets for nuclear energy set out in the 8th Basic Plan, the nuclear reactors expected to be in operation in the ROK in 2030 would be made to operate at a 78% capacity factor, substantially below where they have operated in the past.[21]

Several policy options to achieve greater reductions in carbon dioxide emissions are analyzed below. The list of technical pathways shown is progressively cumulative (e.g., the second includes the first, the third includes the first two, etc.). Each pathway increases either nuclear energy generation or natural gas generation at the expense of existing coal generation.

1. **Scenario 90CF:** Operate nuclear reactors at a 90% capacity factor, which the ROK has achieved in the past, with coal generation decreased by the same amount that nuclear energy generation is increased. This scenario still assumes that planned retirements and reactors under construction continue as scheduled.
2. **Scenario 60LE:** Existing reactor operation licenses are also extended to 60 years, with the added nuclear energy generation reducing coal generation.
3. **Scenario 88NB:** 8,800 MW of cancelled reactors, which were scheduled to be added in the 7th Basic Plan, are reinstated as new builds, and those new reactors also operate at 90% capacity factor, with coal generation decreased to match the increase in nuclear energy generation.[22]
4. **Scenario VLC ("very low carbon"):** Remaining coal operation is eliminated and replaced by liquefied natural gas.

Taken together, these technical pathways could lead to deeper decarbonization of the ROK power sector by 2030, as shown in Figure 12, reducing emissions by 77% from 2017 levels.

Taken together, these technical pathways could lead to deeper decarbonization of the ROK power sector by 2030, as shown in Figure 12 below, reducing emissions by 77% from 2017 levels. The ROK's Intended Nationally Determined Contribution (INDC) towards achieving the objective of the United Nationally Framework Convention on Climate Change is to reduce economy-wide greenhouse gas emissions by 37% compared with a baseline of 850.6 million metric tons of CO$_2$-equivalent (MMTCO$_2$eq) in 2030.[23] That implies a 315 MMTCO$_2$eq reduction, and Figure 13 below shows that a 205 MMTCO$_2$eq reduction by 2030 is possible from the power sector alone, leaving only 109.8 MMTCO$_2$eq in reductions for the rest of the ROK economy.

This would not appear to be a costly approach. As Table 4 shows, the ROK could save money and at the same time reduce carbon dioxide emissions by replacing energy generation from coal plants with greater energy production from its existing nuclear reactors and also by extending the operating license term of existing nuclear plants.[24] A 40% reduction in carbon emissions (compared with 2017 emissions) from the power sector could be achieved in this manner at a net savings compared with the Target 2030 scenario.

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[19] Shin-Kori 4, 5, and 6; Shin-Hanul 1 and 2. Source: KHNP, Nuclear Power Operation, *www.khnp.co.kr/eng/main.do*.

[20] In June 2017, President Moon announced that plans for new power reactors would be cancelled and the operating periods of current units would not be extended beyond their existing operation licenses. Before 2030, this would include: Kori 2, 3, and 4; Wolson 1, 2, 3, and 4; Hanbit 1 and 2; and Hanul 1 and 2. Source: KHNP, Nuclear Power Operation, *www.khnp.co.kr/eng/main.do.*

[21] From 2004 to 2011, yearly capacity factors for the ROK nuclear fleet averaged over 90%, with a peak of 95.5% in 2005. Source: KHNP, Nuclear Power Operation, *www.khnp.co.kr/eng/main.do*.

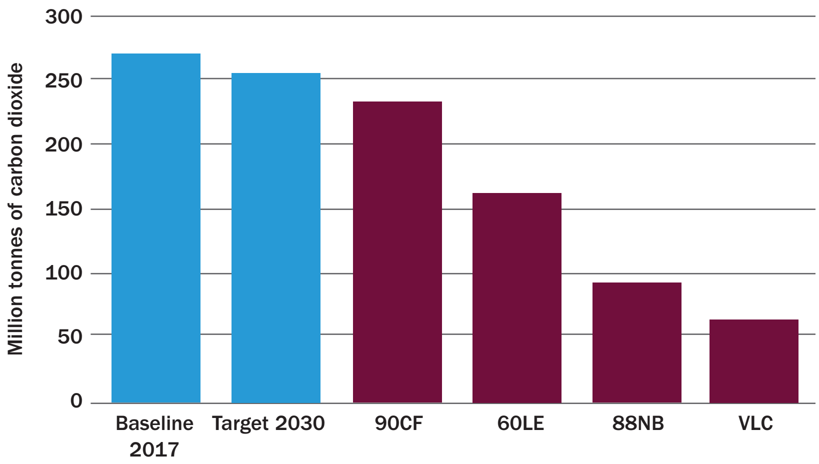
[22] According to the World Nuclear Association website, cancelled projects include: Shin-Hanul 3 and 4 (APR1400); Cheonji 1 and 2 (APR+); Cheonji 3 and 4 or Daejin 1 and 1 (APR+). *http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/south-korea.aspx*

[23] *https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Republic%20of%20Korea%20First/INDC%20Submission%20by%20the%20Republic%20of%20Korea%20on%20June%2030.pdf*

[24] The levelized cost of energy for new nuclear plants in the ROK is $51/MWh; new natural gas plants are $99/MWh; decremental coal generation is $43/MWh. Source: Nuclear Energy Agency, "Projected Costs of Generating Electricity," 2015. Tables 3.9, 3.10, and 3.11. Capital costs for license extension are $500/kW. Source: Nuclear Energy Agency, "The Economics of Long Term Operation of Nuclear Power Plants," 2012. Table E.4. Increased utilization at nuclear power plants is assumed to be $25/MWh.

FIGURE 12

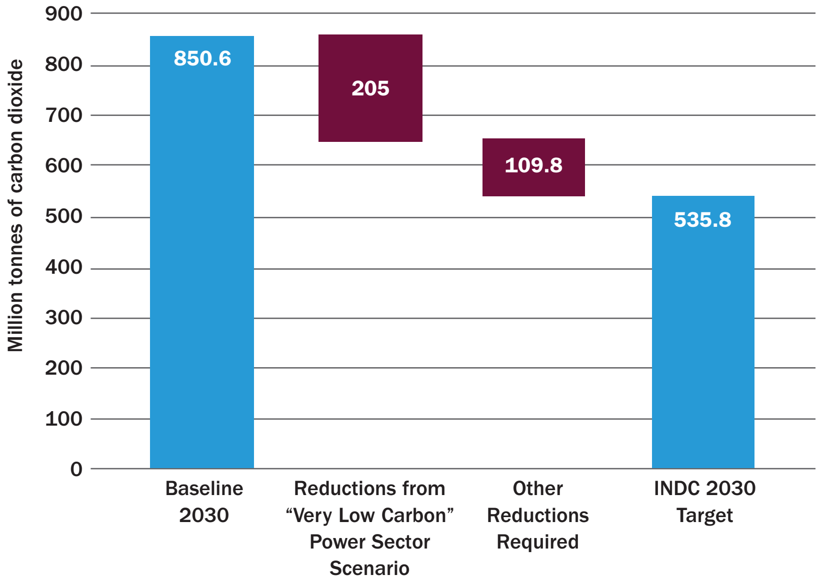
Technical Pathways to Reduce Power Sector Emissions in the ROK



The four columns on the right show carbon dioxide emissions from the ROK electricity sector in 2030 for the technical pathways discussed in the text.

FIGURE 13

ROK INDC Targets and Reductions from Technical Pathways



Even greater reductions in carbon emissions (77%, relative to 2017 levels) are possible at modest cost by building the nuclear power units planned for in the 7th Basic Plan and using additional natural gas generation to replace the remaining coal generation. Simply building the 8,800 MW of previously planned new nuclear reactors that have since been cancelled would displace additional generation from existing coal plants at a relatively modest cost ($8/MWh). The estimated impact on overall system power costs in the ROK (e.g., spread out over total ROK electricity generation in 2030) from all of these technical pathways is modest, around $2.6/MWh.[25]

The average cost for carbon dioxide reductions in the ROK is $8/ton-$CO_2$ for the VLC scenario involving 77% reductions. This result suggests that the ROK could present a positive counter to the example of Germany, showing how an industrialized, technologically advanced country can succeed in greatly decarbonizing its power sector by using nuclear energy and renewable energy technologies at a relatively modest cost and within a timeframe well before mid-century.

Similar to the U.S. air pollution threat discussed earlier in this chapter, eliminating coal use in the ROK electricity sector would also reduce conventional air pollutants (e.g., sulfur dioxide, nitrogen oxides, mercury) that impact public health. As in the United States, air pollution from ROK coal plants could be causing higher rates of sick leave, more expensive medical bills, lower quality of life, and shortened lifespans—particularly among "at-risk" populations. The ROK government has acknowledged in the past that air pollution "… is of the greatest concern in the Republic of Korea… To meet this target, officials are taking measures to reduce coal-fired power plants…"[26] The technical pathways described above would help to achieve this objective. A 2010 U.S. National Academy of Sciences report estimated that the external cost of coal use in the United States attributable to conventional air pollution was $32/MWh in 2005, and *even with* better pollution reduction controls on coal plants, those costs would still be $17/MWh in 2030.[27] Energy policy discussions in both the United States and the ROK must consider these economic and human costs.

Separately, the 20% target in the 8th Basic Plan for "new" and "renewable" energy includes about 15% of system energy from wind and solar. At this

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[25] This analysis is based on publicly available data published in 2015; if trends in the ROK have followed elsewhere in the world, the prices for natural gas have fallen, which would reduce the costs associated with the VLC scenario. The costs for nuclear and coal generation may also have changed since 2015, which would impact the total system cost.

[26] *http://web.unep.org/environmentassembly/republic-korea*

[27] See page 7 of National Research Council. 2010. Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. Washington, DC: The National Academies Press. *https://doi.org/10.17226/12794*

TABLE 4

Cost Analysis of Technical Pathways to Reduce Power Sector Emissions in the ROK

Technical pathway	MWh of coal generation replaced	Net cost of switching from coal generation ($/MWh) for pathway	Net cost of switching from coal generation ($) for pathway	Carbon reduction costs ($/ton-$CO_2$) for pathway
Higher capacity factor	22,300,000	-18	-402,000,000	-18
Life extension	72,000,000	-15	-1,080,000,000	-15
New nuclear builds	69,400,000	+8	555,000,000	+8
New natural gas builds	43,600,000	+56	2,440,000,000	+89
All pathways	207,300,000	+2.6	1,510,000,000	+8

The net cost of switching for all pathways is spread over total ROK electricity generation in 2030.

penetration level, and with the output targets set for other forms of generation, about 4.3% of system energy is surplus and would need to be either wasted or stored. Another technical consideration is that the maximum hourly system ramp requirement in this scenario is estimated to double from the current rate of around 9,300 MW per hour to 19,700 MW per hour.[28]

In the future, if wind and solar targets from the 8th Basic Plan are doubled to 30% of system energy and if coal generation is backed down by an equivalent amount, system surplus energy is estimated to grow to 37%.[29] At this penetration level, the maximum hourly ramp grows to more than 37,000 MW per hour— greater than four times current levels. Bringing this much power on or off the ROK electrical grid at these rates could be technically challenging, and it remains unclear whether the anticipated composition of the ROK system could accommodate these ramp rates.

Figure 14 depicts a scenario where solar and wind energy generation in the ROK is scaled up so that the total amount of energy generated by solar and wind plants in a year is equal to the total amount of energy consumed in the ROK over the course of the year. Generation in this scenario is made up of equal proportions wind and solar.[30]

The average cost for carbon dioxide reductions in the ROK is \$8/ton-CO_2 for the VLC scenario involving 77% reductions.

As Figure 15 shows, there is a substantial mismatch between when solar and wind energy is generated during the course of the year and when individuals and companies in the ROK are actually using electricity. In this analysis, other dispatchable forms of energy would be needed for substantial portions of the year to fill in gaps between electricity supply and demand. Alternately, the ROK could try to store the surpluses in renewable energy generation depicted, but this approach would entail additional cost increases to the system.

This analysis illustrates the similar challenges the ROK would face in attempting a renewables-only approach to decarbonizing its electricity grid as compared with the United States. As with previous U.S. analyses, it argues for the ROK to pursue a diverse portfolio of zero-carbon energy technologies in order to achieve deep decarbonization in a cost-effective manner. This perspective is consistent with the findings of other researchers.[31]

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[28] The maximum hourly system ramp requirement is the maximum rate during the year at which a system operator has to bring power on or off of the grid in order to accommodate changes in hourly demand. The current level is calculated from 2016 hourly ROK demand data from the Korea Power Exchange Open Data Portal at www.data.go.kr. The hourly electricity generation data is from wind and solar photovoltaic units owned by the Korea Southern Power Company (KOSPO) for the year 2015 also from the Korea Power Exchange Open Data Portal. Specifically, hourly data was used from four Hanyung wind units, each with a potential output of 1.5 MW and three Handong solar PV units, with potential outputs of 1 MW, 1.9 MW, and 0.6 MW.

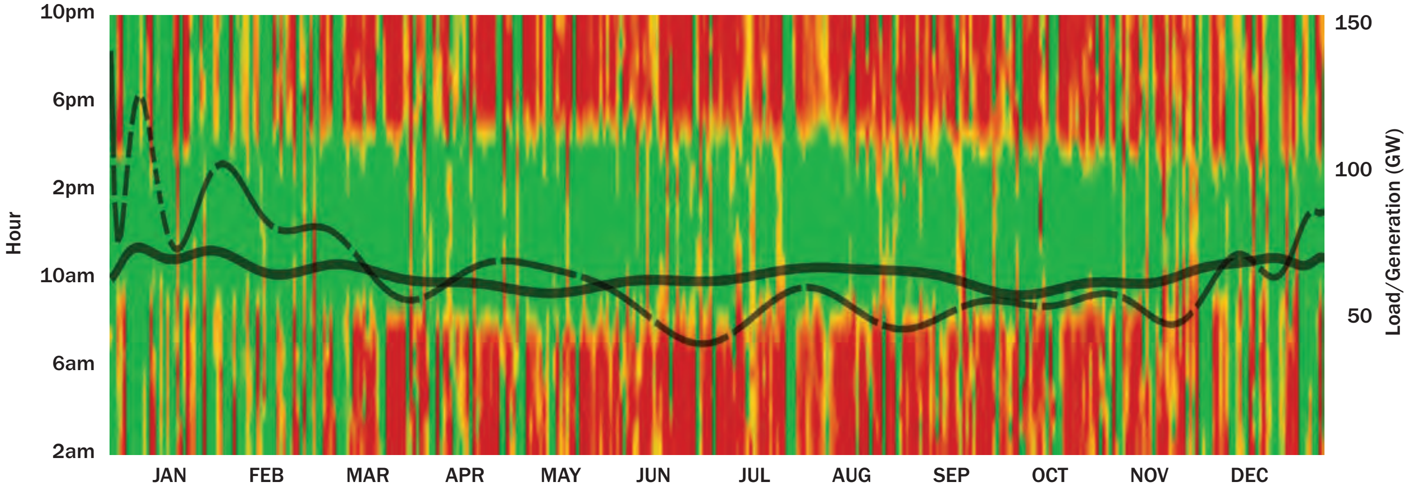
[29] "Surplus system energy" means the sum of energy generated during the year that was above consumption levels at the time of generation.

[30] Hourly wind generation data from Hankyung and photovoltaic solar generation data from Hadong in 2015 was used to represent the hourly generation patterns, and hourly demand data was taken from 2016. Source: Korea Power Exchange, Open Data Portal (*www.data.go.kr*)

[31] A. Sepulveda, Nestor & D. Jenkins, Jesse & J. de Sisternes, Fernando & K. Lester, Richard. (2018). The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. Joule. 2. 10.1016/j.joue.2018.08.006.

FIGURE 14

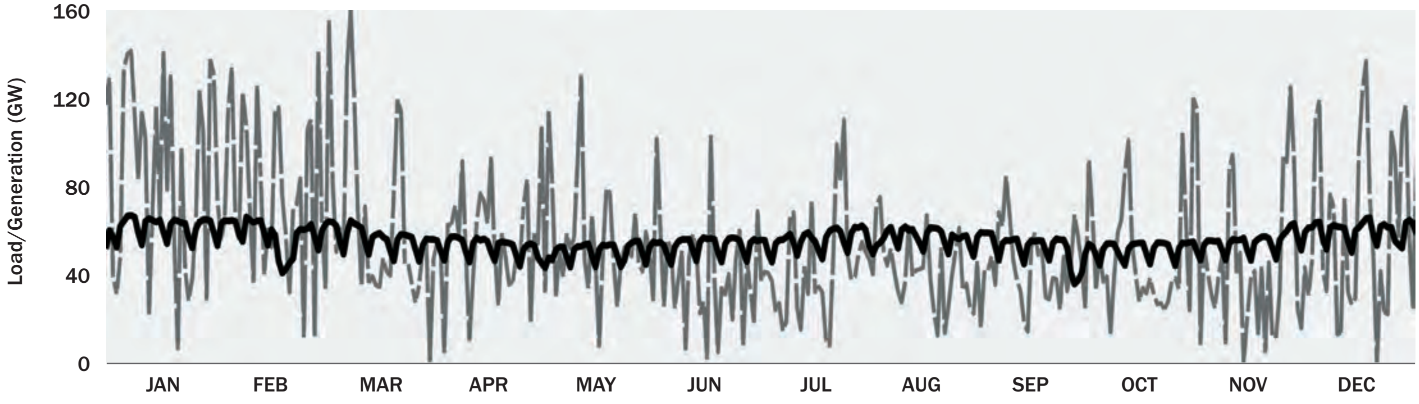
Hourly Comparison of ROK Demand with Scaled Renewable Energy Generation



Red areas indicate nearly 0% load served, while green areas indicate 100% load served or more. The solid line is weekly electricity load and the dashed line is for weekly renewable energy generation, where 2015 wind and solar generation data is scaled so that each meets half of the total 2016 annual ROK load.

FIGURE 15

Scaled Renewable Energy Generation and Daily Demand in the ROK



The average electricity demand for each day in 2016 is shown in black. The average wind and solar generation for each day is shown in dashed grey, where 2015 wind and solar generation data is scaled so that each meets half of the total 2016 ROK annual load.

C. Germany

Germany's approach to addressing climate change is worth examining in that Germany is also a technologically advanced, wealthy country with a diverse mix of electricity generation. In 2007, Germany set a goal that it would achieve a 40% reduction in greenhouse gas emissions by 2020 compared with its emissions in 1990. Tying the emissions reductions to rates from 1990 made the commitment seem more consequential than it was, however. By 2007, greenhouse gas emissions in Germany had already fallen almost 20% compared with emissions in 1990, as shown in Figure 16. The emissions reductions previous to 2007 in part reflected the decline in East German industrial and power sector activity after German reunification. In addition, Germany saw a drop in emissions around 2009 due in part to the worldwide financial crisis.[32]

Even taking credit for these unintentional greenhouse gas emissions reductions, Germany has now essentially abandoned its own stated climate goals.[33] This is a setback for worldwide efforts in

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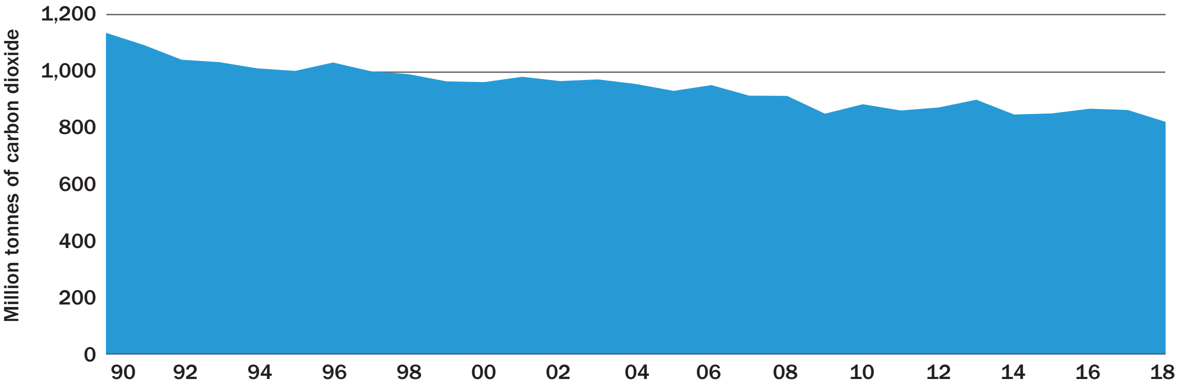
[32] *https://www.cleanenergywire.org/factsheets/germanys-greenhouse-gas-emissions-and-climate-targets*

FIGURE 16

German Carbon Dioxide Emissions from 1990 to 2018



Source: BP Statistical Review of World Energy 2019

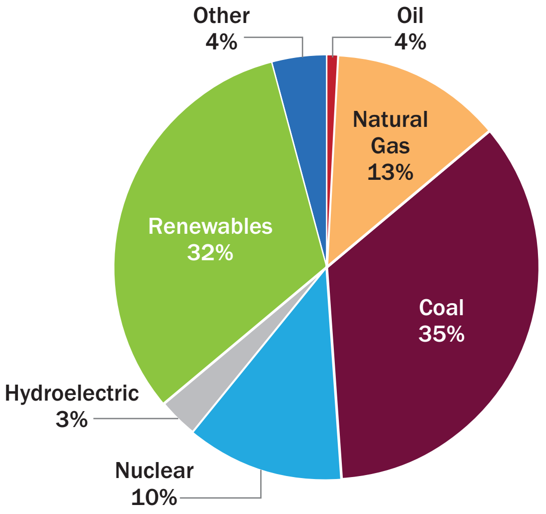
that had Germany achieved the greenhouse gas emission targets it set for itself, it would have served as an example to other countries that reducing greenhouse gas emissions is possible while maintaining a world-class economy. Instead, Germany now serves as a cautionary tale. It spent many billions of dollars subsidizing renewable energy growth but has proved unable to meet its own (relatively modest) climate goals. The public perception of this failure alone is a setback for global efforts to address climate change.

One underlying cause of Germany's failure stems from its decision to phase out nuclear power. In 2000, nuclear power supplied nearly 30% of the country's electricity, but by 2016 that level was down to 13%.[33] Following the Fukushima accident in 2011, the German government shut down eight reactors that year and has decided that the remaining nine plants will be taken offline permanently by 2022.

Closing those reactors has contributed to the lack of progress toward a zero-carbon power system in Germany. Despite steadily rising wind, solar, and biomass use, Germany has continued to rely on large amounts of coal and natural gas for electricity generation, as shown in Figure 17. That is due in part to the reduction in nuclear energy generation. Most of the gains in renewables have gone to replace lost nuclear power generation—with no associated climate benefit.

FIGURE 17

German Electricity Generation by Fuel in 2018



Source: BP Statistical Review of World Energy 2019

From 2010 to 2018, Germany has grown wind and solar generation by 108 TWh, while nuclear output has fallen by 60.7 TWh—thanks to the government's decision to shut down eight reactors in 2011.[35] In that sense, nearly two-thirds of the growth in renewables has not led to carbon dioxide reductions, as renewables merely replaced retiring nuclear plants rather than reducing coal use by an equivalent amount.

If Germany had maintained its nuclear fleet and instead used renewables growth to reduce generation at coal plants by an equivalent 60.7 TWh,

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[33] *https://qz.com/1175308/germany-is-abandoning-its-climate-goals-for-2020-what-happens-next*

[34] *https://www.cleanenergywire.org/factsheets/history-behind-germanys-nuclear-phase-out*

[35] Estimates from: *https://www.energy-charts.de*.

Sequoyah Nuclear Plant, Units 1 and 2, located in the United States.

© TVA

While the U.S. Congress has debated federal energy policies to reduce greenhouse gas emissions from the U.S. electricity sector, no legislation has yet passed into law.

power sector CO_2 emissions would have declined by 71 million metric tons, or about halfway between its 2017 economy-wide emissions and its now-abandoned 2020 climate goals.

Germany plans to phase out the rest of its nuclear fleet by 2022, which will damage the nation's climate goals even further. The remaining German reactors produced 76 TWh in 2018, so Germany will need an equivalent amount of wind and solar growth merely to offset these retirements. This energy strategy has also brought German consumers the highest power bills in the European Union – nearly twice that of the nuclear-dependent French power sector.[36]

As *The Economist* noted in 2015:

> Germany has made unusually big mistakes. Handing out enormous long-term subsidies to solar farms was unwise; abolishing nuclear power so quickly is crazy. It has also been unlucky. The price of globally traded hard coal has dropped in the past few years, partly because shale-gas-rich America is exporting so much. But Germany's biggest error is one commonly committed by countries that are trying to move away from fossil fuels and towards renewables. It is to ignore the fact that wind and solar power impose costs on the entire energy system, which go up more than proportionately as they add more.[37]

D. Discussion

While the U.S. Congress has debated federal energy policies to reduce greenhouse gas emissions from the U.S. electricity sector, no legislation has yet passed into law. A number of states have taken direct action to reduce carbon emissions. California

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[36] *https://www.bloomberg.com/news/articles/2018-09-27/germany-struggles-to-end-coal-reliance-despite-clean-power-shift*

[37] The Economist, "Hot and Bothered," November 28th, 2015.

ultimately passed a 100% clean energy standard to remove carbon from its electricity sector by 2045. The law is not completely technology neutral—at least 60% of the generation must come from renewable energy sources,[38] but other zero-carbon options can compete for the remaining generation. California has taken some steps backwards on decarbonization, however, including the planned closure of the Diablo Canyon nuclear power plant, which currently supplies almost 9% of total in-state electricity generation and a larger percentage of its in-state zero-carbon electricity generation.

Unlike in the ROK, where natural gas prices have been relatively high, low natural gas prices in the United States have created challenges for existing nuclear power plants. In some cases, this has led to economic losses for plant operators and associated pressure to retire those plants early. In response, even U.S. environmental groups that have been historically skeptical of nuclear power have encouraged states to preserve their existing nuclear fleets to avoid increasing carbon emissions.[39] Several states, including New York and Illinois, have passed laws to keep nuclear power plants in operation for reasons that include addressing climate change.

The ROK has a much higher population density than the United States and correspondingly less space per capita for more land-intensive forms of electricity generation, such as solar and wind. ROK government announcements that existing nuclear power plants will retire at the end of their current license periods and that there will be no new nuclear builds in the future makes the decarbonization challenge more difficult.[40] The ROK's energy system also has comparatively fewer renewable resources and a much smaller starting point for solar and wind generation. If the ROK chooses to pursue very high penetrations of renewable energy, similar to barriers in the United States and elsewhere, it will undoubtedly encounter challenges associated with the variability of wind and solar generation.

Given the urgency of rising greenhouse gas emissions and the uncertainty of technological developments in the future, countries such as the United States and the ROK should pursue decarbonization in a technology-neutral manner that allows all current and future zero-carbon options to compete.

Germany's policy decisions have caused it to retain substantial coal and natural gas generation, along with the associated greenhouse gas emissions. Even with highly subsidized renewable energy growth, Germany has failed to meet its own climate goals, in part due to its decision to phase out nuclear power. Further, German consumers pay some of the highest power bills in the European Union—nearly 50% over the EU average.

Each case discussed above argues in favor of a diversified portfolio of zero-carbon technologies in addressing climate change, and nuclear energy as one major tool. Given the urgency of rising greenhouse gas emissions and the uncertainty of technological developments in the future, countries such as the United States and the ROK should pursue decarbonization in a technology-neutral manner that allows all current and future zero-carbon options to compete.

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[38] Renewable energy sources include solar, wind, geothermal, biomass, biogas, and small hydropower.

[39] Union of Concerned Scientists, "The Nuclear Power Dilemma: Declining Profits, Plant Closures, and the Threat of Rising Carbon Emissions," 2018.

[40] *https://www.reuters.com/article/us-southkorea-nuclear-president/south-koreas-president-moon-says-plans-to-exit-nuclear-power-idUSKBN19A04Q*

CHAPTER III

OPPORTUNITIES FOR ADDITIONAL NUCLEAR ENERGY COOPERATION

The U.S. and ROK nuclear industries have a long history of cooperation, with the former playing an integral role in the development of the latter. Westinghouse Electric Corporation in particular has played a foundational role in the ROK's nuclear energy program.[41] Today, U.S. companies still supply the ROK with items such as "instrumentation and control equipment, pumps, other major components, and technical and engineering services."[42] In 2012, a senior vice president from Westinghouse estimated that 19 of 23 reactors in the ROK at the time were based on U.S. technology.[43]

The U.S. and ROK nuclear industries have a long history of cooperation. Today, they are major suppliers to each other's nuclear energy programs.

But the ROK's nuclear industry over time has become more independent. In 2009, the ROK won an open bid to supply four APR1400 reactors to the UAE, which marked its first major reactor supply contract in the international marketplace. The United States is a substantial supplier to the APR1400 builds in the UAE, with over $2 billion worth of content.

The United States and the ROK also supply each other's nuclear energy programs. For example, the AP1000 builds in the United States include reactor pressure vessels, steam generators, condensers, de-mineralizers, heat exchangers, and valves made by ROK entities. U.S. companies are supplying reactor coolant pumps, reactor vessel internals, nuclear fuel, conversion services, and enrichment services to the ROK nuclear energy program.

The United States and the ROK have also collaborated on research and development activities for many decades, including:

- The two countries have been holding meetings of the Joint Standing Committee on Nuclear Energy Cooperation (JSCNEC) over the past nearly 40 years. The annual JSCNEC serves as a forum to exchange views on nuclear R&D and other nuclear energy issues.
- Both countries are members of the Generation IV International Forum and the International Framework on Nuclear Energy Cooperation.
- In 2011, the United States and the ROK agreed to a Joint Fuel Cycle Study (JFCS) on pyroprocessing, which is intended to last 10 years and explore the technical and economic feasibility and nonproliferation aspects of the electrochemical recycling process and other spent fuel management options.

As a competitor to both U.S. and ROK entities, Russia has been winning new reactor bids with a combination of established VVERs, attractive financing, additional non-nuclear offers negotiated

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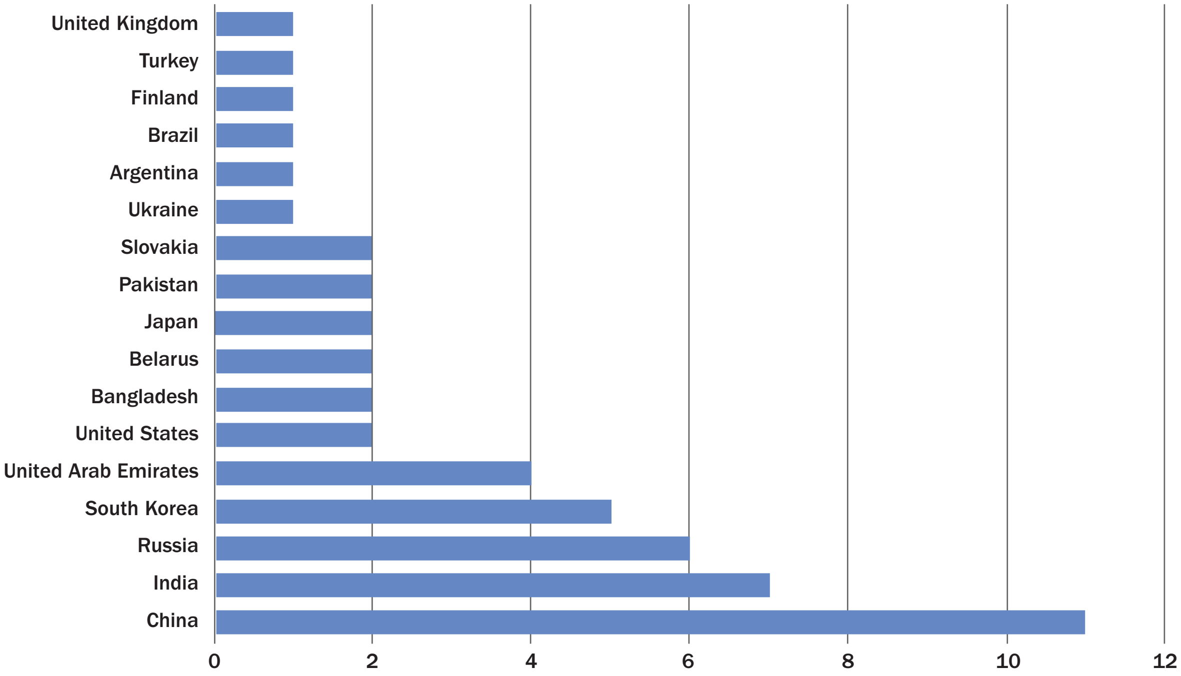
[41] Fred F. McGoldrick, Robert J. Einhorn, Duyeon Kim, James L. Tyson, "ROK-U.S. Civil Nuclear and Nonproliferation Collaboration in Third Countries," 2015.

[42] Congressional Research Service, "U.S. and South Korean Co-operation in the World Nuclear Energy Market: Major Policy Consideration," June 23, 2013.

[43] Dan Lipman, testimony to House Foreign Affairs Committee, June 6, 2012. The testimony itself cites the World Nuclear Association for that figure.

FIGURE 18

Reactors Under Construction by Host Country



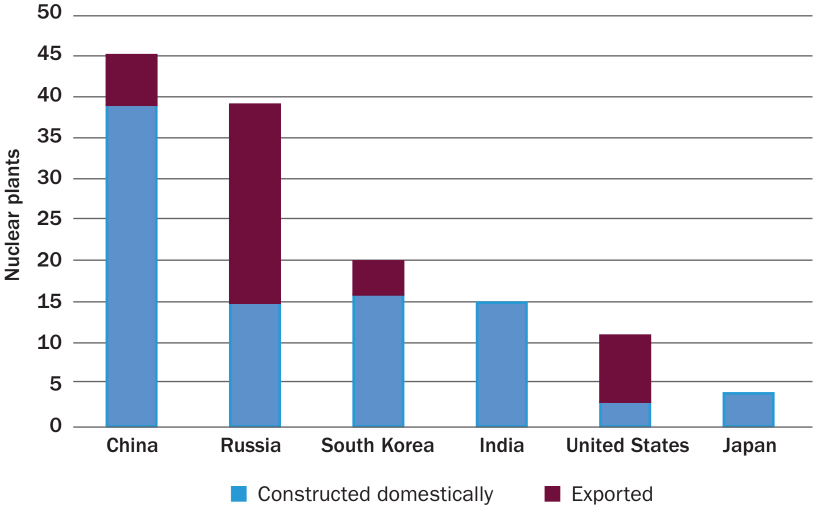
Source: Nuclear Energy Institute, "Nuclear by the Numbers," March 2019.

in parallel with the Russian government, and spent fuel take back packages.[44] Though Russia may currently be winning more reactor bids than U.S. and ROK companies, China could prove to be the more challenging competitor in the long term. With the world's largest construction program of domestic nuclear reactors (see Figure 18), a willingness to offer financing, and substantial non-nuclear business relationships around the world (e.g., in Africa), China is positioned to play a large, if not dominant, role in the international nuclear energy marketplace.

The sale of nuclear reactors to another country begins a century-long partnership, and China and Russia view nuclear energy sales as part of a geopolitical strategy.[45] The United States' early role as the predominant supplier of nuclear power gave it an outsized role in setting supplier norms and nonproliferation practices, and in guiding the development of international nuclear energy. Today, however, the United States has a far smaller role in the market. As shown in Figure 19, Russia is the world's leading exporter of reactors and China is building the most reactors domestically—an

FIGURE 19

Nuclear Reactor Programs for Key Countries Since 1997



Number of nuclear plants under construction and constructed since 1997.

Source: Nuclear Energy Institute, "Nuclear by the Numbers," March 2019.

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44 See Chapter 5 of the Nuclear Innovation Alliance report, "Leading on SMRs," 2017.

45 *https://warontherocks.com/2018/02/geostrategic-nuclear-exports-competition-influence-saudi-arabia*

advantage that positions it to eventually increase its exports.

The alliance of U.S. and ROK entities on international nuclear energy projects may provide a strategically important counterweight to growing Chinese and Russia dominance. One vehicle for greater cooperation could be the high-level bilateral commission (HLBC) created as part of the 2015 nuclear energy cooperation agreement between the ROK and the United States. The HLBC has four working groups dealing with: spent fuel management, the promotion of nuclear exports and export control cooperation, assured fuel supply, and nuclear security. Beyond the HLBC and new reactor construction projects, there are several other opportunities in nuclear energy for the United States and the ROK to collaborate on nuclear energy development.

The existing reactor fleets in the ROK and the United States operate on either their initial licenses or license renewals. The exact retirement dates for the existing reactors in each country present important implications for efforts to curtail greenhouse gas emissions.

A. Extending Reactor Lifetimes and Achieving Higher Capacity Factors

The existing reactor fleets in the ROK and the United States operate on either their initial licenses or license renewals. As analyzed in Chapter I, the exact retirement dates for the existing reactors in each country present important implications for efforts to curtail greenhouse gas emissions.

The U.S. Nuclear Regulatory Commission originally issued 40-year licenses for U.S. reactors. As those reactors approached the conclusion of their initial periods of operation, many owners applied for license renewals. As of June 2019, 93 U.S. nuclear reactors have applied for and received 20-year extensions to their original operating licenses.[46]

In 2018, the first applications were filed by some U.S. nuclear power plant operators to renew their operating licenses a *second time*, which would extend their operational periods to 80 years. As of August 2019, second license renewal applications have been submitted to the NRC for six reactors: Turkey Point 3 and 4; Peach Bottom Units 2 and 3; and Surry Units 1 and 2. Another utility has indicated to the NRC that it intends to apply for second license renewals for two more reactors (North Anna Power Station Units 1 and 2).[47]

As the U.S. nuclear power plants that have applied for a second license renewal are roughly a decade older than the oldest operating nuclear power plants in the ROK, the latter's operators and regulators are in a position to benefit from the U.S. licensing experience and potentially extend their operations beyond 40 years and perhaps beyond 60 years.

The U.S. light water reactor sustainability program at the U.S. Department of Energy has three primary technical areas of R&D:[48]

1. **Materials research:** developing the scientific basis for understanding and predicting long-term environmental degradation behavior of materials in nuclear power plants.
2. **Plant modernization:** addressing nuclear power plant economic viability in current and future energy markets through innovation, efficiency gains, and business model transformation via digital technologies.
3. **Risk-informed systems analysis:** research to support decision making related to economics, reliability, and safety by providing integrated plant systems analysis solutions to enhance the operating fleet's economic competitiveness.

The licensing and safe operation of nuclear reactors for longer periods of time is of mutual interest to both countries and one in which the United States can share its experience with the ROK, which has not operated a reactor beyond 40 years. Each country has also demonstrated that individual reactors are capable of running at high capacity factors.[49] Increasing the utilization of existing and future reactors would generate more zero-carbon energy

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[46] *https://www.energy.gov/sites/prod/files/2019/07/f64/NEGTN02-%23227578-v5-NUCLEAR_INDUSTRY_SCORECARD_SUMMARY.pdf*

[47] *https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html*

[48] *https://www.energy.gov/ne/nuclear-reactor-technologies/light-water-reactor-sustainability-lwrs-program*

[49] For example, the American Nuclear Society published an article by E. Michael Blake in 2017, "U.S. capacity factors: Close to a new peak" that listed several U.S. reactors that averaged above 95% capacity factor during the 2014-2016 period.

Source: U.S. Nuclear Regulatory Commission

U.S. Nuclear Regulatory Commission Chairman Stephen Burns examines the Korea Institute of Nuclear Safety APR1400 Simulator during a 2016 visit to Daejeon, ROK.

in a cost-efficient manner, as described in Chapter II.

B. Cost Reduction Opportunities

The United States and ROK governments could also collaborate more on research to reduce the costs associated with reactor designs from each country. A recent study by the Massachusetts Institute of Technology (MIT) described several areas of research that would provide benefits to light water reactor designs, as well as future advanced reactors. Joint research activities could include:

- **Advanced concrete and construction:** Automated pouring, prefabricated concrete, steel plate composites, ultra-high performance concrete, high-strength reinforcing steel, and other technologies hold potential for reducing capital costs in new nuclear plants.
- **Advanced power conversion:** The use of air or helium Brayton cycles would enable high efficiency and could reduce overnight costs.
- **Coatings and nano-textured surfaces:** Advanced coatings for surfaces in nuclear power plants can improve heat transfer and thus thermodynamic efficiency, translating to better economics.
- **Instrumentation and control:** Advanced instrumentation could improve operational efficiency and reduce uncertainties in key plant parameters such as core power, thermal margin, fuel burnup, and radiation damage.

MIT identified other potential areas for cost reduction, as did a recent report by the Energy Technologies Institute.[50]

C. Advanced Reactor Development

The United States and the ROK have collaborated around the development of various advanced reactor designs. The Korea Atomic Energy Research Institute (KAERI) has pursued a light water small modular reactor (SMR), known as SMART. The United States has also invested in light water SMRs, with the NuScale Power Module being the most

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[50] Energy Technologies Institute, "Nuclear Cost Drivers," 2018. Summary report.

advanced in terms of design and licensing. In July 2019, an ROK company, Doosan Heavy Industries & Construction Co., signed a $1.2 billion business collaboration agreement with NuScale to provide critical parts and equipment.[51]

KAERI has investigated both sodium fast reactor (SFR) and high temperature gas reactor (HTGR) designs and several private companies in the United States are currently seeking to commercialize SFRs (e.g., GE-Hitachi, Advanced Reactor Concepts, Terrapower, and Oklo) and HTGRs (e.g., X-energy). U.S. companies are also developing molten salt reactors (MSRs), such as TerraPower's Molten Chloride Fast Reactor concept, and molten-salt-cooled reactors, such as Kairos Power's Fluoride High Temperature Reactor (FHR). The U.S. Department of Energy has funded work into SFRs, HTGRs, MSRs, and FHRs.[52]

The United States has put in place several policy instruments to aid advanced reactor demonstrations, including the U.S. Department of Energy Loan Guarantee program to provide more attractive financing for new zero-carbon technologies, such as advanced nuclear. In addition, the Energy Policy Act of 2005 established a production tax credit that incentivizes new advanced reactor deployment and operation.

The United States recently selected GE to participate in the development of a SFR as part of the versatile test reactor program.[53] Given the ROK's interest in SFRs, this could be another opportunity for collaboration. The United States could benefit from work the ROK has done in the past, while the ROK could make use of a versatile test reactor facility for experiments and testing.

D. Waste Management

Neither the United States nor the ROK has a geologic repository operating to dispose of spent commercial nuclear fuel. However, the United States is successfully operating a geologic repository in New Mexico—the Waste Isolation Pilot Plant (WIPP)— which is capable of disposing of defense-generated transuranic (TRU) waste. That repository permanently disposes of TRU waste in rooms that have been mined in an underground salt bed layer more than 2,000 feet below the surface.[54] Both countries can benefit from the experience with WIPP and learn lessons for future efforts to dispose of spent commercial nuclear fuel.

In 2010, the ROK and the United States began a 10-year Joint Fuel Cycle Study (JFCS) on the economics, technical feasibility, and nonproliferation implications of spent fuel disposition, including pyroprocessing. KAERI is conducting a laboratory-scale research program on applying pyroprocessing to spent nuclear fuel. A key aspect of the JFCS is to assess whether pyroprocessing technology can be sufficiently monitored by the IAEA to detect diversion and misuse.

In the absence of a repository for disposal, two U.S. companies have recently shown interest in building consolidated interim storage sites.[55] In the ROK, reactor site spent fuel pools have been filling up, and the construction of new spent fuel storage facilities is highly unpopular with the public.[56] Nuclear waste management technologies and public acceptance for repositories and storage facilities are additional areas where the two countries could share lessons and engage in bilateral dialogues at the governmental level.

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[51] *https://www.neimagazine.com/news/newssouth-koreas-doosan-to-supply-equipment-to-nuscale-7331155*

[52] *https://www.energy.gov/sites/prod/files/2015/01/f19/NEACDecemberLyons-Final.pdf*

[53] *https://www.genewsroom.com/press-releases/ge-hitachi-and-prism-selected-us-department-energy%E2%80%99s-versatile-test-reactor-program*

[54] *http://www.wipp.energy.gov*

[55] *https://www.nrc.gov/waste/spent-fuel-storage/cis.html*

[56] Congressional Research Service, "U.S.-South Korea Relations," 2017. Page 41.

CHAPTER IV

CONCLUSIONS

By maintaining and expanding their nuclear fleets, the United States and the ROK could play leading roles in helping the world to achieve decarbonization and mitigate the risk posed by climate change. The ROK in particular appears to be in a position to achieve deeper decarbonization of its power grid in a relatively short time frame, should it choose to do so. The analysis in this report suggests that the ROK could achieve a roughly 77 percent reduction in carbon emissions from its power sector by 2030 at modest cost: $2.6/MWh on a total system basis. Simply running nuclear plants more efficiently and extending their operating lifetimes could reduce emissions by 40% and at a net cost savings to the ROK.

Existing reactor fleets in the ROK and the United States represent the largest source of zero-carbon energy in each country; thus, the timing of existing reactor retirements will have an impact on each nation's greenhouse gas emission profile. Historically, retirement of nuclear reactors has led to increases in greenhouse gas emissions, as at least some of the energy production gap is filled by carbon-emitting sources. Germany, a wealthy country dedicated to tackling climate change, has made little progress decarbonizing its economy over the past decade, despite major investments in renewable energy. Decarbonization efforts in Germany have been hindered in part by the decision in 2011 to retire half of the nation's nuclear plants and the plan to shut down the rest of its nuclear reactor fleet by 2022.

The ROK has shown that it can build nuclear reactors in other countries (e.g., the UAE) on time and on schedule. If this capability is diminished, worldwide efforts to slow the impacts of climate change can only be weakened. In addition, the international nuclear energy market would be further ceded to Russia and China, with attendant geopolitical concerns.

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In the United States, the outlook for further large light water reactor construction projects in the near term appears to be dim.[57] Advanced reactors, including SMRs, represent a new direction that the United States could pursue in the future.

Policies that direct greater resources towards research, development, and demonstration of advanced reactor technologies could accelerate the overall effort to provide zero-carbon power to the ROK, the United States, and the rest of the world.

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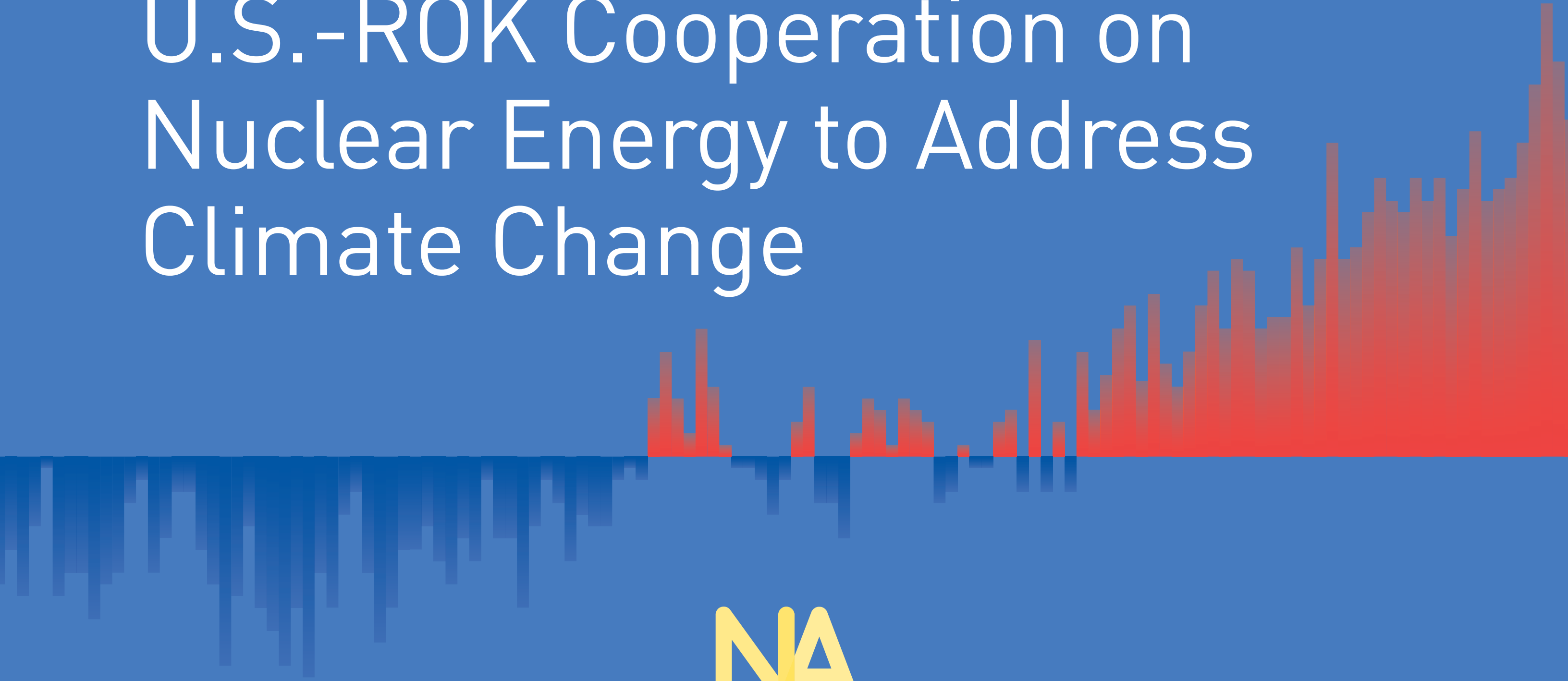
[57] A February 2019 study by the Energy Futures Initiative, "Advancing the Landscape of Clean Energy Innovation," discussed the promise of advanced nuclear power in the United States. Following the report's release, in an interview with Politico, former U.S. Secretary of Energy Ernest J. Moniz stated: "I cannot see another gigawatt-plus plant being built in the United States, at least for not for a very, very long time."

ABBREVIATIONS

CAISO	California Independent System Operator
CATF	Clean Air Task Force
EIA	Energy Information Administration
FHR	Fluoride High Temperature Reactor
HLBC	High-Level Bilateral Commission
HTGR	High Temperature Gas Reactor
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
JFCS	Joint Fuel Cycle Study
JSCNEC	Joint Standing Committee on Nuclear Energy Cooperation
KAERI	Korean Atomic Energy Research Institute
MIT	Massachusetts Institute of Technology
MSR	Molten Salt Reactor
$MMTCO_2eq$	Million Metric Tons of Carbon Dioxide Equivalent
ROK	Republic of Korea
SFR	Sodium Fast Reactor
SMR	Small Modular Reactor
TRU	Transuranic
WIPP	Waste Isolation Pilot Plant

U.S.-ROK Cooperation on Nuclear Energy to Address Climate Change



NUCLEAR
INNOVATION
ALLIANCE

A Report by the Nuclear Innovation Alliance

The purpose of this report is to examine the role that nuclear energy plays in efforts of the United States and the Republic of Korea (ROK) to address climate change. The energy portfolios and greenhouse gas emissions of the United States and the ROK are analyzed, with particular attention to each country's electricity sector. Nuclear power is already a major part of the effort to limit carbon emissions from the power sectors in both countries and its future role will be determined by existing nuclear plant retirements and prospects for new nuclear reactor builds. Some of the challenges associated with trying to decarbonize the electricity sector using only renewable energy are discussed, and it is argued that the United States and the ROK should pursue a diverse portfolio of zero-carbon options to address climate change. Finally, the policy decisions of Germany are assessed in the context of its stated climate change goals and its continued use of coal and natural gas.

Several opportunities are identified for additional nuclear energy cooperation between the ROK and the United States, including: extending the lifetime of existing reactors, running nuclear power plants more efficiently (i.e., at higher capacity factors), cost reduction opportunities for existing and future plants, development of advanced reactors, and managing nuclear waste.

info@nuclearinnovationalliance.org • www.nuclearinnovationalliance.org