Study

Renewable energy potential in Korea and Germany

An overview of different renewable energy sources

adelphi

Imprint

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Content

1 Executive Summary

In order to contribute their national share in the global burden-sharing effort of fighting the climate crisis, both Germany and Korea have set themselves net zero emission goals for 2045 and 2050 respectively.

The transformation into decarbonized economies presents Germany and Korea with comparable challenges. While overall energy consumption figures are set to decline in the respective net-zero-year, electrification and the overall need to decarbonize require rapid expansion of renewable energy sources. Energy efficiency measures should complement the shift to renewables in both countries to further decrease energy needs. While this is valid for both countries, it should be especially emphasized in the case of Korea, that currently has a much higher energy consumption per capita and per unit of GDP than Germany. Looking at the averages of projections for final energy consumption of both countries in their respective net-zero year, Korea shows a higher value than Germany with 1,620 TWh (2050) compared to 1,468 TWh (2045).

This meta study reviewing global and national-level studies demonstrates that both countries can draw on a range of domestic renewable energy sources that have the potential to supply a major part, if not all, of their future energy needs.

Depending on both countries’ respective geographical preconditions, potentials for the individual renewable energy sources vary. While Korea has stronger solar irradiation, and thus a higher solar potential per m^2, it has only a third of Germany’s land area, leaving the overall solar energy potential higher in Germany. The higher availability of suitable areas combined with higher average wind speeds leads to a comparably higher potential for onshore wind in Germany. When looking at offshore wind energy, however, Korea’s roughly eight-times greater marine area leads to a far higher overall potential than Germany has.

Korea’s greater marine area also presents plenty of opportunities for future ocean energy technologies, like tidal or wave energy, while Germany’s potentials in this regard are estimated to be almost non-existent. Korea’s estimated technical potential for ocean energy technologies would be more than enough to cover its current electricity needs but increased research and development and a conducive regulatory framework is necessary to unleash this potential.

Estimates for technical solar energy potential for each country, not considering the regulatory and market framework, are largely exceeding the projected final energy consumption in their respective net zero year. Given Germany’s current political framework more than half of Germany’s final energy consumption needs in 2045 could be supplied by onshore wind. The technical onshore wind potential in Germany largely exceeds the total final energy needs in 2045. For Korea, the mean value of the estimates for the technical offshore wind potential also exceeds the country’s projected final energy consumption in 2050.

Despite the significant estimated renewable potentials in Korea and Germany compiled in this study, both countries will still import some energy for reasons of technical viability and economic efficiency. Nevertheless, overall import dependence would become much smaller through the realization of existing renewable potentials compared to today with both Germany (except for lignite) and Korea importing almost all of their fossil fuels.

Overall, this meta study concludes that both Germany and Korea have the opportunity to reap the manifold benefits of the clean energy transformation with renewable potentials available within their own borders. An independent, cost-efficient and climate-friendly energy supply is therefore dependent on today’s political decisions, research and development and social acceptance of the transformation in the general public.

2 Introduction

With worsening impacts of the climate crisis and still rising global emissions, many countries around the world have set themselves net zero targets in order to avoid its worst consequences. The Republic of Korea (Korea) and Germany are among these countries and have announced to aim for net zero by 2050 and 2045, respectively. This goal is clearly ambitious in the context of both countries' highly carbon-intensive energy, mobility and industrial systems, which produced 616 and 674 million tons of CO_2, respectively, in 2021 (Ritchie et al. 2020b, 2020a). Of these values, roughly 360 and 260 million tons are emitted by electricity and heat generation, more than by any other sector in both countries. At the same time, the need for electricity is expected to further increase in the future due to electrification of other sectors, such as transportation. This puts the energy transition at the heart of any effort to achieve net zero targets, which will not be achievable without a rapid and sustained decarbonization of the power sector.

In addition to addressing the increasing impacts of the climate crisis, the decarbonization of both countries' energy sectors has various further benefits. While Korea was ranking highly among the countries most dependent on fossil gas, oil and coal imports (Welder et al. 2023). Germany's historic reliance on Russian gas has led to significant economic challenges after Russia's invasion of Ukraine. Aside from increasing energy independence, renewable energy deployment will lead to local value creation with myriad economic benefits in both Korea and Germany (Welder et al. 2023; Lutz et al. 2018). Despite improvements in recent years, Korea's air quality still ranks only 30th out of 180 countries analyzed in the Environmental Performance Index in 2022 (Environmental Performance Index 2023). A shift to cleaner forms of energy could therefore contribute to preventing respiratory diseases and premature deaths related to pollution (Jung 2017).

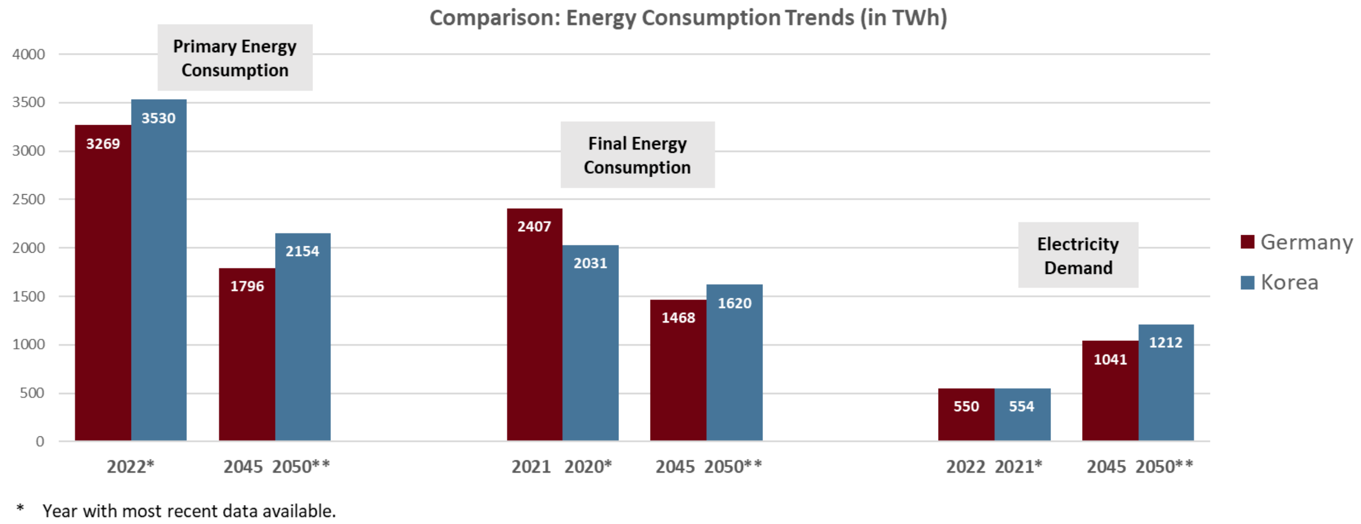
Transformative decarbonization of the power sector is achievable with current technology. Thanks to technological progress and cost reductions in the past years, renewable options like solar and wind power are often cheaper than new fossil fueled power plants or nuclear reactors (U.S. Energy Information Administration 2022; Kost et al. 2021). Implementation of most renewable energy sources is, however, fundamentally different from centralized fossil or nuclear sources, and needs to be rolled out in a decentralized manner. This requires both space for such installations as well as improved infrastructure regarding transmission and storage.

These requirements often lead to concerns that the space and conditions in dense, developed economies like Korea or Germany would be insufficient to provide enough renewable energy to fulfil their energy needs. As such concerns can slow down the necessary comprehensive and rapid expansion of renewable energies, the following study addresses such concerns by providing an overview of renewable energy sources and their respective potential in both Germany and Korea. It is meant as a short guidance to understand the multi-faceted literature on the issue and to gain a comparative overview of the situation in both countries.

The study does so by first demonstrating the current and anticipated energy consumption trends for providing context on the needs for renewable energy production in both countries. Subsequently, the most relevant renewable energy technology options are outlined, before the study looks at the potentials for the most relevant growing renewable energy sources, solar and onshore and offshore wind energy, in Korea and Germany in detail. Afterwards, a brief overview of the potentials for the remaining renewable energy options is given.

3 Energy Consumption Trends in Korea and Germany

In absolute numbers, Korea and Germany are among the countries consuming the most energy globally. A decarbonized future will result in significant changes to energy consumption patterns, for example through the electrification of the transport and heating sectors. This leads to an increase in electricity demand, while overall energy consumption will decrease because of energy efficiency and energy saving efforts.



* Year with most recent data available.
** Forecasts for 2045/2050 are based on different scenario studies; values shown represent averages of the different estimates.

Figure 1: Energy trends in Germany and Korea, today and net-zero year

Data for current consumption: (AG Energiebilanzen 2023; Umweltbundesamt 2022), (Umweltbundesamt 2022), (Ritchie and Roser 2023), (Presidential Commission on Carbon Neutrality and Green Growth 2021), (IEA 2023)

Data for projections: (Ariadne 2021), (Prognos et al. 2021), (Deutsche Energie-Agentur GmbH (dena) 2021), (Bundesverband der deutschen Industrie (BDI) 2021), (Green Energy Strategy Institute et al. 2022), (International Energy Agency (IEA) and Korean Energy Economics Institute (KEEI) 2021)

Decarbonization will change the nature of energy systems due to higher electricity demand as a consequence of the increasing electrification of a wide range of sectors. At the same time, however, primary, and final energy consumption are expected to decrease as a result of more efficient energy use that also will reduce energy costs. Decreasing energy consumption as well as high shares of domestic renewable energy production will make countries like Korea and Germany, which are currently heavily dependent on energy imports less vulnerable to price and supply shocks (Clean Energy Wire 2023; EIA 2023).

Fehler! Verweisquelle konnte nicht gefunden werden. visualizes the electricity and energy consumption of Korea and Germany as it is today compared to the expected consumption in the countries' respective net zero years. The numbers displayed in the figure are averages derived from a range of net-zero scenarios for Germany and Korea. They show similarities and differences between the countries regarding their current and projected Primary Energy Consumption (PEC) and Final Energy Consumption (FEC) as well as their electricity demand. While Germany has a larger size, population and economy than Korea, total energy consumption and electricity demand is currently similar between both countries. Per unit of GDP (PPP), however, Germany consumes almost half the energy Korea does and Germany's electricity consumption per capita is around 70% of Korea's (World Bank Open Data 2023). This can be explained by Germany's advances in energy efficiency and points to Korea's potential in this area. In absolute terms, Korea ranks eighth and Germany ranks eleventh in primary energy consumption globally (Enerdata 2023d).

Recent data shows that Korea consumed more primary energy than Germany in 2022 with 3,530 TWh compared to 3,269 TWh. FEC, on the other hand, is higher in Germany than in Korea with 2,407 TWh in 2021 compared to Korea's 2,031 TWh in 2020. This demonstrates that at present Korea faces higher energy losses than Germany.

Germany's higher ambitions regarding energy efficiency also become evident looking at the expected demand figures in the net zero years - which are higher for Korea than for Germany in all three categories. Projections have assumed less strong improvements in general energy efficiency in Korea leading to the comparably smaller reduction of FEC from 2,031 TWh currently to 1,620 TWh in 2050. In Germany, FEC is projected to decline from 2,407 TWh in 2021 to 1,468 TWh on average by 2045. Nevertheless, PEC is expected to fall drastically in both countries due to fuel switch and measures distinctly aimed at increasing energy efficiency.

As outlined above, electricity demand is going to increase in decarbonized energy systems. Germany's electricity demand of 550 TWh in 2022 is estimated to increase to an average of 1,041 TWh in 2045 In Korea, an even more pronounced increase from 554 TWh in 2021 to 1,212 TWh in 2050 is projected.

4 Renewable Energies – Options, Technologies and Efficiencies

The energy transition is the vital first step towards achieving net zero goals and both Korea and Germany face the need to rapidly expand renewable energy generation. Before renewable potential is discussed in more detail in the following study, it is worthwhile to take a look at the currently existing technological options for renewable energy expansion.

With the increasing focus on renewable energy and a global drive towards decarbonization, solar and wind energy have become particularly popular choices due to their relatively low costs and increasing efficiencies. Solar energy can be harnessed either using photovoltaic cells or solar thermal, while the former is used more widely. Over the years, solar panels have become increasingly more efficient and solar energy costs have decreased significantly, making it one of the most competitive renewable options. It is, however, important to consider solar radiation in a specific location as well as appropriate topography for utility-scale systems. While solar energy tends to exhibit high fluctuations in its output, usually requiring some form of energy storage to use its full potential, it is often cost-competitive even when taking these costs into account (Kost et al. 2021).

Wind turbines can be installed both onshore and offshore, with the latter often providing higher wind speeds, more significant energy generation potential as well as a more continuous energy output. Offshore wind turbines can further be either bottom-mounted or floating. The former is more common and suitable for comparatively shallow water, whereas floating turbines can be deployed in greater water depths. Due to their higher versatility and higher wind speeds further off-shore, floating solutions have been gaining momentum in recent years. They are also better suited for countries with steep coastlines. Technological advancements such as larger rotor diameters and taller towers have led to a steep decline in the cost of wind energy, which – in conjunction with the less volatile output of offshore wind in particular – has contributed to an accelerating wind energy expansion (Ritchie et al. 2022; Sieler 2022). However, a range of factors need to be considered when evaluating an area’s suitability for on- and offshore wind energy, such as the average wind speeds and the regulatory framework regarding land designation, nature conservation and other factors.

Even though wind and solar have experienced significant and accelerating growth over recent years, bringing them to a total global output of 1,800 and 1,000 TWh, respectively (Ritchie et al. 2022), they still do not come close to the world’s leading renewable energy source, hydropower. Hydropower alone provided 4,200 TWh, more electricity than all other renewable sources combined. Despite this significant role on the global scale, hydropower will only be discussed shortly in this study, as it has some characteristics setting it apart from other sources. One of these characteristics is that hydroelectric projects, especially ones of significant size, require somewhat unique geographical conditions. At the same time, high capital costs, significant environmental impacts as well as geopolitical problems have slowed hydropower expansion down, with its year-on-year growth rates being lower than those of solar or wind energy (Ritchie et al. 2022; U.S. Energy Information Administration 2022). Additionally, in both Germany and Korea, much of the economically viable potentials have already been realized in the past.

Even though hydro, solar and wind energy represent more than 90% of the world’s 2021 renewable energy generation, there are a range of other sources to be considered (Ritchie et al. 2022). The first of these is geothermal energy, which relies on higher temperatures deep underground to produce energy. While the operational costs are relatively low, the initial investment required for drilling and exploration can be high and public acceptance is at times low due to potential risks connected to errors in the implementation of geothermal projects. Geothermal resources are very location-specific, with the most suitable sites found near tectonic plate boundaries or volcanic regions, where the Earth's heat is most accessible. Another relevant source of renewable energy can be biomass and biogas, which both involve burning organic waste products. The technology is comparably cheap, even though it is costlier than most onshore wind and solar, and can also be used on a small scale, but can lead to environmental impacts, such as air pollution, or – in case non-waste material is relied on – deforestation (Southern Environmental Law Center 2022; Kost et al. 2021). Last but not least, ocean energy is a less widespread but promising renewable energy source. It uses for instance tidal currents to generate energy. While ocean energy can be both predictable and reliable, its current efficiency varies and implementation is not yet widespread, despite Korea being home to one of the world’s largest tidal power stations (Edmond 2020). Current challenges are mostly related to the novelty of the technologies, high capital costs and its site-dependence.

In conclusion, it can be said that there are a range of renewable energy options available today, each with their own advantages and challenges. Which combination of renewable sources is most preferable essentially depends on each country’s geography as well as general preference. Nevertheless, it can be said that solar and wind energy are currently the most viable options for renewable capacity expansion, which is why this study will focus primarily on these two, while the others will be discussed more briefly.

This study summarizes the findings of potentials for the different renewable energy sources for Korea and Germany from existing studies and reports. However, the assumptions underlying the determination of potentials sometimes differ significantly between sources, which is why results sometimes are only comparable to a limited extent. Roughly speaking, potentials can be divided into three different levels. The first level, referred to as theoretical, or natural potential, takes the simple approach of using the totality of a country’s surface (or exclusive economic zone in the case of offshore wind) and its natural conditions, such as solar irradiation, wind speeds or water depths for calculating the potential of a given technology.

The second level, the technical potential, looks at how much of the theoretical potential can be harvested with available technology considering factors such as conversion efficiency, system configuration, technically needed spacing between e.g. modules/wind mills and in many cases also limitations due to physical obstacles for the installation of the respective renewable technology such as rugged terrain, forests, urbanized/industrial areas.

The third level, the practical potential, considers limitations, which vary greatly depending on the study, and which comprise:

- physical obstacles for the installation of the respective renewable technology if not included in the technical potential,
- land use regulations, e.g. for nature conservation or cropland,
- government support and regulatory policies and the economic viability of a technology.

The political regulation and economic viability influence which share of the technical and geographically possible potential of a given technology is likely to be classified as feasible in a given society. Lastly, it has to be mentioned, that not all of the sources quoted in this study strictly apply the concepts as introduced above. Sometimes, definitions of potentials are blended together or not sharply separated. In these cases, context will be provided.

5 Solar Power

Despite both Korea and Germany having largely temperate climates, solar power holds significant potential, both as utility-scale and as rooftop solar on residential or industrial buildings. Additionally, solar has the appeal of being a comparatively low-cost option that is also feasible on a small scale, enabling citizens to become prosumers of energy. In combination with household batteries or electric vehicles as well as novel architectural approaches like zero-energy houses, solar can also be the key to energy autonomy for households.

5.1 Targets, Policy and current status

In the following, the current status of solar power expansion and political targets for the technology will be introduced briefly and a connection between wider decarbonization efforts will be made.

5.1.1 Germany

As previously mentioned, German climate policy has the target of achieving climate neutrality by 2045 and the transformation of the energy sector is an essential part of the way towards this goal. In this context, the German government aims at a share of 80% of the electricity supply coming from renewable sources by 2030 (Bundesregierung 2023). This implies that the share of renewables must be almost doubled within ten years. To achieve these ambitious goals the so-called “Easter-Package” from April 2022 contained a revamped Renewable Energy Sources Act (EEG), which also contains additional support for rooftop solar. The Act also set a new solar expansion goal of 215 GW[1] until 2030, which would more than triple the installed peak capacity in Germany from 67 GW as of 2022 (Umweltbundesamt 2023c; Bundesministerium für Wirtschaft und Klimaschutz (BMWK) 2023). Accounting for the remaining years until 2030, this would require an installation of almost 18.5 GW of additional peak capacity per year. This target is ambitious, since the highest annual capacity additions have been around 8 GW in the past, achieved during the height of Germany’s short-lived solar boom between 2009 and 2013. Even though the capacity additions amounted to slightly more than 7 GW in 2022, which is a considerable improvement over the past years, the speed of solar expansion needs to increase significantly if Germany wants to reach its goals.

5.1.2 Korea

Korea aims to become climate neutral by 2050, which will require a fundamental shift in its energy supply. Under these circumstances, the country has announced goals to expand the share of renewables in electricity production. While the target outlined in Korea’s roadmap towards net zero from 2021 was a share of 30,2% renewable energy, this target has been lowered to 21.6% in 2030 and 30.6% in 2036 according to the 10th Basic Plan for Electricity Supply and Demand (Enerdata 2023c). The plan, which represents a shift in favor of more nuclear expansion, also underlines the government’s goal to put more emphasis on wind, which is set to increase in importance compared to solar energy. According to the supply plan for renewable energy, the wind energy share in renewable energy production is to rise from 1,8 GW or a share of 7% in overall renewable production in 2022 to 34GW or roughly 33% in 2036. Utility-scale PV is set to increase from ca. 22 GW in 2022 to over 65 GW in 2036, which would also be a significant step forward. Given the current capacity, Korea would require annual capacity additions of ca. 3 GW to reach the government’s PV target. Given that 4.4 GW of both utility and home PV were added in 2021 (Bellini 2022), Korea seems well positioned to achieve the rate necessary for its own solar capacity goals, which could indicate that a higher level of ambition would be feasible. However, Korea has cut capacity allocations in solar tenders (Bellini 2023).

Apart from the achievement of the solar capacity target by 2030, it should be noted that the question of solar energy’s 2050 role is still open. A recent study by several think-tanks estimated that solar could become Korea’s leading source of electricity by 2050. The study states that a share of 38% of solar electricity production would be needed to achieve climate neutrality in 2050 (Green Energy Strategy Institute et al. 2022). This share would require a substantial effort, since solar energy only represents 4% of total electricity generation as of 2021 (BloombergNEF 2021; Lee 2022).

5.2 Potential according to Global Solar Atlas

In this part, the Global Solar Atlas, published by the World Bank, will be used to provide some basic context for the evaluation of both countries’ solar potential.

5.2.1 Germany

The starting point for a consideration of overall solar potential is the natural or theoretical potential, referring only to the total amount of global horizontal irradiation received by a country. According to calculations from the World Bank’s Global Solar Atlas, Germany's theoretical potential is on average 2.98 kWh/m² per day (World Bank Group et al. 2023). The strongest potential can be found in the south, as indicated in **Fehler! Verweisquelle konnte nicht gefunden werden.**below.

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[1] In the context of solar, GW refers to giga watt peak, meaning the peak capacity of solar installations.

A simplified calculation using Germany's total surface area of approximately 357,000 km² and the average natural potential results in a theoretical solar potential of 388,000 TWh per year. To put this in context, the German electricity consumption in 2022 was 550 TWh, which would be equivalent to about 0.14% of this theoretical potential (Enerdata 2023a).

However, solar power installations would not be able to harvest all this energy. Correcting for technical potential (e.g. considering the system configuration, conversion efficiency of PV modules and other factors such as air temperature, soiling and shading) and spacing between modules, the global solar atlas therefore calculates that 2.95% of Germany's total area would need to be converted to utility-scale solar to provide the equivalent of Germany's 2014 electricity consumption. **Fehler! Verweisquelle konnte nicht gefunden werden.**shows the photovoltaic power potential in Germany considering the mentioned technical limitations.

Even apart from technical limitations, it is not realistic to assume that one would be able to harvest this maximum potential due to limitations in land use, which is why the global solar atlas adds two levels of additional limitations to these calculations in an effort to more realistically reflect the actual potential. On level 1, land with identifiable physical obstacles (such as rugged terrain, forests, urbanized/industrial areas) is removed, and on level 2, land possibly under land use regulations (e.g. nature conservation; cropland) is removed. This reduces the theoretically available area to 73.2 and 21.4% of the total land area of Germany, respectively.

This reduction in available space also impacts the theoretical average efficiency of solar panels in Germany. Taking technical limitations and the distribution of the available land into account, the atlas calculates a practical efficiency of 2.96 kWh/kWp per day for the land available under level 1. This would be equal to around 1,080 kWh per kWp per year, meaning that Germany would need around 510 GW installed solar capacity to meet its 2022 electricity demand of 550 TWh through solar alone.

When using a simplified approach based on the assumptions made in the Global Solar Atlas regarding land use restrictions (level 2) and using the entire country's average solar irradiation for the 21.4% theoretically available, a technical potential of 7,438 TWh for solar PV can be calculated for Germany (Rechner Online 2023).

5.2.2 Korea

As in the case of Germany, the ideal starting point for the analysis is the overall theoretical solar potential of the country. In the case of Korea, the average theoretical potential per unit of land area is slightly higher than in the case of Germany due to higher solar radiation and amounts to 3.99 kWh/m² per day according to the Global Solar Atlas. Considering the smaller land area of Korea of approximately 100,339 km², the total theoretical potential, however, is, lower and amounts to approximately 146,000 TWh.

Putting this in the context of Korea's 2021 electricity consumption of 554 TWh, around 0.38% of the total theoretical solar potential would be needed to fulfil Korea's current electricity needs (Enerdata 2023b). Taking technical limitations into account, the Global Solar Atlas calculates that 4.51% of Korea's land area would be needed for solar if solar were to provide all its energy demand.

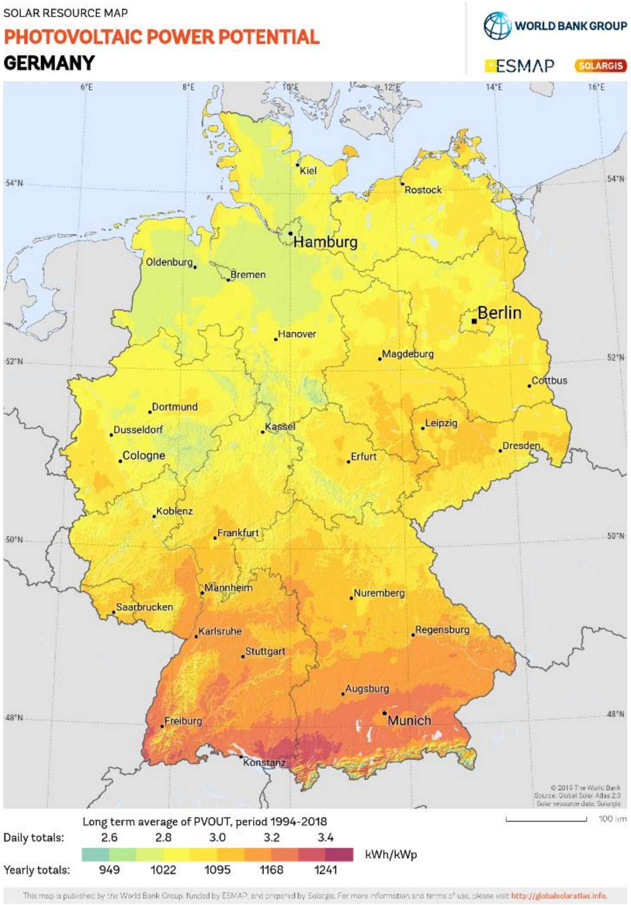

Figure 2: Photovoltaic power potential in Germany considering technical limitations

Map obtained from the "Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info/
The photovoltaic power potential shown here considers how much of the theoretical potential (solar radiation) can be harvested with available technology, considering factors such as conversion efficiency, system configuration, technically needed spacing between modules.

As discussed previously, the global solar atlas introduces two levels of practical land availability limitations to provide a more accurate representation of the solar potential. For South Korea, due to more mountainous terrain, the available land under level 1 restrictions (identifiable physical obstacles) is reduced to 54,2% and to 19% under level 2 (land possibly under land use regulations).

Due to higher solar irradiation, the output of solar PV units is, however, comparably high, with a value of 3.816 kWh/kWp per day according to the Atlas. This translates to 1,390 kWh/kWp per year meaning that around 400 GW would be needed to power Korea entirely by solar. Using the same simplified approach as for Germany on the basis of the Global Solar Atlas' data, a technical potential of 2,377 TWh for solar PV can be calculated for Germany.

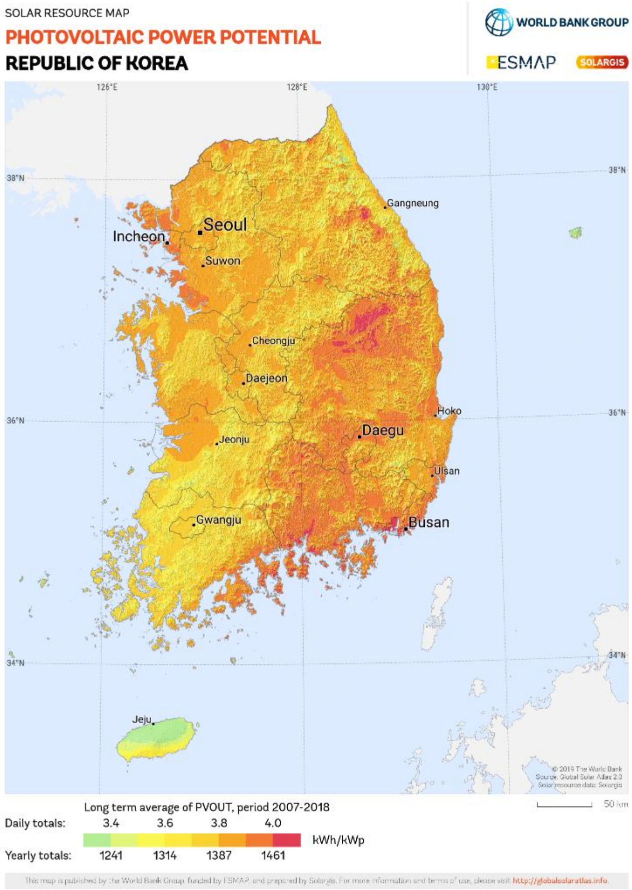

Figure 3: Photovoltaic power potential in Korea considering technical limitations

Map obtained from the “Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalsolaratlas.info/

The photovoltaic power potential shown here considers how much of the theoretical potential (solar radiation) can be harvested with available technology, considering factors such as conversion efficiency, system configuration, technically needed spacing between modules.

5.3 Specific potential according to national level studies

As mentioned, it needs to be kept in mind that the global solar atlas calculations use a somewhat theoretical scenario assuming utility-scale solar under ideal conditions, only excluding land with clearly detectable limitations. Such overarching potential analyses are naturally not reflective of the practical conditions on the ground. To get a better sense of the technical and practical potentials, a look at the diverse literature on the topic proves valuable. This chapter will summarize results from national level studies to give a more nuanced overview of the specific solar energy potentials of both countries.

5.3.1 Germany

The most important detail left unaddressed by the Global Solar Atlas’ estimations concerns the various potential use-cases for solar energy. Thanks to its versatility, solar can be used in a multitude of circumstances, such as building-integrated solar, swimming solar on lakes and reservoirs or solar in mixed use with agricultural land. Fraunhofer ISE calculates the technical potential (excluding surfaces that cannot be used for the respective technology but not considering other regulatory and economic limitations) for these different applications in Germany and highlights in particular the high potential for building-integrated and agricultural solar. According to their calculations, the potential for the former amounts to 1000 GW and for the latter to 1700 GW. In addition, various other sources, such as swimming solar, solar alongside transportation infrastructure or solar in urban areas offer an additional 450 GW (Conexio GmbH 2021). Putting this overall estimate of 3150 GW or approximately 3400 TWh in the context of Germany’s solar expansion goal, only around 7% of this technical potential would be needed to reach the 2030 expansion goal of 215 GW – not accounting for traditional utility-scale solar.

A literature review by the “Stiftung Klimaneutralität” using mostly older sources gets to a practical economically usable solar potential of 300-350 GW for free standing solar, including agri-solar and floating solar, 400 GW for rooftop and 320 GW for facade solar. This results in an overall potential of 1,070 GW or approximately 1,155 TWh (Stiftung Klimaneutralität 2021). Even though being slightly lower, these values are somewhat comparable to the Fraunhofer estimates, with estimates for building-integrated solar being 720 and 1,000 GW, respectively.

Another study focusing exclusively on rooftop solar for single- and two-family homes estimates a technical potential of up to 38.6 TWh p.a. for this category, even though the authors assume that a part of this potential is not economically viable. The study also looks at opportunities for rooftop solar in the agricultural and food retail sectors. There, the potential is estimated to be 3.8 TWh p.a. (Prognos 2016). This would be equal to a capacity potential of roughly 36 and 3.6 GW, respectively.

The relevance of solar, in particular building-integrated solar becomes apparent from the findings of a study analyzing different scenarios for Germany’s climate neutrality in 2045 written as part of the Ariadne project (Ariadne 2022). Regarding potential scenarios for Germany to become climate neutral by 2045, rooftop solar plays a central role, with a combination of renewable sources scenario requiring almost all available rooftops to be covered with solar power.

Regarding solar thermal, Fraunhofer ISE quotes other studies assuming a potential of around 30 TWh per year until 2050 (Wirth et al. 2021).

It is also relevant to take a look at the costs of solar PV, which the Fraunhofer ISE study estimates to be 2-7ct per kWh (Wirth et al. 2021). A more recent study by Fraunhofer ISE estimates costs to be between 3.1 and 5.7EuroCt per kWh for utility-scale solar and 11-13EuroCt/kWh for small-scale rooftop solar (Wirth 2023). The estimates of the Global Solar Atlas are similar with an average of 11 USDct/kWh (2016), which is roughly equal to 10 EuroCt.

5.3.2 Korea

Apart from the calculations based on the global solar atlas laid out in Chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**, the government of Korea has also done its own calculations about the total potential of renewable energy sources, including solar energy, which have been published in the form of a White Paper in 2021. The calculations are split into theoretical, technical and market potential. In this case, the theoretical potential refers to the complete utilization of the solar radiation while the technical potential considers not only technical but also geophysical limitations. The market potential reflects government support and regulatory policy excluding economically inefficient uses, and thus is subject to potential change. The market potential also includes land use restrictions similar to level 2 above, such as natural parks. The calculations get to a total theoretical potential of 137,347 TWh/year, which is very close to the results of the previously mentioned calculations based on data from the Global Solar Atlas (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021).

For the technical potential, the Korean White Paper looks at solar PV and solar thermal separately and calculates a potential of 2,409 GW or 3,349 TWh[2] for solar PV and 4,778 GW or 6,181 TWh for solar thermal considering only common buildings with hot water heating/cooling (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021).

The calculation of the market potential of the White Paper results in a potential of 369 GW or 513 TWh annually, which would be equal to around 90% of Korea’s 2021 electricity demand, and 141 GW or 187 TWh for solar thermal, considering only buildings for which water for heating/cooling is provided. This would be roughly equal to a total of 510 GW or 700 TWh.

A study by the Korea Energy Economics Institute from 2018 calculates the total economically feasible solar potential to be 318 GW or 293GW if land cost is included (Lee and Jo 2018). This is roughly equal to three times the updated 2036 target. The study also considers the potential for building-integrated solar separately and suggests an overall potential of additional 44.2GW. Considering Korea’s 2021 electricity demand of 554TWh and the average efficiency calculated by the Global Solar Atlas, this would cover around 85% of electricity demand.

In a similar order of magnitude is another study looking into options for Korea’s net zero goal. The report written by GESI and other think tanks estimates a practical and achievable potential of 375 GW by 2050 (Green Energy Strategy Institute et al. 2022). An additional study by Climate Analytics estimates a total techno-economic potential of 584 GW of open-field and 57GW for rooftop PV, resulting in an estimated total capacity of 641GW. Converting this according to the metric provided in the global solar atlas, this would be equal to around 893 TWh, while the more precise estimation from the study itself puts the value at 1115 TWh, which would be almost twice Korea’s 2021 electricity demand (Welder et al. 2023).

Regarding the cost of solar PV, the Korea Energy Economics Institute estimates that the levelized cost of electricity will fall to 100 Won/kWh in 2023 and 84 won in 2030 (Korea Energy Economics Institute (KEEI) 2018). The global solar atlas estimates an average of 10 USDct/kWh (2016), which would be comparable to around 100 Won. This value would be somewhat lower than the estimation of 11USCct/kWh for Germany.

5.4 Comparison

Theoretically, using just a fraction of around 3% of Germany’s and 4.5% for Korea’s total surface area respectively would be enough to supply them with enough solar power to cover all of their current electricity needs. While Germany’s more than three times larger surface area leads to a higher total theoretical solar energy potential, Korea has the advantage of higher solar irradiation, leading to a theoretical average daily photovoltaic power output per m^2 which is significantly higher than Germany’s (3.99 kWh/m^2compared to 2.68 kWh/m^2). The technical and practical potential for the two countries is only comparable to a limited degree as is calculated in different studies with differing underlying assumptions. Estimates range from 1,155 – 7,438 TWh for Germany and from 513 TWh – 3,350 TWh for Korea for solar PV. Nevertheless, the mean values of these estimates for solar energy potential for each country are exceeding the projected final energy consumption in their respective net zero year (1,468 TWh for Germany and 1,620 TWh for Korea; see Chapter 3). Low values for the practical/market potential, such as the 513 TWh estimated for Korea, typically presume a less favorable regulatory and market framework.

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[2] This number is calculated based on the average efficiency given in the global solar atlas to make it comparable to the German case. The White Paper itself does a slightly different conversion, resulting in 3,117 TWh.

6 Onshore Wind Power

In theory, wind power has the potential to be one of the most significant sources of energy in both Germany and Korea. Typically, in both countries areas with lower solar radiation are seeing higher wind speeds and can therefore play at least a complementary role to solar power. In Germany, the map of wind potential appears as the inverse of the solar potential map. Especially in the flatlands of Germany's North, wind power can provide clean electricity reliably. Korea's mountainous geography, on the other hand, diminishes the area usable for wind energy. Nevertheless, wind speeds in certain areas of the country make onshore wind turbines a promising contributor to the Korea's future energy mix.

6.1 Targets, Policy and current status

In the following, we will introduce the countries' targets for onshore wind expansion, the plans for implementation and how far each country has come already.

6.1.1 Germany

As with the other renewable expansion targets, Germany's onshore wind energy targets stand in the context of Germany's renewed Climate Change Act of 2021 and its greenhouse gas neutrality goal set for 2045. The coalition agreement of Germany's government and the adjusted Renewable Energy Sources Act (EEG 2023), set new targets for onshore wind energy expansion as well. In order to achieve an "almost completely" decarbonized electricity mix by 2035, the overall capacity for onshore wind is to be expanded to 115 GW by 2030 and further to 157 GW by 2035 and 160 by 2040. By 2025, yearly onshore wind capacity additions need to reach 10 GW.

By the end of 2022, 58 GW of onshore wind energy were installed in Germany. In 2022, the net-expansion of new wind energy capacity has been 2.1 GW, which was significantly higher than in previous years but still far below the required installation numbers. However, the upwards trend could intensify strongly through the implementation of regulatory adjustments made by the government, like the prioritization of wind energy projects in planning and approval processes (Umweltbundesamt 2023d).

Of the total electricity demand in 2022 (550 TWh), 18 % (99 TWh) were supplied by onshore wind energy (Umweltbundesamt 2023b).

6.1.2 Korea

Currently, onshore wind energy is supplying only a very limited share to Korea's electricity mix. Despite a 6% growth in generation in 2022, onshore wind still accounted for less than one percent of total electricity generation (Ember 2023: 142).

Under the 10th Basic Plan for electricity supply and demand, the Korean government sets targets for the capacity of various renewables energy technologies. By 2030, 19.3 GW of combined (on- and offshore) wind energy capacity is to be installed (Ministry of Trade, Industry and Energy (MOTIE) 2023). This is falling short of modelling by the Korean think tank Next Group, which has suggested that for the fulfillment of Korea's NDC pledge, 22 GW of total wind capacity would need to be achieved (Park et al. 2023). By 2036, overall wind energy capacity is set to increase to 34 GW, which is consistent with Next Group's modelling of the government's goal of supplying 25% of electricity through wind and solar (Park et al. 2023). With the total capacity of wind energy standing at only 1.7 GW in 2021 (International Renewable Energy Agency (IRENA) 2022b), a rapid acceleration in wind energy deployment is needed in order to achieve these goals.

6.2 Overall potential in Germany and Korea

Compared to solar energy, many more variables go into calculating overall wind energy potentials of a country. Fluctuating wind patterns, turbine heights and rotor diameter sizes make theoretical wind energy potentials harder to calculate. Calculating a scientifically sound overall potential for wind, both on- and offshore, thus requires a much bigger set of variables than for solar, some of which are not openly available. Therefore, calculating a theoretical potential was not possible under the scope of this study. In order to account for these nuances, this study will rely on the assumptions made in the baseline studies introduced below. Many of them do not give an overall theoretical potential but only technical and practical potentials reflecting the various levels of limitations.

Nevertheless, the data presented in the Global Wind Atlas can provide some context for the comparison of Germany's and Korea's wind energy potential. In the height of 100 meters above the ground (an average turbine's height), the mean power density for the 10% windiest areas of the respective country is 595 W/m2 for Germany and 552 W/m2 for Korea. Average wind speeds in said areas are 8.45 m/s in Germany and 7.35 m/s in Korea. In addition to these slightly higher wind speeds, Germany has a three times bigger surface area than Korea theoretically available for the deployment of wind energy. As visible in Figure 3, the wind speeds in Germany are generally higher in the Northern part of the country. In Korea, the highest wind speeds can be found in the mountainous areas of the country and along the coastlines (see Figure 4).

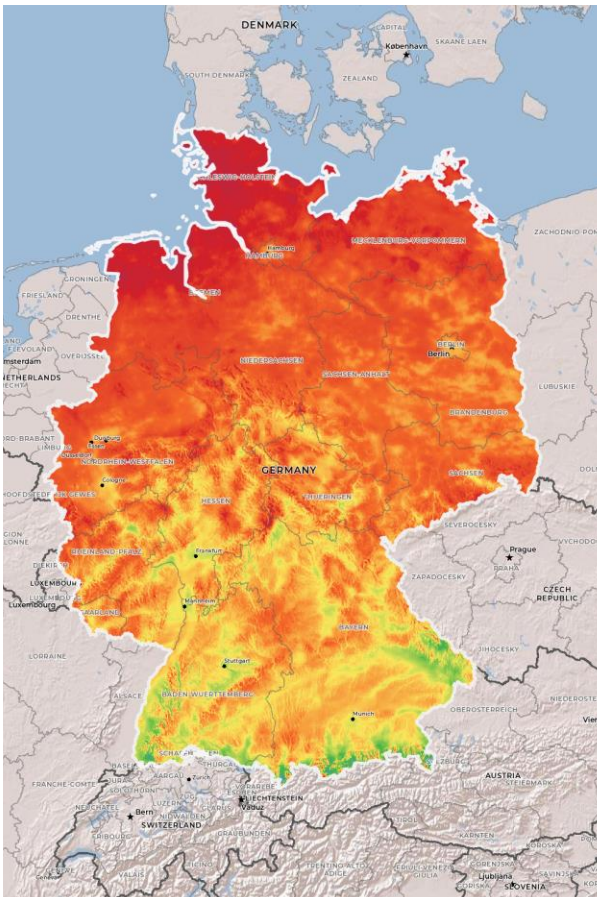

Figure 4: Onshore wind power potential in Germany

(darker shades indicating higher wind speeds)

Map obtained from the “Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info

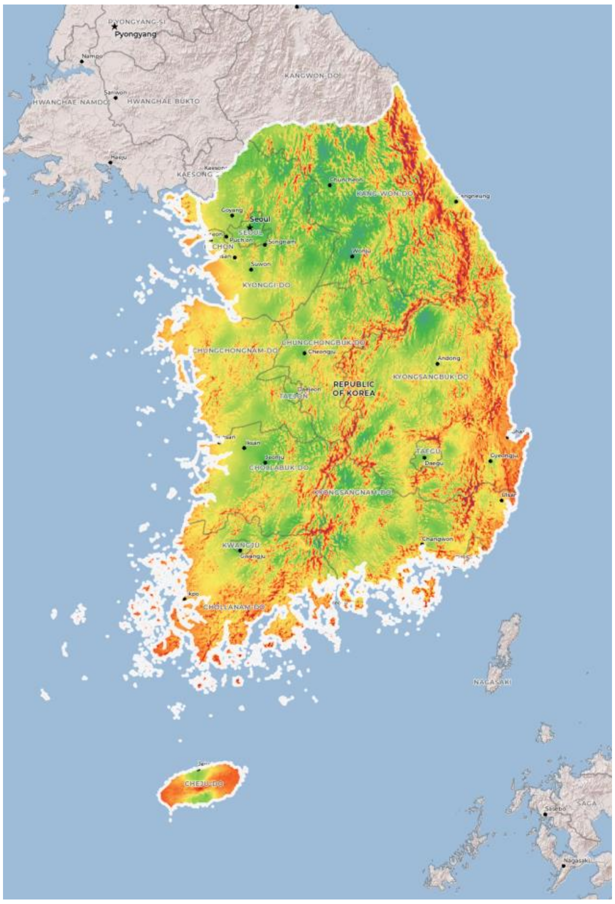

Figure 5: Onshore wind power potential in Korea

(darker shades indicating higher wind speeds)

Map obtained from the “Global Wind Atlas 3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas 3.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info

6.3 Specific potential according to national level studies

In this part, studies indicating the various levels of onshore wind potentials for both countries will be introduced and context regarding the respective study’s assumptions will be provided.

6.3.1 Germany

As with solar energy, the theoretical potential of the total surface area of a country for onshore wind energy capacity and generation is in practice limited by various factors.

A Fraunhofer study conducted in 2012 looks at technically and geographically (excluding physical obstacles) viable areas for wind energy turbines and classifies three levels of possible restrictions in said areas: areas without regulatory restrictions, areas in forests without nature protection requirements and those under nature protection. When all technically and geographically viable areas are included, 22% of Germany’s land surface would be usable for wind energy, allowing the country to install wind turbines with a capacity of 1,500 GW. When only considering areas without any geographic or nature preservation restrictions, the potentially usable area would still be 8% of the country, leading to a possible capacity of 722 GW (Fraunhofer-Institut für Windenergiesysteme (Fraunhofer IWES) 2012).

Another study by Umweltbundesamt identifying all technically suitable areas using geo information system data demonstrates Germany's onshore wind energy potential in relation to the various possible minimum distances to be kept between wind energy sites and buildings. The study finds that with a minimum distance requirement of 600 meters, 13.8 percent of Germany's total surface area could be used for wind turbines. This would allow for the installation of 1,190 GW in wind energy capacity, providing around 2,900 TWh of power per year. Increasing the minimum distance by 200 or 400 meters would shrink the available surface area to 9.1 percent or 5.6 percent respectively (Lütkehus et al. 2013). Overall, the omission of some of the most important economic and regulatory factors in the study significantly diminishes the applicability of the findings to an actual political and social context.

A more recent study, using more advanced geoinformation data sets, conducted by Fraunhofer IEE differentiates areas regarding "conflict risks" by looking at factors standing in the way of wind energy usage. Conflict risk factors reflect the possible interference of wind energy plants with matters of nature or landscape protection. When disregarding said factors for conflict risk and incorporating all areas technically and geographically viable for wind energy use, 26% of Germany's surface area could be used for the installation of 2.086 GW of wind energy capacity. However, more importantly, when considering only areas with "very low" to "medium" conflict risk for practical viability, 5.6% of the total area would be available for wind power turbines. This could translate to a wind power capacity of 366 GW and an annual generation of 971 TWh. Additionally, if old turbines were replaced by technically more advanced new ones (Repowering), a further 39 GW providing 109 TWh/a of electricity could be added without designating further areas (Pape et al. 2022).

A focus in the political debate in Germany surrounding wind energy lies on the designation of land area. Currently, minimum distance requirements vary between Germany's federal states, ranging from 420 meters to ten times the height of a given turbine, but a regulatory harmonization has been initiated by the current German government. When assuming the availability of 2% of the country's surface, a goal that has enjoyed the most prominence in German political discourse and was formulated by the government, erecting onshore wind turbines with a capacity of roughly 200 GW would be possible, generating 390 TWh/a and thereby supplying 71% of Germany's current electricity demand (Fraunhofer-Institut für Windenergiesysteme (Fraunhofer IWES) 2012). In a recent update to this study, it is stated that under today's technical standards, said 200 GW of capacity could generate 770 TWh per year (Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik (Fraunhofer IEE) 2022). However, it has to be mentioned that due to increased electrification in all sectors of the economy, scenario reports expect Germany's overall electricity demand to rise to between 1,000 and 1,350 TWh/a by 2045 (Ariadne 2021).

As demonstrated in some of the aforementioned studies, using more areas than reflected in the 2%-goal would be technically, ecologically and economically viable for wind energy generation. A utilization of these areas could further strengthen the role onshore wind energy plays in Germany's energy transition.

6.3.2 Korea

Just like in Germany, there have been discussions about minimum distance requirements between wind turbines and other areas in Korea. Currently, regional governments have individual regulations on the distance to be kept between a wind turbine and buildings, roads and other protected areas. The national government has tried to harmonize these regulations with the release of a guideline suggesting e.g. a standard distance of 1,000m from residential areas and 500m from roads. Yet, so far, there is no unified regulation for all of Korea. Consequently, varying distance requirements are one of the main regulatory factors restricting onshore wind power deployment in the country.

The white paper released by the Korean government in 2021 differentiates between three levels of potential for wind energy. Theoretical potential refers to the total capacity that could be installed and power that could be generated on the entire surface area of the country accounting only for the limitation of a certain density of generation capacity per km2 (5MW/km2). Technical potential excludes geographically infeasible areas and technically inefficient uses. Market potential then highlights economic potentials reflecting regulatory and support policies and excluding economically inefficient uses. It thereby also includes land use regulations for e.g. national parks (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021).

The theoretical potential for onshore wind energy as assessed in the white paper would translate to a power generation capacity of 499 GW and an electricity generation of 968 TWh per year. The technical potential, considering geographical and technical limitations, lies at 352 GW capacity and 781 TWh of yearly generation.

The study further assesses the market potential for onshore wind energy with a generation capacity of 24 GW leading to an electricity generation of 52 TWh/year. Even considering that these numbers take into account land use restrictions, e.g. nature conservation areas, these much lower numbers indicate that the current Korean regulatory framework is not conducive to a significant expansion of onshore wind energy that would be able to contribute more to Korea's decarbonization goals and its energy independence (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021).

Due to geographical reasons and the high population density in certain areas of the country, almost three quarters of the current onshore market potential identified by the government's white paper lies in four provinces (Gyeongsangbuk-do, Jeollanam-do, Chungcheongnam-do, Jeju). This poses challenges for the social acceptance of wind energy projects and grid expansion especially in these provinces. Of the provinces mentioned, the island Jeju has the highest market potential relative to its surface area, further amplifying these challenges.

A study from 2009 analyzing non-forested, non-urban areas in various countries and assuming a capacity of 2.5 MW per turbine, finds an overall potential of 130 TWh/a of onshore wind power generation in Korea. The study uses geo-information data for its inquiry and considers efficiency implications of turbine spacing (Lu et al. 2009). It should be noted that the study also works with the technical assumptions on wind turbine capacity valid in 2009, which have since then increased.

The recently published study by Climate Analytics identifies practical potentials for solar and wind energy. The study considers many practical exclusions regarding the availability of land, like buffer zones around infrastructure, the general build environment and areas designated for nature protection. This makes the identified potentials very much applicable to an actual political and social context. Unsurprisingly, the potential found for onshore wind was not very high with 42 GW (121 TWh/year) (Welder et al. 2023). However, it was higher than the market potential identified by the government white paper.

6.4 Comparison

As visible in the above paragraphs, Germany's geography endows it with a significantly higher potential for onshore wind energy. Germany's onshore surface area is about three-times the size of Korea's and the mean power density in the windiest areas as well as the average wind speed in these areas are higher in Germany. Consequently, the technical and practical potentials for onshore wind calculated in various studies are higher for Germany than for Korea. For Germany, estimates lie between 200 GW, which is based on the current political framework of the designation of 2% of land area, and 2,086 GW. If implemented, these capacities could translate to a yearly generation of between 770 TWh and 7,822 TWh.[3] Thus, with the current political framework the practical onshore wind potential could supply more than half of Germany's final energy consumption needs in 2045. The technical potential exceeds the projected energy consumption many times over. For Korea, the highest estimate of a technical potential is 352 GW, leading to 781 TWh of electricity generation, which is similar to the lowest estimate for Germany but does not consider the regulatory framework including nature protection areas. The lowest estimate for the practical market potential in Korea is only 24 GW leading to an electricity generation of 52 TWh/year. As indicated above, the figure could probably be higher if the regulatory framework changed to a more conducive system.

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[3] Simplified calculation based on assumptions made about the average efficiency of onshore wind turbines in Germany: https://stromrechner.com/wie-viel-strom-produziert-ein-windrad/

7 Offshore Wind Power

Offshore wind energy, a very promising source of electricity due to the high wind speeds on sea, plays a very important role in both Germany's and Korea's energy transition. Having access to marine areas, both countries can use offshore wind projects to complement often highly contested onshore wind projects.

7.1 Targets, Policy and current status

In the following, an overview over the current levels of implementation, the wider political framework and future goals concerning the expansion of offshore wind energy in Germany and Korea will be given.

7.1.1 Germany

The German government targets to reach 30 GW of offshore wind capacity by 2030, 40 GW by 2035 and 70 GW by 2045 (Bundesministerium für Wirtschaft und Klimaschutz (BMWK) 2022). This would approximately correspond to a generation of 220 TWh in 2045. In order to reach these goals, tender volumes were increased and planning simplifications were introduced by law. To achieve the capacity target for 2030, every year three to four GW would need to be installed (Agora Energiewende et al. 2020).

As of the end of 2022, 8 GW of offshore wind energy capacity were installed, contributing almost 5% (25 TWh) to Germany's overall electricity demand. While offshore expansion was slowing down almost to zero in 2021 due to higher commodity prices and an unfavorable regulatory framework, regulatory adjustments introduced by the current government should lead to an immediate uptick in project development.

The German government has recently unveiled a plan with European partners to develop the North Sea into a hub for offshore wind energy, building wind parks with a combined capacity of up to 300 GW and a grid network connecting plants with the participating countries' national grids in the context of the European Electricity Market (Tagesschau 2023).

7.1.2 Korea

As mentioned in chapter 5, the Korean government does not differentiate between offshore and onshore wind in the communication of its 10th Basic Plan for electricity supply and demand (Park et al. 2023). However, it states that in total, by 2030 19.3 GW and by 2036 34 GW of wind energy are needed. Given the trajectory of the former government's plans to expand offshore wind capacity to 12 GW by 2030 (International Energy Agency (IEA) 2019), offshore wind is still likely to be the bigger contributor to the overall wind energy expansion. The Offshore Wind Outlook 2019, published by the International Energy Agency, predicts a further growth to 25 GW in 2040 under the then relevant policies. If those goals were reached, offshore wind could supply 10% of the country's current electricity demand. The offshore wind expansion predicted in the report's scenario would further save Korea almost $2 billion in additional gas import bills required to supply the same electricity with gas-fired power generation (International Energy Agency (IEA) 2019). It has to be added, that this estimate reflects gas prices before Russia's invasion of Ukraine, which has led to sharply increasing prices globally.

While annual capacity factors for offshore wind energy in Korea are not comparable to those of the windiest areas in Europe (around 60%), they have reached around 40% for new projects in 2019, thereby approaching the factors reached in China (45%) (International Energy Agency (IEA) 2019). With further technological advancement in offshore wind turbines, including for floating plants, capacity factors are likely to increase.

The global and regional growth in offshore wind deployment poses interesting opportunities for the Korean industry. In 2021, Korea has held a 2.6% share of global offshore wind manufacturing capacity, making it the fourth largest manufacturing hub behind China, the European Union and Taiwan. This indicates its potential role in diversifying global supply chains away from the increasing dominance of Chinese manufacturers. The Global Wind Energy Council expects Offshore wind power installations in Asia excluding China to increase to 7,100 MW annually by 2031. Recent Investments and announcements show, that Korea is an attractive market with a relatively mature supply chain ("one of the hubs in the region"). However, industry has demanded the delivery of a bill fast tracking project development in order to truly unlock offshore wind energy potential in the country. If this was implemented, offshore wind also presented interesting opportunities for the build-out of Korea's nascent hydrogen economy (Global Wind Energy Council 2022).

7.2 Overall potential in Germany and Korea

As mentioned in 5.1, calculating a theoretical potential such as for solar energy for Germany and Korea was not possible under the scope of this study. However, some general remarks can be made regarding the geographical predisposition of Germany and Korea for the use of offshore wind energy.

As shown in the Global Wind Atlas, offshore wind speeds are generally higher in German waters than in Korea. In the German sea, average wind speeds of between 9 and 10 m/s are the norm, while in Korea average wind speeds lie between 7 and 8 m/s (World Bank et al. 2023). Higher wind speeds of around 8.5 m/s are reached in the sea off Jeju. While the German coast reaches higher wind speeds, Korea has a much bigger marine area along its coast to utilize with over 443,000 km^2 (MOLIT 2023). Without getting too much into the depths of public international law, in this study 'marine area' will signify the area the respective state could theoretically exploit for energy generation according to their respective government's official position, thus combining territorial waters and exclusive economic zone (EEZ). It is important to mention that part of Korea's EEZ (total EEZ size: 288,000 km^2) is subject to competing claims of Japan and will, therefore, likely not be used for renewable expansion in the near future. Compared to Korea, Germany's marine area covers only an area of roughly 57,000 km^2, almost 33,000 km^2 of which are part of its EEZ.

Additionally, almost half of Germany's marine area is protected for marine biodiversity, while only 1.8 % of Korea's marine area are under full environmental protection (Marine Conservation Institute 2023).

Due to the shallow water depths of the German marine areas, only fixed-bottom offshore wind installations are needed. Korea also has potential for fixed-bottom solutions with shallow waters alongside the west and south coast but needs floating technologies for the east coast and areas further away from the shore.

Figure 6 and 7 show the offshore wind potential of Germany and Korea respectively, differentiated by wind speeds, the potentially available area and water depth (indicating whether fixed or floating are viable options).

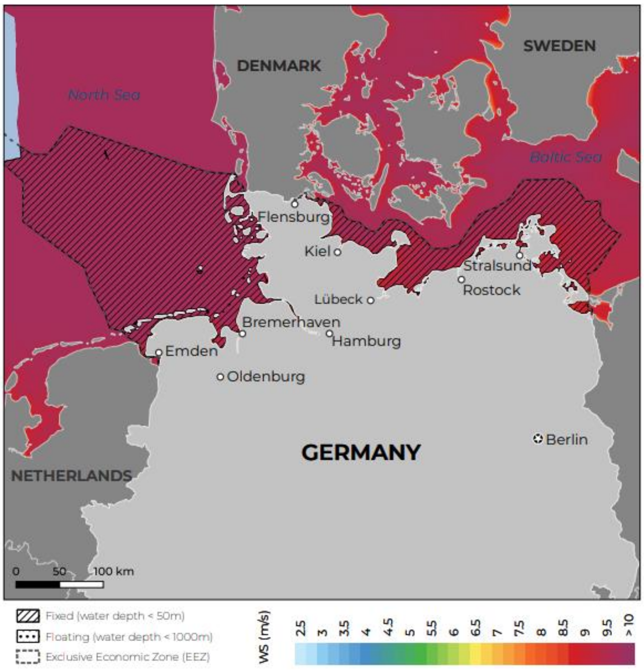

Figure 6: Offshore wind energy potential in Germany

Map obtained from Global Wind Energy Council (2021) under: https://gwec.net/wp-content/uploads/2021/06/Germany_Offshore-Wind-Technical-Potential_GWEC-OREAC.pdf

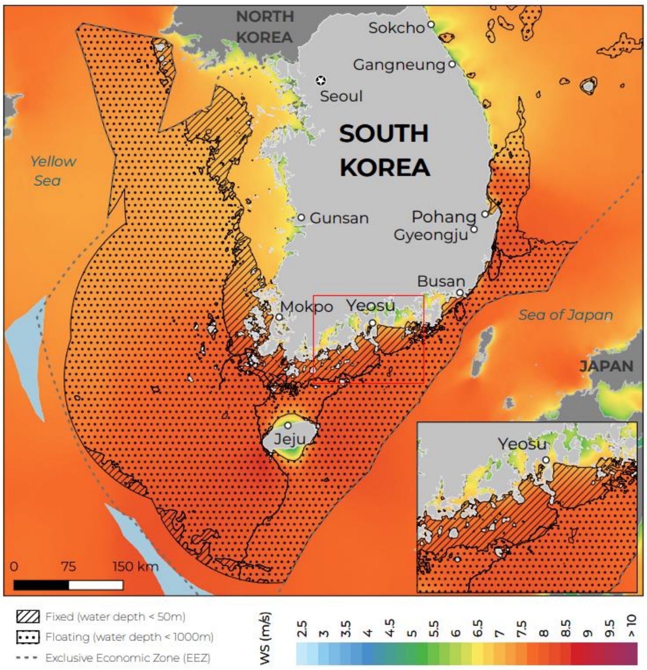

Figure 7: Offshore wind energy potential in Korea

Map obtained from Global Wind Energy Council (2021) under: https://gwec.net/wp-content/uploads/2021/06/South-Korea_Offshore-Wind-Technical-Potential_GWEC-OREAC.pdf

7.3 Specific potential considering national circumstances and outlook

In this part, theoretical, technical and practical potentials of offshore wind energy expansion in both countries as evaluated by different studies will be shown.

7.3.1 Germany

A study from 2009 looks at the offshore wind potential available within 100 kilometers off each country's shoreline. Despite working with the assumption of wind turbines' technical standard of 2009, the study finds an impressive total offshore wind potential of 940 TWh per year for Germany (Lu et al. 2009). It has to be mentioned, however, that given the limited size of Germany's marine area and the vast area under nature protection, this potential seems far from implementable.

An analysis by the Global Wind Energy Council from 2021 finds that within 200 kilometers off the German shoreline, 203 GW of fixed-bottom wind energy capacity could be installed. The potential is a technical one, focusing on turbine planting densities of 3 MW per km^2 for wind speeds between 7–8 m/s and 4 MW per km^2 for wind speeds greater than 8 m/s (Global Wind Energy Council 2021a).

In the following, some studies identifying practical potentials are introduced. These potentials are generally excluding areas under nature protection, shipping routes, areas neighboring cables or pipelines, or such reserved for military or research purposes.

An article by German Institute for Economic Research references a study from 2017 stating that Germany's marine area offers a practical potential of 84 GW of offshore wind energy capacity (Deutsches Institut für Wirtschaftsforschung (DIW) 2018). A similar capacity potential of 82 GW is identified by a 2022 study from Fraunhofer IWES. In this scenario, Germany could receive an annual power yield of 292 TWh (Fraunhofer-Institut für Windenergiesysteme (Fraunhofer IWES) 2022).

Agora Energiewende mentions that most net-zero scenarios for Germany assume an installed offshore wind energy capacity of between 50 and 70 GW by 2050, generating some 200 to 280 TWh per year. While the range communicated here is a practical potential, one very significant point is made in the paper regarding further, technically possible expansion: As the German marine area is limited, increasing the capacity further would lead to decreasing yields because the winds would be unable to regenerate due to the smaller spaces in between wind parks (Agora Energiewende et al. 2020).

The achievement of the current government's offshore wind expansion target of installing 70 GW by 2045 would put the country on track of reaching its decarbonization goals in the area of offshore wind. As various scenarios have stated, for Germany's net-zero target, between 190 and 280 TWh per year would need to be generated through this energy form (Stiftung Klimaneutralität 2022). In some studies analyzed above, existing practical potentials would even allow for a slightly bigger expansion.

7.3.2 Korea

The IEA Offshore Wind Outlook 2019 analyzes Korea's potential in the sector. In order to assess the potential, a geoinformation system analysis with satellite pictures was conducted. The areas considered are excluding regions with low wind speeds (less than 5 m/s), maritime protection areas, buffer zones for cables, important shipping lanes, earthquake fault lines and competing uses. Further, different wind turbine designs for different wind speeds, distance from shore and water depth were considered (International Energy Agency (IEA) 2019).

The report finds that the technical potential for offshore wind in Korean waters lies at over 3,000 TWh of yearly generation (International Energy Agency (IEA) 2019). In theory, this would be enough to supply 1.5-fold Korea's final energy consumption in 2018, and five times Korea's current electricity demand (Ember 2023). Of this potential, 613 TWh could be generated in shallow waters and 2,434 TWh in deep waters (International Energy Agency (IEA) 2019).

The study conducted by the Global Wind Energy Council from 2021 finds that within 200 kilometers off the Korean shoreline, 78 GW of fixed-bottom and 546 GW of floating wind energy capacity could be installed. The potential is a technical one, considering turbine planting densities of 3 MW per km^2 for wind speeds between 7–8 m/s and 4 MW per km^2 for wind speeds greater than 8 m/s (ESMAP 10.05.2023; Global Wind Energy Council 2021b).

The study from Lu et al. from 2009 referenced above finds a total offshore wind potential of 990 TWh per year for Korea (Lu et al. 2009). The aforementioned study by Climate Analytics identifies a technical potential of 870 GW of capacity and 3,710 TWh of yearly generation already considering a range of excluding technical factors such as water depths for fixed-bottom turbines, as well the practical factors protected areas and shipping routes. The potential includes both fixed-bottom and floating turbines, which partly explains the high numbers. And while floating turbines are not yet market-ready, the authors argue that eventually, long run marginal costs for all forms of offshore will be significantly cheaper than Korea's fleet of gas plants (Welder et al. 2023).

The Korean government white paper calculates with a theoretical potential for offshore wind energy of 482 GW and 1,298 TWh/a of generation and only a slightly lower technical potential of 387 GW and 1,176 TWh/a. However, the current market potential for offshore is estimated much lower than the technical potential but still evaluated to be almost double the onshore potential, with 41 GW of capacity translating to approximately 119 TWh of yearly electricity generation (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021).

The realization of the combined market potential for onshore and offshore wind energy identified by the white paper would thus lead to a yearly power generation of 171 TWh. According to this scenario, 31% of Korea's current electricity demand could be met by the expansion of wind energy under the current regulatory framework. As increased electrification will lead to higher power demand (estimates project an increase from currently 554 TWh/a to around 1,200 TWh/a (Park et al. 2023)), regulatory changes might be necessary to realize higher shares of wind energy, that are potentially available according to estimates from other studies previously summarized.

7.4 Comparison

In contrast to onshore wind, for offshore Korea has more favorable overall parameters for a high potential. While average wind speeds in the Korean marine area (7 – 8.5 m/s) are lower than those in Germany's waters (9 – 10 m/s), Korea's roughly eight-times taller marine area, of which only a comparably small share of around 2% is under full environmental protection, allows the installment of much more offshore wind capacity. This is especially true once floating offshore wind turbines become economically competitive and allow to complement fixed-bottom turbines, which are challenging to install in large parts of Korean water due to high water depths. Considering both fixed-bottom and floating offshore wind systems, estimates for the technical potential range from 990 to 3,710 TWh (870 GW) of yearly generation. In Germany, the limited size of its marine area would allow for a technical potential of up to 203 GW (highest value for capacity) and 940 TWh/a (highest value for generation). However, most studies look at the practical potential for Germany, which is especially limited by the large areas that are under nature protection. Estimates for the practical potential range from 50 to 84 GW, which is close to the government's aim of 70 GW by 2045.

8 Other Renewable Sources

Despite solar and wind energy being the frontrunners in the renewable energy mix in both Germany and Korea, other forms of renewable energies also can play an important part in the countries' energy transition. This chapter briefly looks and compares their potentials.

8.1. Geothermal

When analyzing geothermal energy, the basic differentiation between deep and shallow geothermal is crucial. Deep geothermal concerns the utilization of heat[4] in depths of 400 to 5,000 meters for heating applications or to generate electricity (Agentur für Erneuerbare Energien 2023). Shallow geothermal regards energy generated in smaller depths and is currently mainly used for the heating applications in private homes (e.g. through heat pumps).

Germany

In Germany, geothermal energy is mainly seen as a possible contributor to the residential heating sector supplying heat to existing district heating grids or by powering heat pumps in individual buildings.

According to the German Geothermal Association, the overall capacity of the existing utility-scale deep geothermal heat plants in Germany amounted to 452 MW in 2021. Nine plants generated electricity with an installed capacity of 46 MW. Despite the relatively low current figures, an annual growth of 1.1 TWh is achievable according to the industry. Since the exploration and deployment is expected to accelerate after 2030, an annual energy generation of 56 TWh could be possible by 2040. According to the industry association, this is not a theoretical but a realistically implementable potential (Richter 2023).

In November of 2022, the Federal Ministry for Economic Affairs and Climate Action has formulated the goal of generating 10 TWh of deep geothermal energy by 2030. This roughly corresponds to the industry association's outlook (Richter 2023).

A 2010 study by Umweltbundesamt identifies almost 38 % of Germany's surface as usable for deep geothermal energy generation, excluding areas of settlement, forests, waters and other unsuitable areas. This estimate converts to a potential of almost 50 TWh of geothermal electricity generation with an installed capacity of 6.4 GW and thus comes very close to the estimation of the German Geothermal Association for 2040 (Thomas et al. 2010).

Another study mentions a practical potential for deep geothermal energy generation of 118 TWh annually. According to the study, this does not seem achievable by 2045 (Germany's net-zero goal year), though, because of the required expansion of district heating networks and exploration duration for geothermal projects (Richter 2023). It does, however, give a hint for a significantly larger potential of geothermal energy in Germany for the future. An Ifeu study from 2017, sets the technical potential of Germany's deep geothermal resources at 1,400 TWh/a (Jochum et al. 2017).

Shallow geothermal energy is already supplying a significant share to renewable heating in Germany. In 2022, shallow geothermal heating grew by 13% to 22 TWh of generation. Its share among renewable heating sources grew to 11 % thanks to record-growth for heat pumps (Umweltbundesamt 2023b). The Ifeu study mentioned above assesses the practical potential for shallow geothermal heating under the then applicable regulatory framework in a net-zero scenario at between 145 and 186 TWh (Jochum et al. 2017). A Fraunhofer IEG paper from 2022 assesses the technical potential of geothermal heat pumps alone to be around 600 TWh/a (Born et al. 2022).

Korea

As of now, geothermal energy in Korea has primarily been utilized for direct use or geothermal heat pump (GHP) installations. GHP capacity has increased to 1.6 GW supplying 0.9 TWh of energy in 2021 (Song and Lee 2022). The exploration for deep geothermal energy sites has been halted after an earthquake at an exploration site in 2017.

In the White paper released by the Korean government, the potential for geothermal energy is assessed including a differentiation between shallow and deep geothermal. In the paper's definition, shallow geothermal energy is referring to heat found up to 300 meters below the surface and is mainly used directly for supplying heat to buildings in district heating or to power heat pumps. Deep geothermal energy, on the other hand, is found at deeper levels below the surface and can be used as heat or to generate electricity (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021).

Each form of geothermal energy is divided into theoretical, technical and market potential. Theoretical potential refers to a total potential accounting only for the power generation capacity of the application device. Technical potential considers areas geographically infeasible for geothermal energy use. The market potential given in the study, then, accounts for the existing regulatory framework and economic considerations. Noticeably, in this definition of market potential, only the building stock with existing district heating grids is included and, for deep geothermal, only areas with economically feasible connections are included.

The theoretical potential of shallow geothermal energy is calculated to translate to a capacity of 22,236 GW and an energy generation of 55,796 TWh/a. The technical potential considering geographical limitations was calculated to be at 1,256 GW (capacity) and 932 TWh/a (generation). The market potential found in the study led to a generation capacity of 334 GW and a yearly generation of 29 TWh. The study did not address, why such a difference in capacity factors was found for market potential of geothermal sites compared to those solely included under technical potential. For deep geothermal, the potentials where described as significantly lower with a theoretical potential of 350 GW (3,066TWh/a), a technical potential of 3 GW (19 TWh/a) and

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[4] Temperatures of over 90°C allow for economically viable electricity generation.

no market potential under the current circumstances (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021).

8.2 Hydropower

Currently, between 3 and 4 percent of electricity in Germany is generated by hydropower plants with a capacity of 4.2 GW. For geographical reasons, the majority of plants is located in Bavaria. In general, the potential for hydropower generation in Germany is limited. Further, ecological and economic considerations have led to a decreased importance of hydropower in the German energy transition debates (Wissenschaftlicher Dienst Deutscher Bundestag 2022).

A study on Hydropower in Germany commissioned by the Federal Ministry for the Environment from2010 referred to in the Bundestag publication identifies a technical potential for an additional generation of 14.7 TWh/year. Of this, 10.75 TWh are classified as non-permittable due to ecological regulations. Modernization of existing plants could add a yearly generation of 2.7 TWh. Another study conducted for the Federal Ministry of Transport and Digital Infrastructure finds a realistically viable additional generation potential of 3.4 TWh (Wissenschaftlicher Dienst Deutscher Bundestag 2022).

(Wissenschaftlicher Dienst Deutscher Bundestag 2022)The current hydropower generation capacity in Korea stands at 6.5 GW, supplying 1.9 TWh of power in 2021. The government’s white paper identifies an additional 8.9 TWh of yearly hydropower generation potential. The potential is given as a market potential, reflecting regulatory and economic feasibility. 75% of this potential lie in four provinces (Gyeonggi-do, Gyeongsangnam-do, Gangwon-do, Gyeongsangbuk-do) (Power Technology 2023).

8.3 Ocean Energy

Due to the limited extent of its coastline and access to deep waters, Germany’s potential for the different types of ocean energy is evaluated as rather small by Forschungsverbund Erneuerbare Energien. It is, however, seen as a relevant contributor to the European electricity market and as a potential business opportunity for German enterprises in the field. The technical potential of wave energy in Europe is estimated to lie at around 1,200 TWh/a. The global potential for tidal energy is estimated at 1,500 TWh/a, 10 per cent of which are to be found in Europe (Forschungsverbund Erneuerbare Energien 2023). A 2010 study tasked by the German Ministry for the Environment and Nuclear Safety evaluates the theoretical potentials for all forms of ocean energy in Germany as negligible. As an example, a tidal dam with a yearly generation of 2 TWh was modelled. Due to the shallow sea off the country’s shores, water and wave pressures are unable to supply the required primary energy for existing plants (GKSS Forschungszentrum et al. 2010).

Korea, being surrounded by water in all but northern directions, is home to one of the world’s largest tidal power plants. The Sihwa Lake tidal range power plant, which is operated by Korea Water Resources Corporation, known as K-water, generates 552GWh of clean, green energy every year, replacing the equivalent of 862,000 barrels of oil a year (Edmond 2020).

In the white paper released by the Korean government, potentials of the different forms of ocean/marine energy are identified. The technical potential for different applications using tidal currents are estimated to be 83 GW of capacity converting into 679 TWh/a of energy. The technical potential for wave power generation in Korean waters is set at 46 TWh per year. Despite these impressive technical potentials, the market potential for all of these marine technologies is evaluated to be non-existent at this point (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021). This highlights the need to increase research and development and set up a conducive regulatory framework in order to unleash the potential of ocean energy generation off Korea’s shores.

8.4 Biomass

IRENA estimates in its energy profiles the theoretical biomass potential of a country by its average net primary productivity, which is “the amount of carbon fixed by plants and accumulated as biomass each year”. It is slightly higher with 6.5 tC/ha/yr for Korea than for Germany with 5.5 tC/ha/yr. Both countries’ values lie above the world average of 3-4 tC/ha/yr (International Renewable Energy Agency (IRENA) 2022b, 2022a).

In Germany’s energy system, biomass plays an important role due to its flexible applicability in many sectors of the economy. Currently, it supplies 52% of renewable energies’ contribution to the country’s final energy consumption (Umweltbundesamt 2023b). In 2022, 50.2 TWh of electricity and 169 KWh of heating were produced using biomass. A 2021 study states that biomass utilization could cover almost a quarter of Germany’s declining primary energy consumption in 2050, reaching an energy generation of 750 TWh (Fachagentur Nachwachsende Rohstoffe 2023). However, due to high land use per kWh generated and ecological concerns, the discourse in Germany around biomass is increasingly critical. This has led to a stagnating market share and some net-zero scenarios completely avoiding incorporating biomass energy generation into their forecasts (Umweltbundesamt 2023a). Nevertheless, biomass still plays a role in Germany’s future energy system as a backup for fluctuating solar and wind energy yields due to its flexibility (Fachagentur Nachwachsende Rohstoffe 2023).

Biomass could also contribute to Korea’s future energy system, potentially covering days of low wind speeds and low solar radiation. The white paper by the Korean government sets the technical potential for biomass-powered energy generation at 71.5 TWh per year. However, the current market potential reflecting economic feasibility and regulatory circumstances is only 3.1 TWh per year (Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021).

8.2 Comparison of other renewable potentials

As to be expected, the potentials for other renewable sources in Korea and Germany, again, vary depending on natural factors. For hydropower, estimated numbers for additional practical potential, taking environmental regulations into account, are 3 TWh for Germany and 9 TWh for Korea. For geothermal, biomass and ocean energy, estimates of different studies are difficult to compare, as no single study considered here looks at both Korea’s and Germany’s potentials and the underlying assumptions in the studies differ greatly.

For shallow geothermal energy technical potential identified by studies was higher in Korea with estimates at 932 TWh, compared to a still high number of 600 TWh for Germany. Consequently, shallow geothermal energy for heat pumps can play a decisive role in transforming the heating sector in both countries. When considering the current regulatory framework (practical potential), the estimate for Germany is between 145 and 186 TWh. For Korea, the number calculated by the white paper of the Korean government, additionally taking economic viability of a technology into account, is very low compared to the technical potential with around 30 TWh.

For deep geothermal, technical potentials were examined as up to 1,400 TWh in Germany but only 19 TWh for Korea. The practical potential for Germany is estimated to be between 50 TWh and 118 TWh annually while for Korea the white paper of the Korean government states no market potential at all under the current circumstances. The low estimates for Korea might be due to the very cautious approach taken after an earthquake at an enhanced geothermal exploration site in 2017.

While all forms of ocean energy are still pretty much a black box when it comes to their market potentials, it is clear that due to its larger marine area, Korea has far greater technical potentials in this regard. Due to the limited extent of its marine area and shallow waters, Germany's potential for the different types of ocean energy is evaluated as negligible. In Korea, on the other hand, the combined technical potential for various forms of ocean energy is estimated to be 725 TWh/a. Increased research and development and a conducive regulatory framework could unleash the potential of ocean energy generation off Korea's shores.

While Irena's estimates for the theoretical biomass potential of a country based on its average net primary productivity, are slightly higher for Korea than for Germany, the total estimated technical potential for biomass found in the literature is much higher for Germany than for Korea. This is likely to be explained primarily, again, by Germany's larger total land area.

9 Conclusion

Both Korea and Germany have a multitude of renewable energy solutions at their disposal. Looking at the numbers presented in the study, it becomes apparent that for both countries, domestic renewables can satisfy their current electricity needs and have the potential to meet a large part of their future energy needs. Achieving their respective net-zero goals will require government support for an accelerated roll-out of renewable solutions and accompanying infrastructure.

Looking at wind, solar as well as a range of other renewable energy sources, it becomes clear that both Korea and Germany are in a position to pick and choose from a range of renewable options with significant renewable energy potential. This result is good news, especially in light of the ambitious, but crucial net zero targets of both countries. These goals, alongside with Korea's and Germany's similar economic structure mean that both countries have comparable challenges in front of them. Considering the geographic contrasts between the countries, however, some differences with regards to renewable energy potential, and therefore also ideal policy and decarbonization choices, become apparent.

Regarding solar energy, Korea has general efficiency advantages due to a higher exposure to sunshine, while Germany has the bigger overall potential due to its larger land area. This difference in size alone means that Germany has a theoretical solar potential more than twice that of Korea. Focusing on more details and considering technical and practical feasibility, the potential for Germany is calculated to be between 1,155 and 7,438 TWh and between 513 TWh and 3,350 TWh for Korea. The comparison is, however, imperfect due to methodological differences between the studies. For instance, the overall potential of more than 3000 GW in Germany calculated by the aforementioned study by Fraunhofer (see 5.3.1) looks at a range of novel deployment options for solar energy, that are not included in some of the other studies, which could have led to the very high estimate for total potential. Importantly, however, both Korea and Germany would theoretically be able to cover most if not all of their current electricity needs using solar power alone, even when considering more cautious market-focused estimates. Additionally, the mean values of the estimates for solar energy potential for each country are exceeding the projected final energy consumption in their respective net zero year (1,468 TWh for Germany and 1,620 TWh for Korea).

When it comes to onshore wind power, estimates of potentials rely on more variables than in the case of solar energy. Therefore, differing regulatory and technical assumptions lead to an even wider range of overall potentials and the boundaries between technical and practical potentials are sometimes less clear. If technical and practical potentials are regarded together, the potential capacity in Germany lies between 200 and 2,086 GW which could translate to a yearly generation of between 770 TWh and 7,822 TWh (see 6.4). Thus, with the current political framework the practical onshore wind potential could supply more than half of Germany's projected final energy consumption in 2045. Technical potentials exceed the projected energy consumption many times over. For Korea, the highest estimate for a technical potential is 352 GW, converting to 781 TWh of annual electricity generation, while the lowest estimate for practical market potential is only 24 GW leading to an electricity generation of 52 TWh/year (see 6.3.2). While these numbers for Germany and Korea stem from different studies using diverse approaches, it is evident that Germany has a larger technical potential for onshore wind energy. This difference can be explained by the very different geographic circumstances between both countries. Korea's land area is largely covered by forested mountains and flat parts are occupied by large cities. Germany has comparatively many flat areas with a low population density and higher average wind speeds. The realistic level of implementation of the technical onshore wind potential is dependent on conservation areas and political decisions about the respective country's regulatory framework, such as minimum distances, and wider economic conditions for the expansion of onshore wind energy.

Concerning offshore wind power, the situation between Germany and Korea differs due to the different geographies of both countries, as well. Germany has higher average wind speeds (9-10 m/s compared to 7-8.5 m/s in Korea), but it only has a comparably short coastline and a limited marine territory, while Korea faces the opposite situation, being almost completely surrounded by water (German marine area: ca. 57,000 km^2; Korean marine area: 443,000 km^2). Germany has favorable conditions for installing proven and relatively cheap fixed-bottom wind turbines due to its shallow waters. Korean waters are suitable for fixed-bottom solutions near the west and south coast, while off the east coast and areas further from the shore, wind energy expansion will be reliant on novel floating wind turbines (see 7.2). For Korea, estimates for the technical potential range from 990 to 3,710 TWh (870 GW) of yearly generation. Meanwhile, for Germany, technical potentials are evaluated at 203 GW capacity and 940 TWh of generation at the maximum (see 7.4). Most studies look at the practical potential for Germany, which is especially limited by the large areas that are under nature protection. Estimates for the practical potential range from 50 to 84 GW, which is close to the government's aim of 70 GW by 2045. This shows that despite higher wind speeds than in Germany, Korea's offshore wind potential is far greater, especially once floating turbines decrease in costs.

Germany appears to have a larger geothermal potential, with the relatively established market for shallow geothermal heat pumps promising an overall technical potential of 600 TWh and estimates for deep geothermal of up to 1,400 TWh. When considering the current regulatory framework, the practical potential is estimated between 145 and 186 TWh for shallow geothermal and between 50 TWh and 118 TWh for deep geothermal energy. For Korea, the whitepaper has estimated the technical potential of shallow geothermal at 932 TWh, but calculates only 30 TWh as market potential. For deep geothermal energy it estimates the technical potential to be only at 19 TWh and the market potential to be non-existent (see 8.1).

A wild card for the future energy systems could be the development of ocean energy technologies. While Germany has only negligible potentials due to its limited marine area and shallow waters, Korea's calculated technical potential of 725 TWh could become an asset to the country's future energy independence and its decarbonized economy if research and development and a conducive regulatory framework is implemented to increase the market potential of ocean energy (see 8.3).

While potentials for hydropower are mostly fulfilled in both countries, studies have identified an additional practical generation potential of 3.4 TWh/a for Germany and 8.9 TWh/a for Korea (see 8.2).

Although estimates for the theoretical biomass potential of a country based on its average net primary productivity, are slightly higher for Korea than for Germany, the total estimated technical potential for biomass found in the literature is much higher for Germany than for Korea (750 TWh/year compared to 71.5 TWh/year). This is likely to be explained primarily, again, by Germany's larger total land area as well as different underlying assumptions of the calculations.

In summary, Germany has advantages because of its larger land area when it comes to renewable energy deployment, especially for solar and onshore wind, while Korea has advantages for offshore wind and a potential future expansion of ocean energy solutions because of its larger marine area.

Both countries have a similar level of overall energy consumption despite Germany's larger size, economy, and population, which can be attributed largely to Germany's better energy efficiency. Per unit of GDP (PPP), Germany consumes almost half the energy Korea does, while Germany's electricity consumption per capita is around 70% of Korea's (see 3). Learning from Germany's path of energy intensity reduction could therefore be a way for Korea to reduce the need for additional renewable expansion towards its net zero goal. This is especially relevant with increased electrification in other sectors leading to higher overall electricity demand in both countries. However, it is even more relevant in Korea with projections anticipating on average 1,620 TWh of final energy consumption compared to Germany's 1,468 TWh (see 3.). Some key parameters regarding energy consumption and renewable energy potentials are visualized in Table 1 below.

Despite the significant renewable potentials in Korea and Germany, both countries will likely still import some energy for reasons of technical viability and economic efficiency. This especially concerns the expected rising demand for clean hydrogen and its derivates for decarbonizing industry and transport sectors. While the different scenario studies and government plans consulted here vary significantly in their assumptions regarding the use of hydrogen, all project a significantly rising demand. Consequently, energy will still be imported both by Germany in Korea in their respective net-zero years. Nevertheless, overall import dependence would become much smaller through the realization of existing renewable potentials compared to today with both Germany (except for lignite) and Korea importing almost all of their fossil fuels in 2021 (Clean Energy Wire 2023; EIA 2023).

What this study shows is that neither Germany nor Korea need to be worried about a lack of renewable potential to power them on their way to net zero and beyond. With a policy mix aimed at ensuring a rapid expansion and integration of renewable sources, electrification and improved energy efficiency, net zero comes within reach. The crucial task for governments on all levels in both countries is, to implement such a policy mix and ensure that they are able to deliver net zero – in order to slow down climate change, reduce future damages and kick-start the green economy of the future.

Table 1: Energy consumption and parameters for renewable energy potentials in Korea and Germany

	Germany	**Korea**
Electricity Consumption 2022/2021	550 TWh	554 TWh
Projected Final Energy Consumption Net Zero Year[1]	1,468 TWh	1,620 TWh
Projected Electricity Consumption Net Zero Year[2]	1,041 TWh	1,212 TWh
Combined Currently installed Solar & Wind Energy Capacity	133 GW	27 GW
Combined 2030 Targets Solar & Wind Capacity	330 GW	73 GW
Theoretical Solar PV Potential per day (Global Solar Atlas data)	2.68 kWh/m^2	3.99 kWh/m^2
Average wind speeds (onshore)[3]	8.45 m/s	7.35 m/s
Mean power density wind (onshore)	595 W/m2	552 W/m2
Size of Marine Area	57,000 km2	443,000 km2
Range of average wind speeds (offshore)	9 – 10 m/s	7 – 8.5 m/s

[1] [2] Numbers are averages of different studies' projections.

[3] Average wind speeds in the 10% windiest areas of the respective country's surface.

Data sources: (Ariadne 2021), (Prognos et al. 2021), (Deutsche Energie-Agentur GmbH (dena) 2021), (Bundesverband der deutschen Industrie (BDI) 2021), (Green Energy Strategy Institute et al. 2022), (International Energy Agency (IEA) and

Korean Energy Economics Institute (KEEI) 2021), (World Bank Group et al. 2023), (MOLIT 2023), (Marine Conservation Institute 2023), (Ministry of Trade, Industry and Energy (MOTIE) 2023), (Bundesministerium für Wirtschaft und Klimaschutz (BMWK) 2022)

Bibliography

Agentur für Erneuerbare Energien 2023: Tiefengeothermie. Retrieved 15 May 2023, from https://www.unendlich-viel-energie.de/erneuerbare-energie/erdwaerme/tiefengeothermie#:~:text=Als%20Tiefengeothermie%20bezeichnet%20man%20die,auch%20f%C3%BCr%20die%20Stromerzeugung%20nutzbar.

Agora Energiewende; Agora Verkehrswende; Technical University of Denmark (DTU) and Max-Planck-Institute for Biogeochemistry, Biospheric Theory and Modeling 2020: Making the Most of Offshore Wind. Re-Evaluating the Potential of Offshore Wind in the German North Sea.

Ariadne 2021: Deutschland auf dem Weg zur Klimaneutralität 2045. Szenarien und Pfade im Modellvergleich 2021.

Ariadne 2022: Deutschland auf dem Weg zur Klimaneutralität 2045. Szenarien und Pfade im Modellvergleich 2022.

Bellini, Emiliano 2022: South Korea installed 4.4 GW of PV capacity in 2021. Retrieved 10 May 2023, from https://www.pv-magazine.com/2022/01/10/south-korea-installed-4-4-gw-of-pv-capacity-in-2021/.

Bellini, Emiliano 2023: South Korea cuts capacity allocations from 4 GW to 2 GW in solar tenders. Retrieved 10 May 2023, from https://www.pv-magazine.com/2023/03/28/south-korea-cuts-capacity-allocations-from-4-gw-to-2-gw-in-solar-tenders/.

BloombergNEF 2021: Solar Power to Retain Lead in South Korea’s Green Plans. Retrieved 10 May 2023, from https://about.bnef.com/blog/solar-power-to-retain-lead-in-south-koreas-green-plans/.

Born, Holger; Rolf Bracke; Timm Eicker and Michael Rath 2022: Roadmap Oberflächennahe Geothermie. Erdwärmepumpen für die Energiewende - Potenziale, Hemmnisse und Handlungsempfehlungen: Fraunhofer-Gesellschaft IEG.

Bundesministerium für Wirtschaft und Klimaschutz (BMWK) 2022: Überblickspapier Osterpaket. Berlin:

Bundesministerium für Wirtschaft und Klimaschutz (BMWK) 2023: Installierte Leistung (kumuliert) der Photovoltaikanlagen in Deutschland in den Jahren 2000 bis 2022 (in Megawattpeak). Retrieved 10 May 2023, from https://de.statista.com/statistik/daten/studie/13547/umfrage/leistung-durch-solarstrom-in-deutschland-seit-1990/.

Bundesregierung 2023: Mehr Energie aus erneuerbaren Quellen. Retrieved 10 May 2023, from https://www.bundesregierung.de/breg-de/themen/klimaschutz/energiewende-beschleunigen-2040310#:~:text=Bis%202030%20Wind-%20und%20Solarstrom%20verdoppeln&text=Bis%202030%20soll%20der%20Bruttostromverbrauch,als%20zehn%20Jahren%20fast%20verdoppeln.

Bundesverband der deutschen Industrie (BDI) 2021: Klimapfade 2.0. Ein Wirtschaftsprogramm für Klima und Zukunft.

Clean Energy Wire 2023: Germany, EU remain heavily dependent on imported fossil fuels. Retrieved 04 Aug 2023, from https://www.cleanenergywire.org/factsheets/germanys-dependence-imported-fossil-fuels#:~:text=In%20the%20midst,a%20key%20solution.

Conexio GmbH 2021: 36. PV-Symposium BIPV-Forum 18.-26. Mai 2021. Tagungsunterlagen.

Deutsche Energie-Agentur GmbH (dena) 2021: dena-Leitstudie Aufbruch Klimaneutralität.

Deutsches Institut für Wirtschaftsforschung (DIW) 2018: GENeSYS-MOD v2.0 – Enhancing the Global Energy System Model. Model Improvements, Framework Changes, and European Data Set.

Edmond, Charlotte 2020: A new tidal energy project just hit a major milestone in Scotland. World Economic Forum. Retrieved 10 May 2023, from https://www.weforum.org/agenda/2020/01/tidal-renewable-energy-turbine-electricity-generation-scotland/.

EIA 2023: Country Analysis Brief: South Korea.

Ember 2023: Global Electricity Review 2023.

Enerdata 2023a: Germany Energy Information. Retrieved 10 May 2023, from https://www.enerdata.net/estore/energy-market/germany/.

Enerdata 2023b: South Korea Energy Information. Retrieved 10 May 2023, from https://www.enerdata.net/estore/energy-market/south-korea/#:~:text=Electricity%20consumption%20increased%20by%205,2018%20(2.2%25%2Fyear).

Enerdata 2023c: South Korea targets 34.6% nuclear and 30.6% renewable power generation in 2036. Retrieved 10 May 2023, from https://www.enerdata.net/publications/daily-energy-news/south-korea-targets-346-nuclear-and-306-renewable-power-generation-2036.html#:~:text=South%20Korea%20targets%2034.6%25%20nuclear,power%20generation%20in%202036%20|%20Enerdata&text=The%20most%20comprehensive%20and%20up-to-date%20annual%20energy%20database.

Enerdata 2023d: Total energy consumption. Retrieved 04 Sep 2023, from https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html.

Environmental Performance Index 2023: Air Quality. Retrieved 10 May 2023, from https://epi.yale.edu/epi-results/2022/component/air.

ESMAP 10.05.2023: Offshore Wind Technical Potential. Analysis and Maps. Retrieved 10 May 2023, from https://www.esmap.org/esmap_offshorewind_techpotential_analysis_maps.

Fachagentur Nachwachsende Rohstoffe 2023: Bioenergie: Biomasse-Potenziale. Retrieved 15 May 2023, from https://bioenergie.fnr.de/bioenergie/biomasse/biomasse-potenziale/.

Forschungsverbund Erneuerbare Energien 2023: Meeresenergie – Wie funktioniert das? Retrieved 26 Jun 2023, from https://www.fvee.de/forschung/energiebereitstellung/meeresenergie.

Fraunhofer-Institut für Energiewirtschaft und Energiesystemtechnik (Fraunhofer IEE) 2022: Flächenpotenziale für die Windenergie an Land. Retrieved 15 May 2023, from https://www.iee.fraunhofer.de/de/presse-infothek/Presse-Medien/2022/flaechenpotenziale_windenergie_an_land.html.

Fraunhofer-Institut für Windenergiesysteme (Fraunhofer IWES) 2012: Windenergie Report Deutschland 2011.

Fraunhofer-Institut für Windenergiesysteme (Fraunhofer IWES) 2022: Offshore Flächenpotenziale: Analyse der Energieerzeugungseffizienz in der deutschen AWZ. Studie im Auftrag des BWO und BDEW.

GKSS Forschungszentrum; ECOFYS and Greater Good Science Center (GGSC) 2010: Nutzung der Meeresenergie in Deutschland. Endbericht.

Global Wind Energy Council 2021a: Offshore Wind: Technical Potential in Germany. Retrieved 26 Jun 2023, from https://gwec.net/wp-content/uploads/2021/06/Germany_Offshore-Wind-Technical-Potential_GWEC-OREAC.pdf.

Global Wind Energy Council 2021b: Offshore Wind: Technical Potential in Korea. Retrieved 26 Jun 2023, from https://gwec.net/wp-content/uploads/2021/06/South-Korea_Offshore-Wind-Technical-Potential_GWEC-OREAC.pdf.

Global Wind Energy Council 2022: Global Offshore Wind Report 2022.

Green Energy Strategy Institute; Institute for Green Transformation; NEXT Group and Agora Energiewende 2022: 2050 Climate Neutrality Roadmap for Korea. K-Map Scenario. Agora.

International Energy Agency (IEA) 2019: Offshore Wind Outlook 2019. Special Report.

International Energy Agency (IEA) and Korean Energy Economics Institute (KEEI) 2021: Reforming Korea’s Electricity Market for Net Zero.

International Renewable Energy Agency (IRENA) 2022a: Energy Profile Germany.

International Renewable Energy Agency (IRENA) 2022b: Energy Profile Republic of Korea.

Jochum, Patrick; Julia Lempik; Saskia Böttcher; Dennis Stelter; Tobias Krenz; Peter Mellwig; Martin Pehnt; Amany von Oehsen; Sebastian Blömer and Hans Hertle 2017: Ableitung eines Korridors für den Ausbau der eneuerbaren Wärme im Gebäudebereich. Enbericht: Beuth Hochschule für Technik Berlin, Institut für Energie- und Umweltforschung Heidelberg (ifeu).

Jung, Woosuk 2017: South Korea’s Air Pollution. Retrieved 10 May 2023, from https://www.isdp.eu/publication/south-koreas-air-pollution-gasping-solutions/.

Korea Energy Economics Institute (KEEI) 2018: Energy News. Retrieved 10 May 2023, from http://www.keei.re.kr/main.nsf/index_en.html?open&p=%2Fweb_keei%2Fen_news.nsf%2FXML_Portal%2F268d0d3a7500bcfc4925836d00257938&s=%3FOpenDocument%26menucode%3D%26category%3D%25EC%2597%2590%25EB%2584%2588%25EC%25A7%2580%25EB%2589%25B4%25EC%258A%25A4%26Click%3D.

Korean New and Renewable Energy Center (KNREC) and Ministry of Trade, Industry and Energy (MOTIE) 2021: New and Renewable Energy White Paper 2020. (Korean).

Kost, Christoph; Shivenes Shammugam; Verena Fluri; Dominik Peper; Aschkan Davoodi Memar and Thomas Schlegl 2021: Levelized cost of electricity renewable energy technologies: Frauenhofer ISE.

Lee, Keun-Yeong 2022: South Korea's solar power generation exceeds 7%. Retrieved 26 Jun 2023, from https://www.hani.co.kr/arti/society/environment/1055687.html.

Lee, Seok-Ho and Sangmin Jo 2018: Estimating solar market potential and analyzing implementation costs considering regional economics: Korea Energy Economics Institute.

Lu, Xi; Michael B. McElroy and Juha Kiviluoma 2009: Global potential for wind-generated electricity. In: Proceedings of the National Academy of Sciences of the United States of America 106:27, pp 10933–10938.

Lütkehus, Insa; Hanno Salecker and Kirsten Adlunger 2013: Potenzial der Windenergie an Land. Dessau-Roßlau: Umweltbundesamt.

Lutz, Christian; Markus Flaute; Ulrike Lehr; Andreas Kemmler; Almut Kirchner; Alex auf der Maur; Inka Ziegenhagen; Marco Wünsch; Sylvie Koziel; Alexander Piégsa and Samuel Straßburg 2018: Gesamtwirtschaftliche Effekte der Energiewende: Fraunhofer ISI; Prognos; Deutsches Zentrum für Luft- und Raumfahrt; Deutsches Institut für Wirtschaftsforschung; Gesellschaft für wirtschaftliche Strukturforschung.

Marine Conservation Institute 2023: Marine Protection Atlas. Retrieved 26 Jun 2023, from https://mpatlas.org/countries/DEU/.

Ministry of Trade, Industry and Energy (MOTIE) 2023: Announcement of the 10th Basic Plan for Electricity Supply and Demand (2022~2036). Retrieved 22 May 2023, from https://www.motie.go.kr/motie/ms/nt/announce3/bbs/bbsView.do?bbs_seq_n=68162&bbs_cd_n=6&currentPage=1&search_key_n=&cate_n=&dept_v=&search_val_v=&biz_anc_yn_c=.

MOLIT 2023: Offshore Practice Q&A. Retrieved 02 Aug 2023, from https://www.molit.go.kr/USR/policyTarget/dtl.jsp?idx=203.

Pape, Carsten; David Geiger; Christoph Zink; Miron Thylmann; Wolfgang Peters and Silvio Hildebrandt 2022: Flächenpotenziale der Windenergie an Land 2022: Frauenhofer IEE; bosch & partner.

Park, Won Young; Nikit Abhyankar; Paliwal Umed; James Hyungkwan Kim; Nina Khanna; Kenji Shiraishi; Jiang Lin; Amol Phadke; Yong Hyun Song; Hee Seung Moon; Eunsung Kim; Sanghyun Hong and Seung Wan Kim 2023: A Clean Energy Korea by 2035. Transitioning to 80% Carbon-Free Electricity Generation: NEXT Group; Lawrence Berkeley National Laboratory; University of California.

Power Technology 2023: Hydropower capacity in South Korea and major projects. Retrieved 15 May 2023, from https://www.power-technology.com/data-insights/hydropower-in-south-korea/.

Prognos 2016: Eigenversorgung aus Solaranlagen. Das Potenzial für Photovoltaik-Speicher-Systeme in Ein- und Zweifamilienhäusern, Landwirtschaft sowie im Lebensmittelhandel.

Prognos; Öko-Institut and Wuppertal-Institut 2021: Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann.

Rechner Online 2023: Photovoltaik - Größe einer Freiflächenanlage MWp/ha. Retrieved 15 Sep 2023, from https://rechneronline.de/photovoltaik/freiflaeche.php.

Richter, Manuela 2023: 2022 Country Report Germany: IEA Geothermal.

Ritchie, Hannah; Max Roser and Pablo Rosado 2020a: CO_2 and Greenhouse Gas Emissions. Retrieved 10 May 2023, from https://ourworldindata.org/co2/country/germany.

Ritchie, Hannah; Max Roser and Pablo Rosado 2020b: CO_2 and Greenhouse Gas Emissions. Retrieved 10 May 2023, from https://ourworldindata.org/co2/country/south-korea.

Ritchie, Hannah; Max Roser and Pablo Rosado 2022: Energy. Retrieved 26 Jun 2023, from https://ourworldindata.org/renewable-energy.

Sieler, Roman Eric 2022: Offshore Wind. Achieved Cost Reductions in Germany. Berlin: adelphi.

Song, Yoonho and Tae Jong Lee 2022: 2021 Republic of Korea Country Report: IEA Geothermal.

Southern Environmental Law Center 2022: Satellite images show link between wood pellet demand and increased hardwood forest harvesting.

Stiftung Klimaneutralität 2021: Photovoltaik Potentiale. Literaturrecherche. Berlin: Stiftung Klimaneutralität.

Stiftung Klimaneutralität 2022: Szenarienvergleich. Retrieved 26 Jun 2023, from https://www.stiftung-klima.de/de/themen/klimaneutralitaet/szenarienvergleich/.

Tagesschau 2023: Nordsee-Anrainer setzen auf Ausbau der Windkraft. Retrieved 10 May 2023, from https://www.tagesschau.de/wirtschaft/windkraft-gipfel-105.html.

Thomas, Klaus; Carla Vollmer; Kathrin Werner; Harry Lehmann and Klaus Müschen 2010: Energieziel 2050. 100% Strom aus erneuerbaren Quellen. Rosslau: Umweltbundesamt.

U.S. Energy Information Administration 2022: Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022.

Umweltbundesamt 2023a: Bioenergie. Retrieved 22 May 2023, from https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/bioenergie#bioenergie-ein-weites-und-komplexes-feld-.

Umweltbundesamt 2023b: Erneuerbare Energien in Zahlen. Retrieved 10 May 2023, from https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#uberblick.

Umweltbundesamt 2023c: Photovoltaik. Retrieved 10 May 2023, from https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/photovoltaik#photovoltaik.

Umweltbundesamt 2023d: Windenergie an Land. Retrieved 10 May 2023, from https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/windenergie-an-land#flaeche.

Welder, Lara; Neil Grant; Tina Aboumhaboub; Jonas Hörsch; Victor Maxwell and Claire Fyson 2023: Clean power in South Korea. A roadmap to zero fossil gas in South Korea’s power sector.

Wirth, Harry 2023: Aktuelle Fakten zu Photovoltaik in Deutschland: Frauenhofer ISE.

Wirth, Harry; Christoph Kost; Korbinian Kramer; Holger Neuhaus; Dominik Peper; Jochen Rentsch and Charlotte Senkspiel 2021: Solaroffensive für Deutschland. Wie wir mit Sonnenenergie einen Wirtschaftsboom entfesseln und das Klima schützen: Frauenhofer ISE; Greenpeace.

Wissenschaftlicher Dienst Deutscher Bundestag 2022: Zu Ausbaupotentialen der Wasserkraft in Deutschland.

World Bank; ESMAP; VORTEX and Technical University of Denmark (DTU) 2023: Global Wind Atlas. Retrieved 26 Jun 2023, from https://globalwindatlas.info/en/area/South%20Korea.

World Bank Group; Energy Sector Management Assistance Program (ESMAP) and SOLARGIS 2023: Global Solar Atlas 2.0.

World Bank Open Data 2023: GDP per unit of energy use (PPP $ per kg of oil equivalent). Retrieved 22 May 2023, from https://data.worldbank.org/indicator/EG.GDP.PUSE.KO.PP?locations=DE-KR.

List of Figures

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