Wind and solar benchmarks for a 1.5°C world

Developing national-level benchmarks to achieve renewables deployment in line with the Paris Agreement

Germany

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Executive Summary

Context

- In 2023, nearly half of Germany's electricity came from fossil fuels. Per capita emissions were above the global average.
- Wind (27%) became the largest single contributor to electricity generation, marginally surpassing coal (26%). The share of wind and solar (39%) is 3x that of the global average (13%).
- As part of its RE law, Germany aims to achieve more than 80% of electricity through renewables by 2030, and 100% by 2035. The country's Climate Law has set ambitious total net zero emissions target for 2045, which includes clearly defined annual build-out targets enshrined in law.
- This implies a complete phase-out of coal in the next decade, although the pace of fossil fuel phase-out is less clear and remains controversial.
- This report examines the wind and solar capacity installation Germany needs for a 1.5°C compatible pathway, aligning with the goal of tripling renewables by 2030.

Key findings

- By 2030, Germany's wind and solar generation must more than triple from 2022 levels, with wind capacity more than doubling and solar capacity almost quadrupling.
- Rollout projections show solar meeting the 250 GW benchmark, but wind falling short of the 145 GW benchmark.
- Germany's wind and solar 2030 targets broadly align with the 1.5°C benchmarks.
- Over the rest of this decade, annual capacity additions need to grow almost 5x on average for wind and almost triple for solar. The country has achieved comparable deployment rates in the past for wind, showing that these benchmarks are achievable.
- Despite a recent slowdown, our modelling predicts wind power will continue to generate more electricity than solar, consistent with country studies and government efforts to promote wind power.
- Fossil fuel phase-out in the next decade is crucial for meeting national targets and ensuring alignment with 1.5°C wind and solar benchmarks; our analysis suggests the share of fossil fuels must decrease by 68-76% by 2030.

Context

At COP28, governments agreed to triple global renewable capacity by 2030 globally. This report highlights the potential implications of this COP28 decision at the national level, focusing on **Germany**.

Wind and solar deployment is accelerating around the world. However, expected wind and solar capacity deployment under current policies falls short of what is needed for 1.5°C, and is concentrated mainly in a few regions.

Research is needed to understand the pace of wind and solar deployment that aligns with the highest possible ambition and is compatible with 1.5°C

This project aims at answering the following questions:

- **How much wind and solar generation is needed (TWh) at the national level?**
- **How much wind and solar needs to be built (GW of capacity)?**
- **When does it need to be built by?**

Summary of our method

Our method takes a series of steps to calculate the wind and solar generation needed for 1.5°C, and the resulting capacity deployment. The key methodological steps are highlighted below.

1. We project future electricity demand in the country.
2. We calculate the pace of fossil fuel phase-out needed to align with 1.5°C.
3. Bringing these trajectories together defines the level of clean electricity generation required to meet electricity demand growth while phasing out fossil fuels in the power sector.
4. We project non- wind and solar clean electricity generation based on country-level literature. This allows us to identify the wind and solar generation necessary to align with 1.5°C.
5. Having produced this wind and solar generation trajectory, we feed it into a simplified electricity system model, which calculates for a given set of cost assumptions around wind and solar, a split into wind versus solar and the associated capacity requirements.

Our method is focused on including multiple different analytical elements

Integrating multiple different elements

High-ambition country-level studies

Use ambitious country-level studies as inputs to inform key parameters of the methodology

1.5°C compatible IPCC global pathways

Link to global goal of tripling renewable capacity by 2030

Renewable energy potential and power system analysis

Capture local potential for wind and solar

Key global milestones

Include key global guardrails on the pace of fossil phase-out and the level of electrification

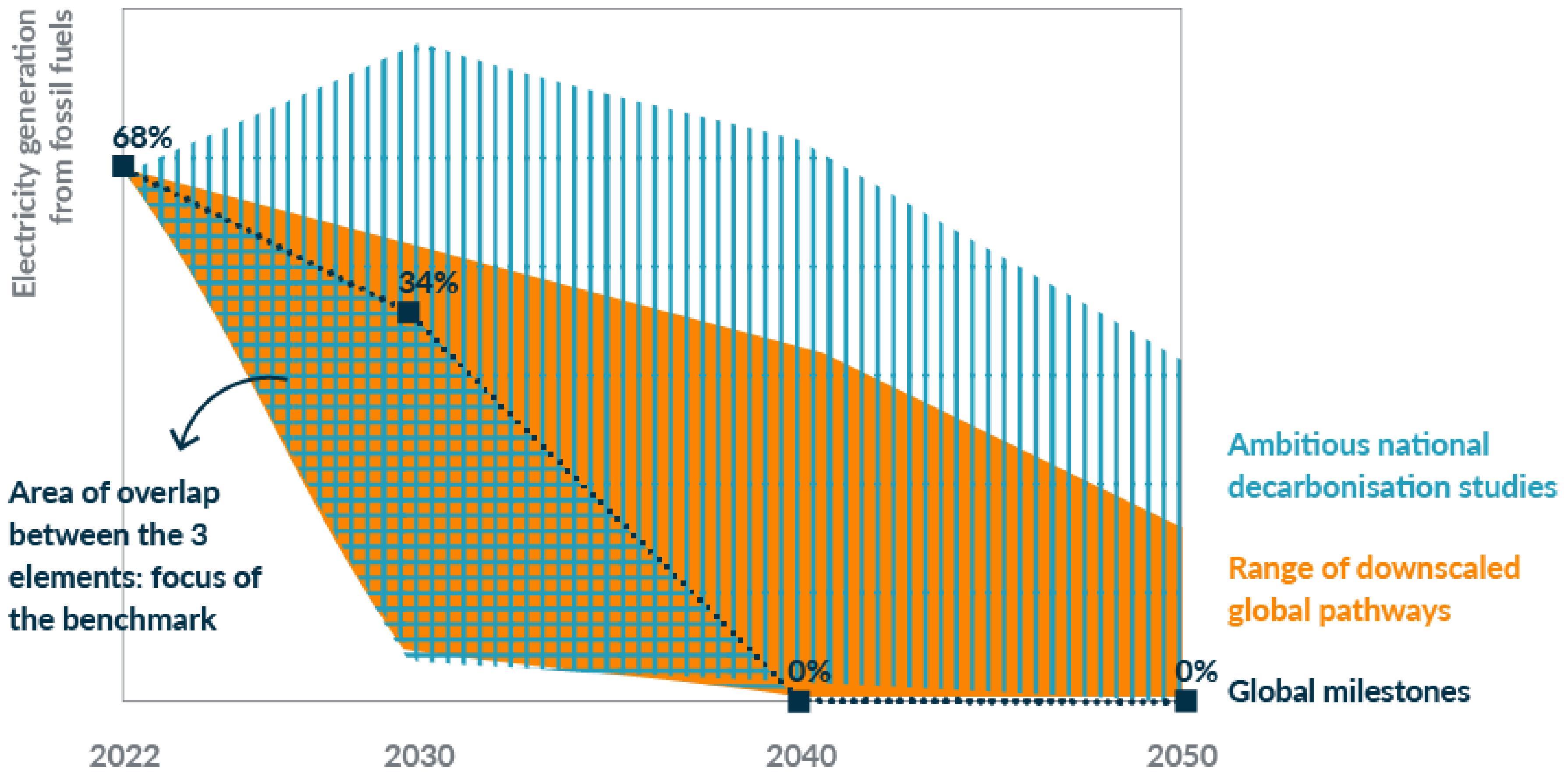
For more details see the Methods Annex

Overlap of different elements

Our method focuses on the overlap between different elements. By looking at the range of fossil phase-out which is outlined in both high ambition country-level studies and downscaled 1.5°C compatible global pathways, and is informed by key global milestones, we identify benchmarks which are both consistent with a global least cost pathway to limiting warming to 1.5°C but are also aligned with national–level modelling.

Combining multiple different analytical elements can help identify the most robust path to achieving a zero-carbon energy system.

Overlapping multiple analytical elements can provide more robust benchmarks



National enabling factors

Key enabling factors for ambitious wind and solar rollout include:

- **Institutional capacity.** A rapid build-out of wind and solar will require the governance and institutional capacity to develop, implement and enforce policy frameworks.
- **Just transition.** A just transition will be needed to take along all stakeholders, particularly those employed by the fossil economy.
- **Grid development.** Substantial increases in both transmission and distribution grid infrastructure will be necessary to integrate large-scale new wind and solar generation into the power system.
- **Fossil phaseout.** Existing fossil fuel infrastructure often will need to be retired earlier than its economic lifetime. Policies need to be developed to achieve the early phase out of fossil fuel plants.
- **System flexibility.** Energy storage (diurnal and seasonal), flexible generation technologies such as hydro and geothermal, and increased demand side flexibility will all be crucial.
- **Market design.** Reform of market designs and regulation to incentivize and mobilise investments to install renewable energy at the scale needed (e.g., minimise cost of capital, ensure revenue certainty, etc)

Policy context

Germany's current NDC is to reduce emissions to at least 65% below 1990 levels by 2030, **a 53% reduction on 2010 levels** excluding LULUCF. The country has a net zero target for 2045.

Germany's current renewable targets are to reach **215 GW of solar and 145 GW of wind by 2030**, as per the Renewable Energy Sources Act (EEG 2023) and the Windenergie-auf-See-Gesetz (WindSeeG), released by the German government. Build out targets are separated by year and technology (including on and offshore wind). In total the law aims for a minimum generation share of 80% from RE by 2030.

Under current policies and market conditions, the IEA estimates that **solar capacity will reach 181 GW in 2028**, up from 67 GW of solar in 2022. Meanwhile, **wind capacity is projected to reach 99 GW in 2028**, up from 66 GW in 2022.

Results

Future electricity demand

Electricity demand is taken from the Szenarienvergleich der “Big 5” Klimaneutralitätsszenarien study comparing net zero pathways by 2045 for Germany, in line with the German net zero target. We take demand from the BMWK’s LFS TN Strom pathway, which achieves net zero CO_2 emissions by 2045.

Total electricity generation in Germany almost doubles by 2050 relative to 2020 levels, reaching 1,000 TWh. This is driven mainly by increased electrification.

Generally, studies in Germany that evaluate the 2045 targets tend to largely agree on the expected electricity generation in 2045 ranging from 910 TWh to 1,200 TWh, according to a comparison between the most relevant scenarios. The growth in electricity demand due to electrification drives the expected growth of RE significantly. Our demand estimate is in the middle of the presented range.

Pace of fossil phaseout needed

The rate of fossil phase-out is set by the overlap between the bottom-up country-level studies and the downscaled 1.5°C compatible global pathways and the global milestones of the IEA's Net Zero roadmap, in which Germany achieves a clean power system by 2035.

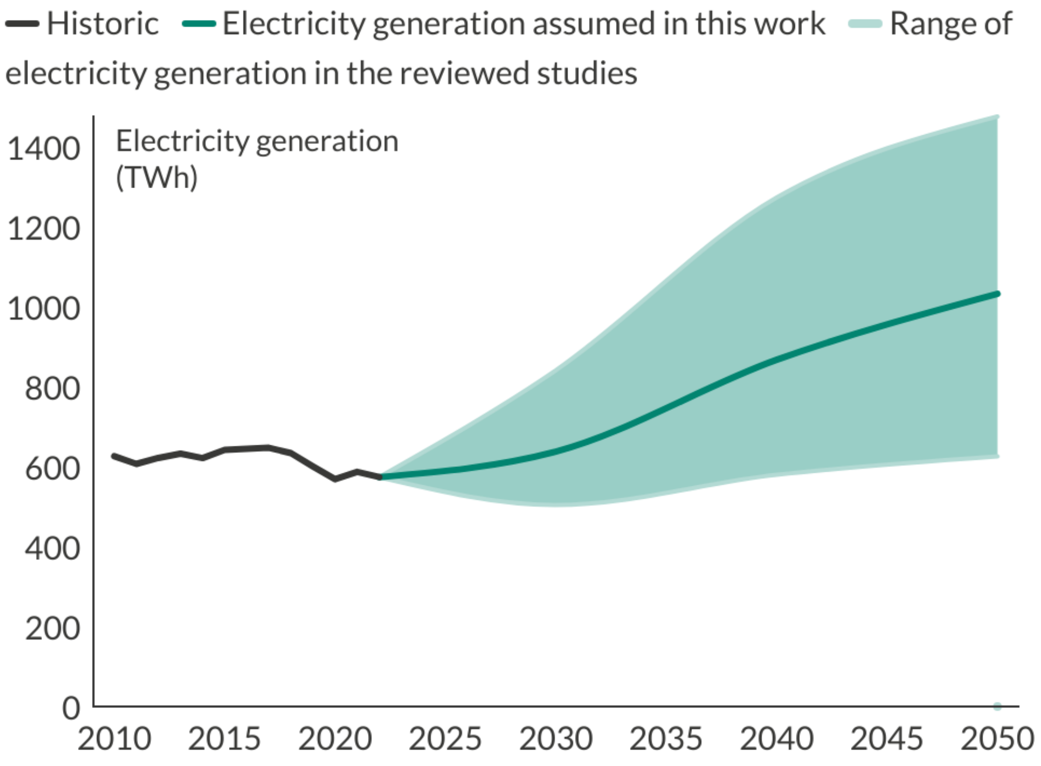
To align with 1.5°C, fossil fuels must exit the German power sector during the 2030s.

The time frame until 2030 is critical. Fossil fuel generation needs to fall by 68-76% by 2030, compared to 2022 levels.

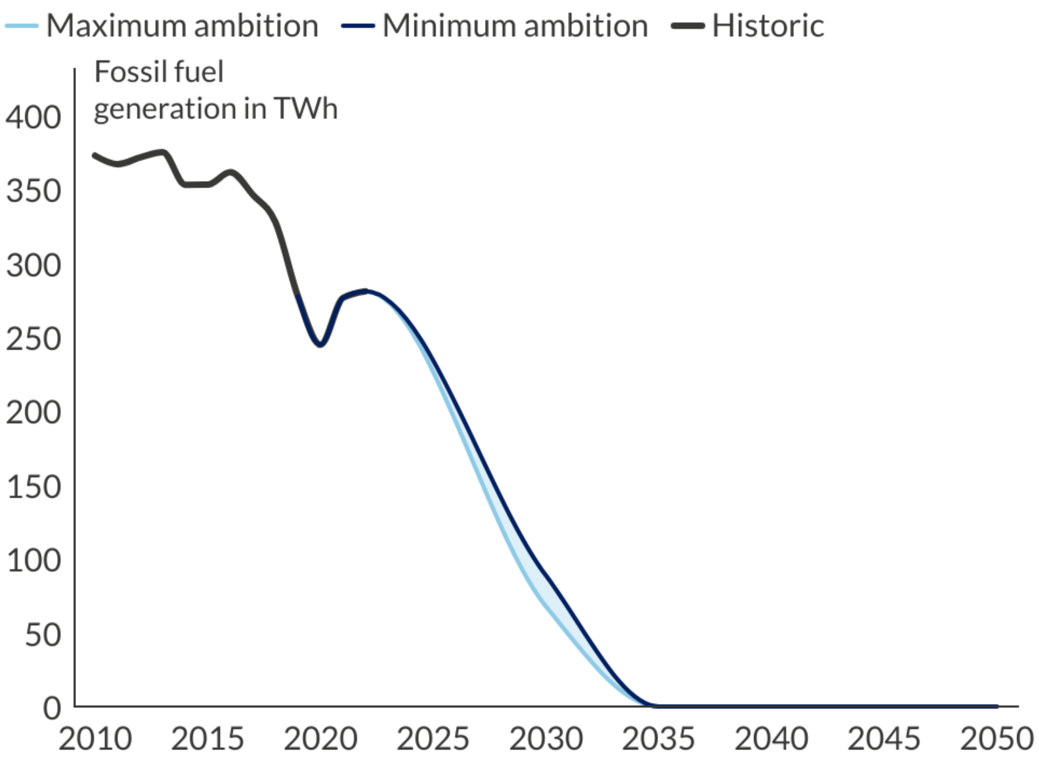
The fastest rate of fossil phase-out is set by the Fraunhofer et al. study (Langfristszenarien für die Transformation des Energiesystems in Deutschland).

To align with 1.5°C, fossil fuels must exit the power sector in Germany by 2035, while growing electricity demand

Electricity generation almost doubles in Germany over 2022–2050



Germany would need to achieve clean electricity by 2035



The role of other clean electricity generation

While wind and solar will be the workhorse of the energy transition, other clean electricity generation may play a role, particularly in certain countries. We estimate the role of non-wind and solar clean electricity generation* (largely hydro, biomass, nuclear and geothermal) from country-level studies.

In our modelling, we assume that generation from non- wind and solar clean technologies in Germany would reach 45 TWh by 2030 and 55 TWh by 2050. This is provided by nuclear, hydrogen, biomass, and other renewable technologies.

* We do not consider CCS in the power sector, as we do not consider CCS a viable source of large-scale emissions reductions in the power sector.

Total wind and solar generation needed to align with 1.5°C

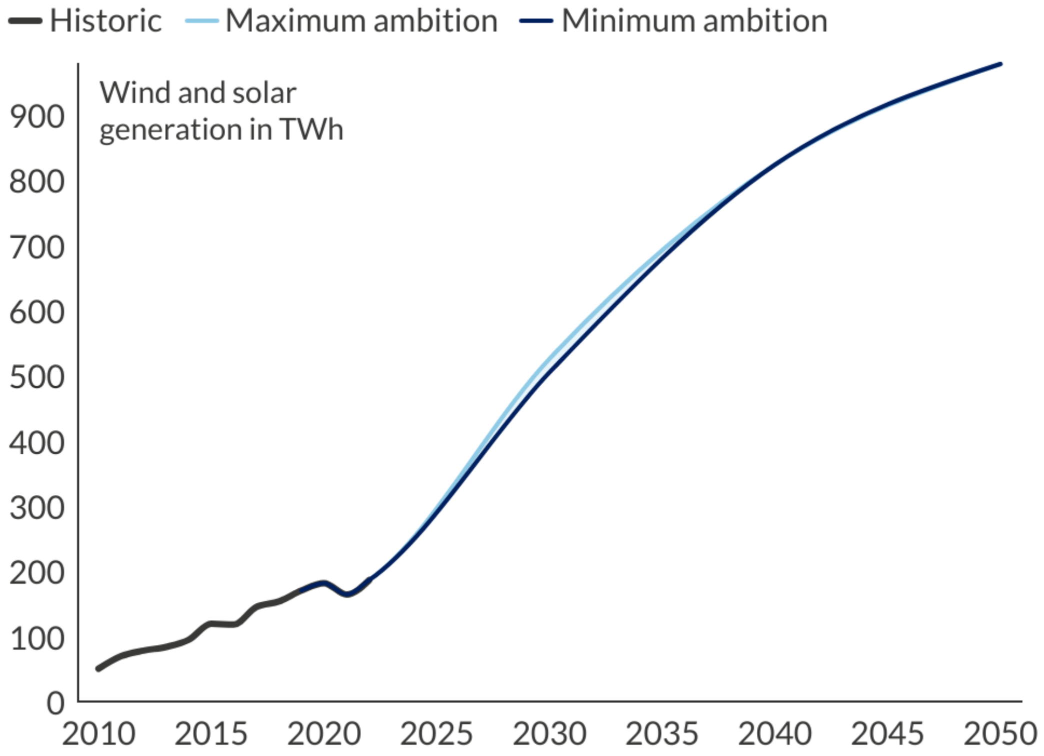
Wind and solar is then needed to drive the phaseout of fossil fuels while meeting demand requirements due to higher electrification rates.

To align with 1.5°C, wind and solar generation in Germany would need to reach 600 TWh by 2030. Generation in 2022 was 186 TWh. This is therefore a greater than 3-fold growth in wind and solar.

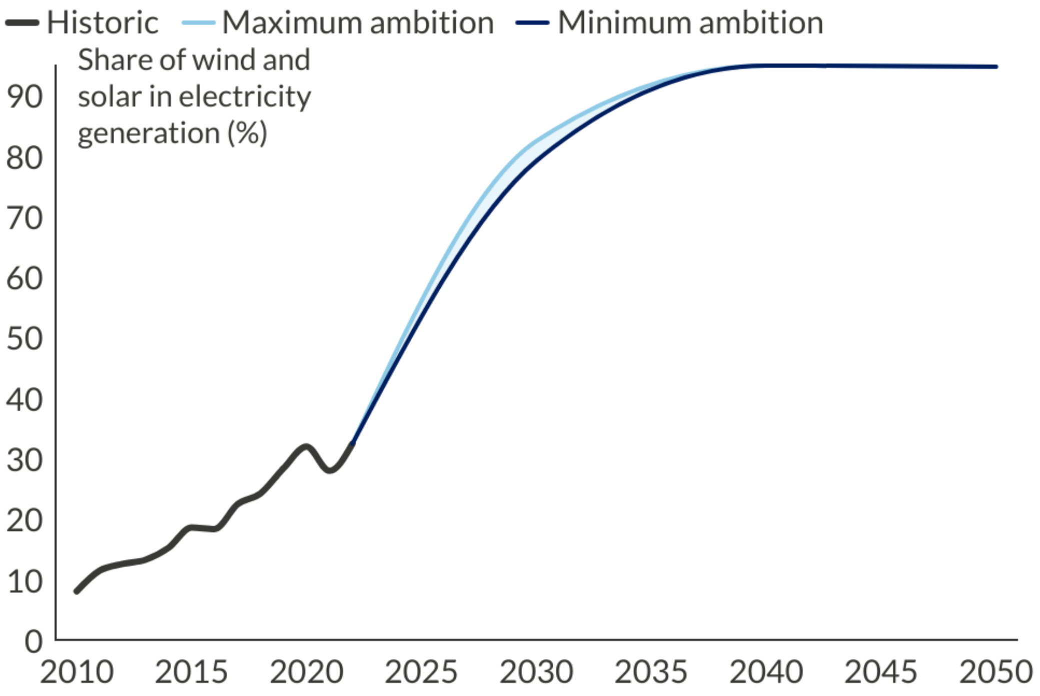
Wind and solar provides 79-82% of overall electricity generation in 2030, and 95% of overall generation in 2050.

To align with 1.5°C, wind and solar generation would need to grow rapidly in Germany

Wind and solar generation needs to almost triple by 2030 relative to 2022 in Germany



Wind and solar would need to provide around 95% of electricity generation in Germany by 2050



Possible splits into wind and solar

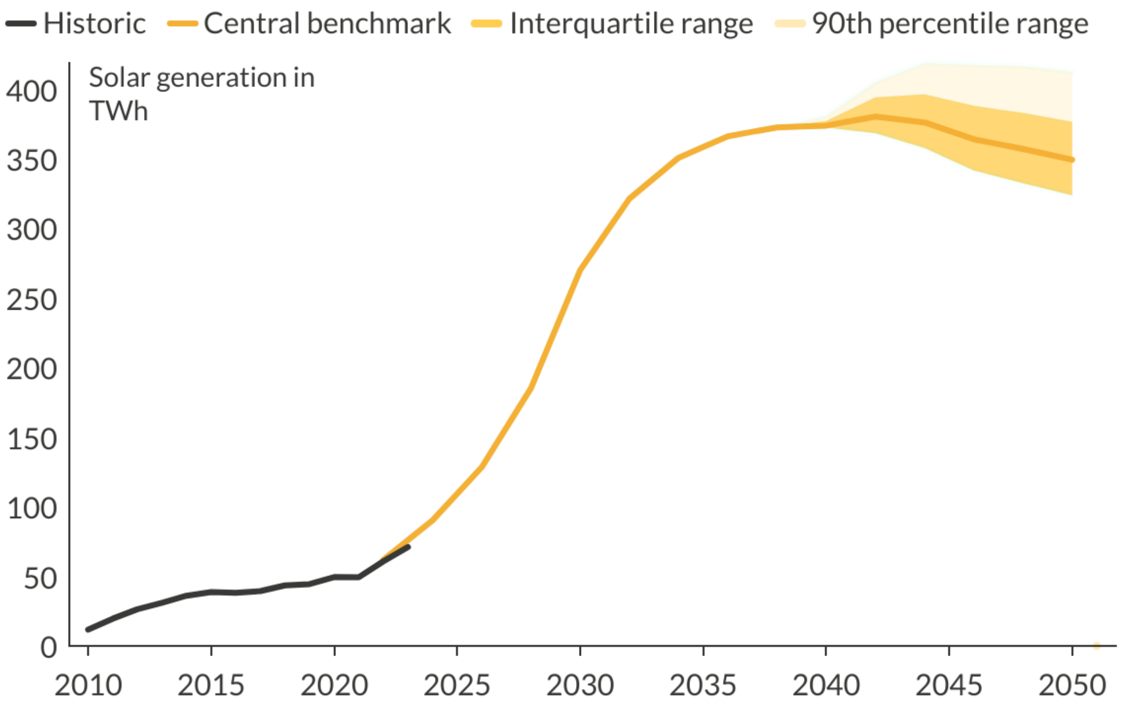
The relative share of wind and solar deployment will vary depending on how various factors develop in the future. We explore one key uncertainty, the relative cost of solar and wind electricity generation (see methods). When accounting for this uncertainty, we see a range of possible future generation mixes between wind and solar.

We highlight the median of the range as our **central benchmark**, but do not suggest that this is the only possible breakdown into wind versus solar. In the central benchmarking scenario, solar becomes the main source of generation, providing on average twice as much generation as wind in the electricity mix by 2050. This will require a rapid uptake of non-fossil flexibility options.

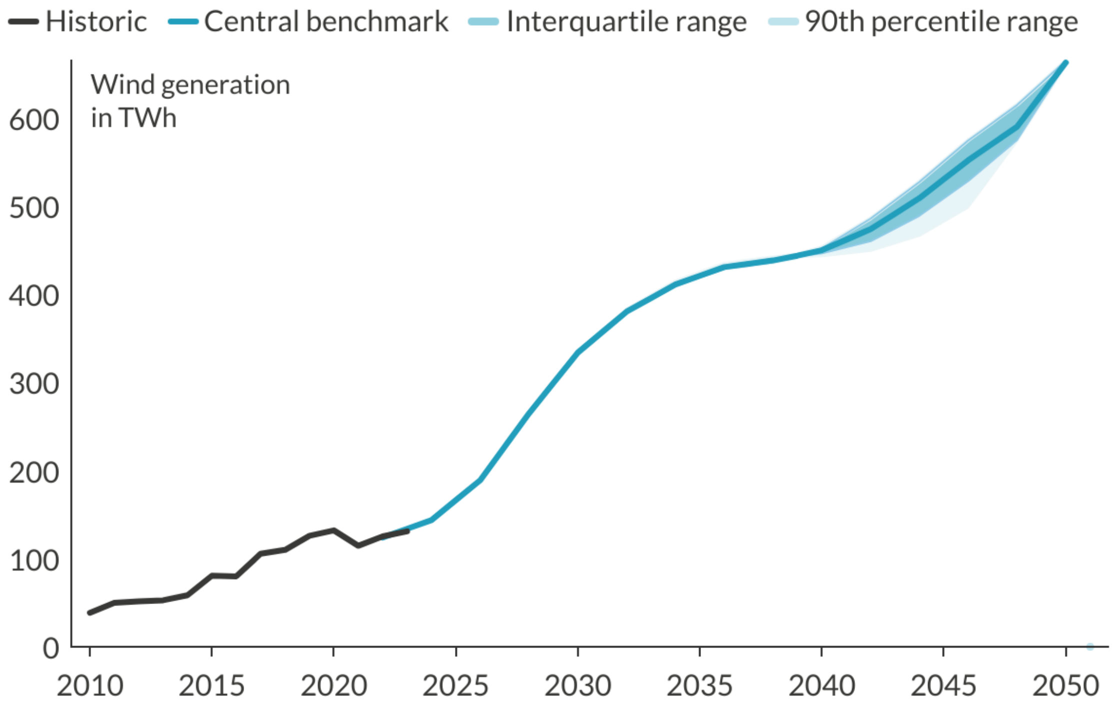
In this scenario, **Germany would need to deploy around 400 GW of wind and solar by 2030 to limit warming to 1.5°C**. By 2050, total wind and solar capacity would need to reach towards **580 GW**. Due to its higher capacity factor, greater wind deployment would reduce total capacity requirements.

On average, wind provides nearly double the electricity as solar by 2050 in Germany

Solar generation in Germany would reach around 350 TWh by 2050 in a 1.5°C-aligned transition



Wind generation in Germany would reach over 660 TWh by 2050 in a 1.5°C-aligned transition



Germany needs to install almost 400 GW of wind and solar by 2030 to align with 1.5°C

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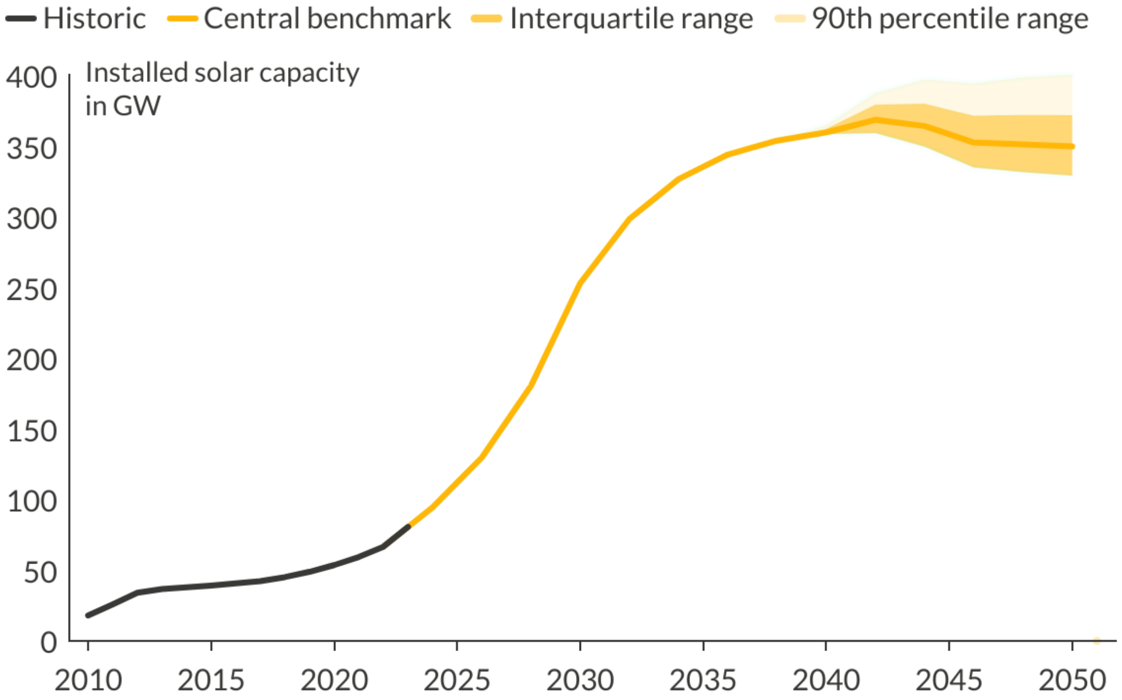
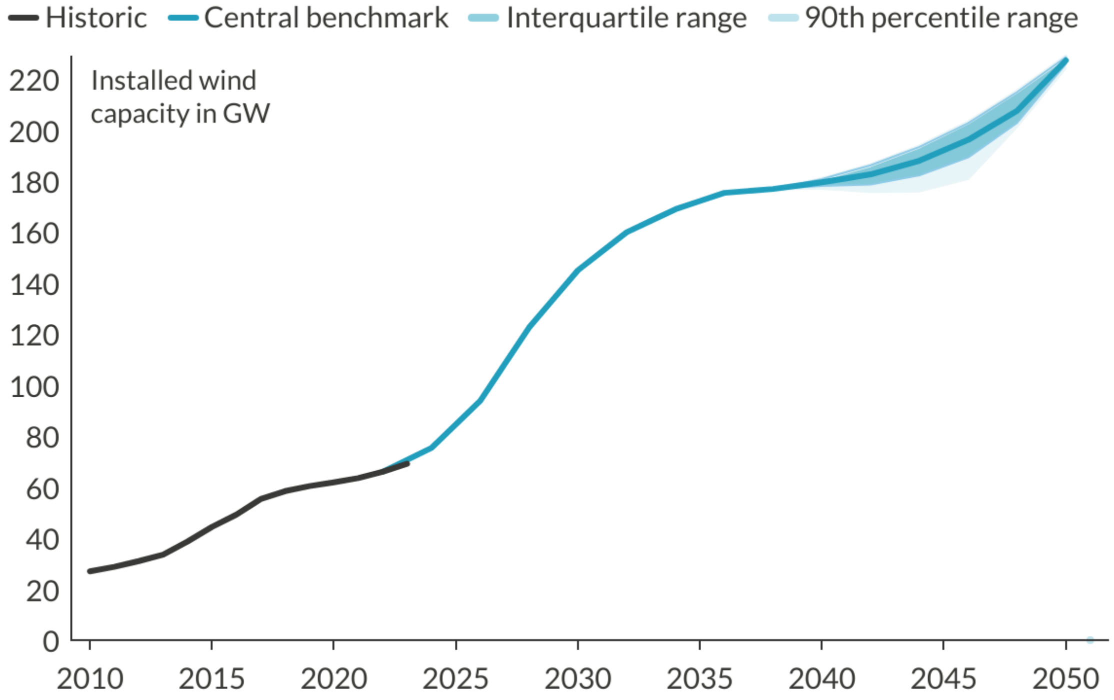
Solar capacity would reach 250 GW in Germany by 2030 in a 1.5°C-aligned scenario



Wind capacity would reach almost 150 GW in Germany by 2030 in a 1.5°C-aligned scenario



Comparison to current rollout

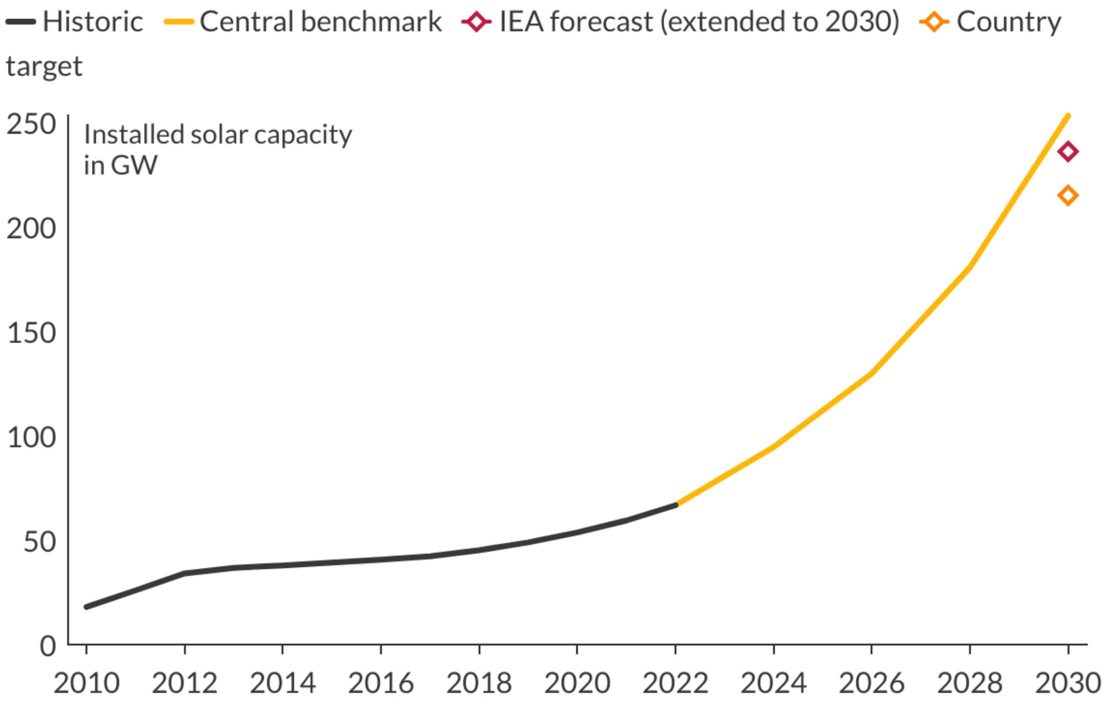
Under current policies and market conditions, the projected solar deployment in Germany is in line with the 1.5°C benchmark. This development exceeds the targets set out in law.

In contrast, while the target for wind power is aligned with a 1.5°C buildout, the projected wind rollout for Germany by the IEA is below the wind benchmark outlined in our analysis by 2030. However, German law has a mechanism to correct for this misalignment. The largest risk in the country is a potential roll-back of the existing target under more conservative future governments.

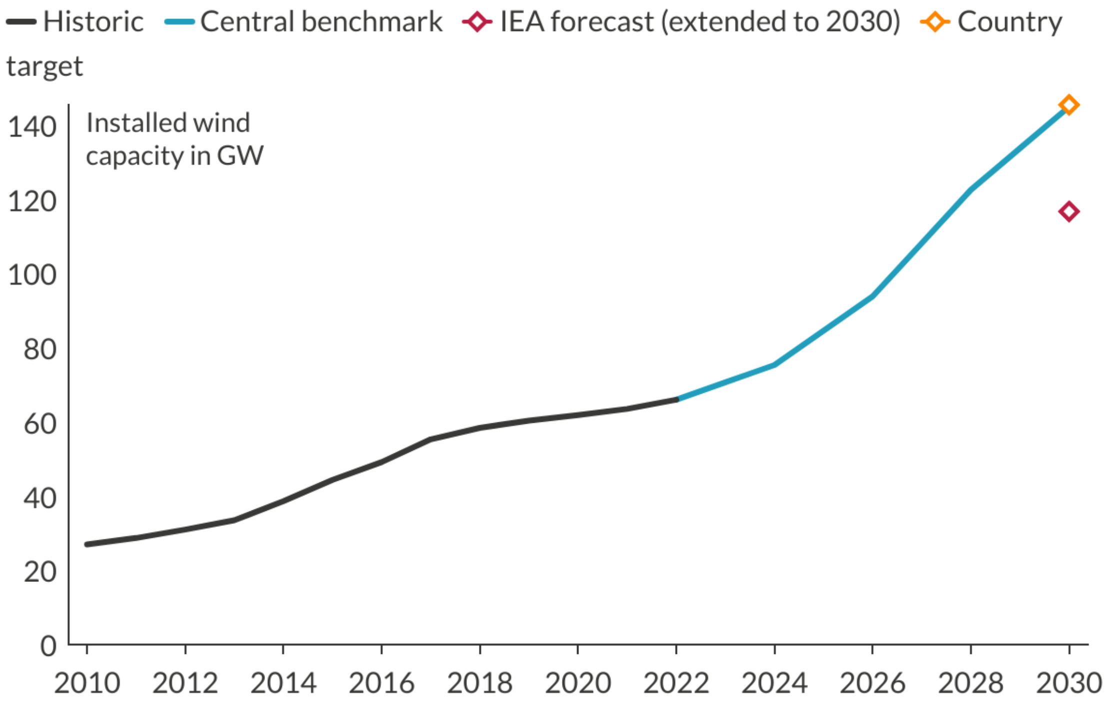
To align with the 1.5°C target, the period until 2030 is critical. Despite recent progress, the country must substantially accelerate the pace of annual capacity installations over the remainder of the decade, compared to 2020–2023. Annual capacity additions need to grow almost five-fold on average for wind and almost triple for solar. However, Germany has done it in the past, where they were able to deliver on the buildout speed needed for wind.

Germany's solar rollout broadly aligns with 1.5°C, while wind rollout needs accelerating in line with the buildout outlined by the law

Current rollout of solar in Germany comes close to aligning with 1.5°C

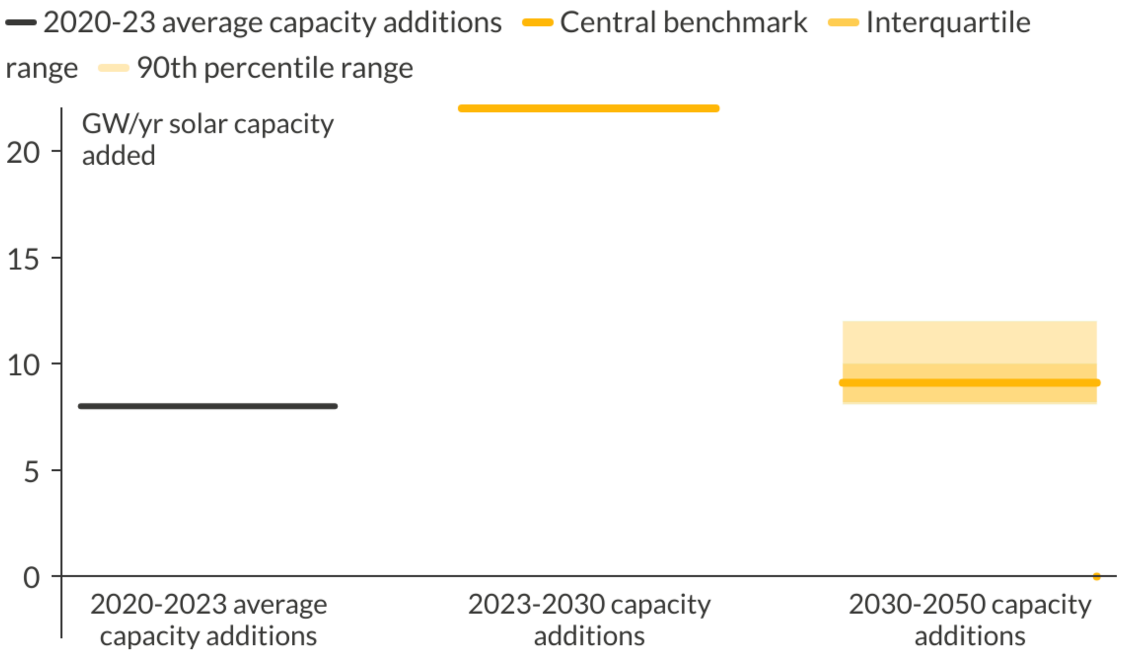


The current wind capacity target in Germany aligns with 1.5°C, but current rollout needs accelerating

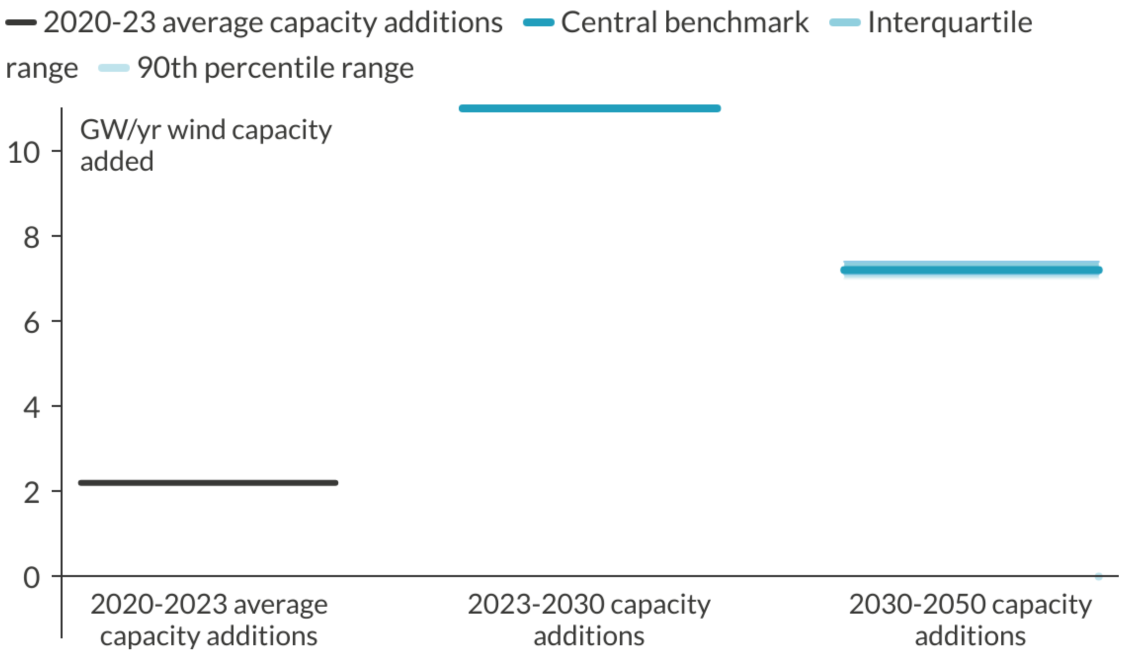


Solar additions in Germany must continue their exponential growth, while wind needs to return to its highest historical growth rates

Germany would need to add on average 22.0 GW/yr of solar capacity until 2030, and 9.1 GW/yr by over 2030–2050.



Germany would need to add on average 11.0 GW/yr of wind capacity until 2030, and 7.2 GW/yr by over 2030–2050



Comparison with other studies

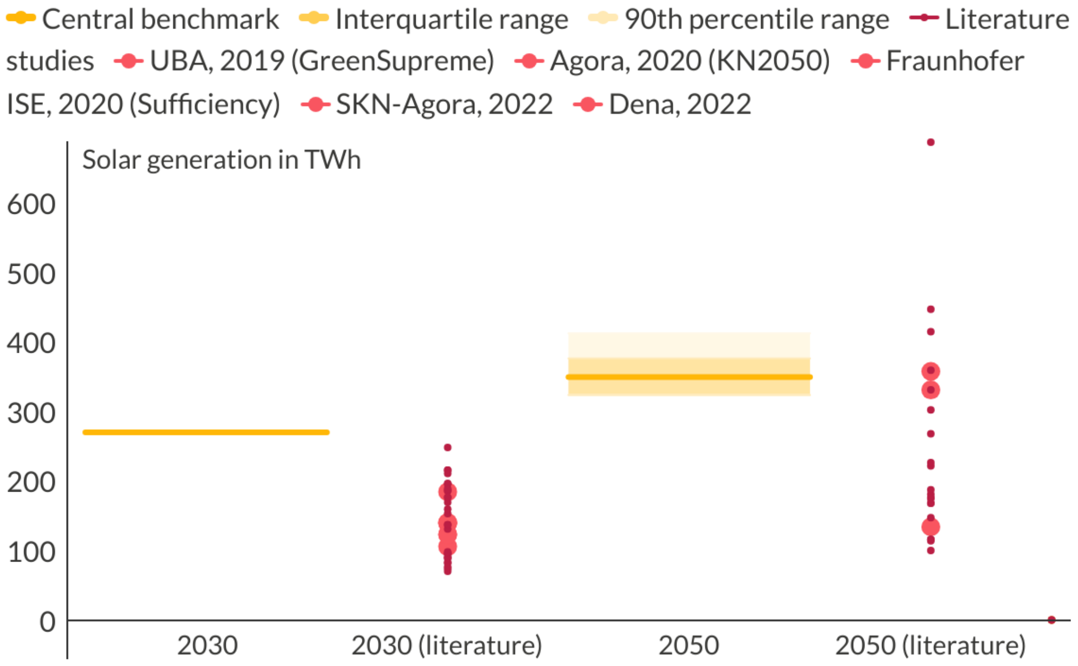
We compare the wind and solar generation seen in our analysis to that in the literature review of country-level studies. In particular, we highlight the results of modelling from the Ariadne Projekt Big 5, exploring net zero pathways for Germany.

We see that the wind and solar generation that our method produces is broadly within the range of the national literature. Our analysis shows solar and wind generation at the higher end of the pathways in the study highlighted from the Ariadne Projekt Big 5, particularly by 2050.

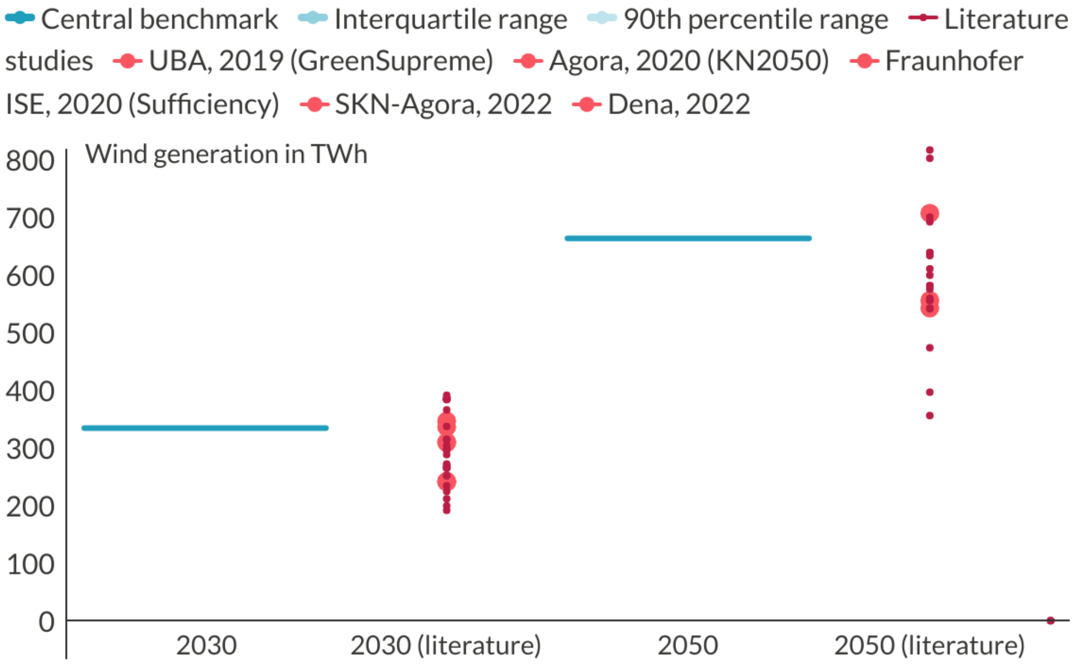
Despite the recent slowdown in wind development, our modelling sees wind power generating more electricity than solar in 2030, 2040, and 2050, in-line with country-level studies and government efforts to promote wind development.

The increase in wind and solar generation in our benchmarks aligns with national literature

Electricity generation from solar: comparison with literature in Germany



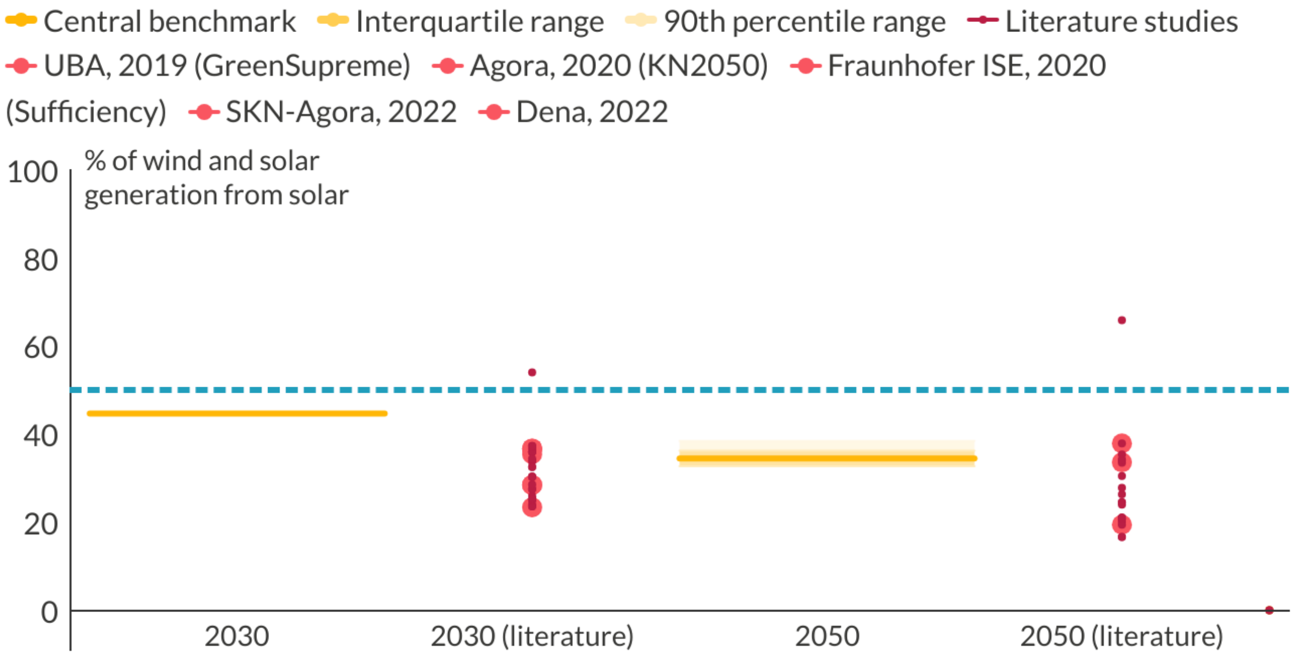
Electricity generation from wind: comparison with literature in Germany



In Germany, our benchmarks suggest that wind will provide more generation than solar

Share of wind and solar generation that comes from solar: comparison with literature in Germany

The area above the blue dashed line represents a power system in which solar provides more electricity generation than wind.



Summary data

The following table shows the wind and solar deployment needed to align with the central 1.5°C compatible benchmark produced. 2022 is historical data. All benchmark data from 2030 onwards is reported to two significant figures.

Scenario	Variable	Unit	2022	2030	2035	2040	2050
Central 1.5°C benchmark	Solar generation	TWh	62	270	360	370	350
Central 1.5°C benchmark	Wind generation	TWh	124	330	420	450	660
Central 1.5°C benchmark	Solar capacity	GW	67	250	340	360	350
Central 1.5°C benchmark	Wind capacity	GW	66	150	170	180	230

Annex 1

Overview of analytical elements

Different analytical elements

Our method takes multiple different analytical elements to try and understand a possible 1.5°C aligned wind and solar rollout that is informed by both bottom-up approaches and top-down perspectives.

The integration of multiple different analytical elements can help compensate for the limitations of any individual perspective, and provide a more robust and better-informed ultimate set of results.

In the following section, we provide some further detail on three of the main analytical elements. For more detail, please see the Methodology Report.

Global pathways

We use the global 1.5°C compatible pathways to bring a link back between national level action and the global goal of limiting warming to 1.5°C. All our benchmarks are consistent with pathways which achieve this goal at the global level, and in which renewable capacity triples by 2030 relative to 2022.

We focus on a set of 24 pathways from the IPCC's Sixth Assessment Report which avoid unsustainable levels of CDR deployment, as defined by the literature, and in which high-income countries take the lead in reducing emissions faster than low and middle-income countries. For more details see here.

Having selected these pathways, we then downscale them from the regional level (e.g. Sub-Saharan Africa) to the national level. We do this using the SIAMESE tool, which provides a cost-effective breakdown of energy consumption and emissions at the national level.

Country-level studies

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We use national-level studies, whether conducted by in-country actors (preferable), or otherwise external studies, to help provide national context. These studies help to ground-truth the top-down evidence being provided by the global downscaled pathways.

Studies are then filtered based on level of

- **Ambition**: We select studies which full decarbonise the power sector by the 2050s at the latest
- **Scope**: We prioritise studies with energy-wide sectoral representation, high levels of electrification and that provide data out to 2050
- **Robustness**: We focus on detailed power system modelling studies, avoiding simple heuristics

The resulting set of filtered studies are used to help inform future electricity demand, the future fossil fuel phase-out schedules in the country, and the level of non-wind and solar clean electricity generation that could be deployed out to 2050.

Country-level studies

List of scenarios selected (1/3)

Study	Publication	Scenario Selected
Agora Energiewende, 2020	Klimaneutrales Deutschland	• Climate-neutral 2050 (KN2050) • Klimaneutral Minimalvariante (KNmin)
Agora Energiewende, 2023	Climate neutral power system 2035	KNS2035
ARIADNE, 2019	Szenarienvergleich der "Big 5" Klimaneutralitätsszenarien	• REMIND Mix • REMod Mix • Times PANEU Mix
Bartholdsen *et al.*, 2019	Pathways for Germany's low-carbon energy transformation towards 2050	• Green Democracy (GD)BDI
Bundesverband der Deutschen Industrie (BDI), 2018	Klimapfade für Deutschland	• Global Climate Protection 80 • Global Climate Protection 95
BDI, 2022	Szenarienvergleich der "Big 5" Klimaneutralitätsszenarien	Klimapfade 2.0 Zielpfad

Country-level studies

List of scenarios selected (2/3)

Study	Publication	Scenario Selected
BMWK, 2022	Szenarienvergleich der "Big 5" Klimaneutralitätsszenarien	LFS TN Strom
Deutsche Energie-Agentur (dena), 2018	Integrierte Energiewende: Impulse für die Gestaltung des Energiesystems bis 2050	• Electrification95 • TechnologyMix9
Dena, 2022	Szenarienvergleich der "Big 5" Klimaneutralitätsszenarien	KN 100
Forschungszentrum Jülich (FZJ), 2020	Wege für die Energiewende	Scenario 95
Fraunhofer *et al.*, 2020	Langfristszenarien für die transformation des Energiesystems in Deutschland	
Fraunhofer *et al.*, 2023	Stromsystem Deutschland Leistung T45_var2023 / Electricity System Germany Capacity T45_var2023	T45-Strom*
Fraunhofer ISE, 2020	Wege zu einem klimaneutralen Energiesystem	• Reference • Persistence • Non-acceptance • Sufficiency

Country-level studies

List of scenarios selected (3/3)

Study	Publication	Scenario Selected
Joachim Nitsch, 2021	Was für einen erfolgreichen Klimaschutz erforderlich ist	KLIMA-21
SKN-Agora, 2022	Szenarienvergleich der "Big 5" Klimaneutralitätsszenarien	KNDE2045
Teske *et al.*, 2023	Net-zero 1.5°C sectorial pathways for G20 countries: energy and emissions data to inform science-based decarbonization targets	1.5°C
UBA, 2019	Transformationsprozess zum treibhausgasneutralen und ressourcenschonenden deutschland	• GreenEe1 • GreenEe2 • GreenLate • GreenMe • GreenLife • GreenSupreme

Global milestones

As well as the high-ambition country-level studies and the downscaled global pathways, we ensure that our benchmarks are compatible with the milestones identified in the IEA's net zero scenario, which sees:

- Advanced economies achieving net zero power sector emissions in 2035
- China achieving this milestone in 2040
- All other economies achieving this in 2045

Annex 2

Step-by-step method

Summary of our method

Our method takes a series of steps to calculate the wind and solar generation needed for 1.5°C, and the resulting capacity deployment.

First, we project future electricity demand. We then calculate the pace of fossil fuel phase-out needed to align with 1.5°C. Bringing these data points together, we can calculate the level of clean electricity generation required. We subtract non-wind and solar generation to calculate the wind and solar generation necessary to meet electricity demand growth and phase out fossil fuels in line with 1.5°C.

Having produced this wind and solar generation trajectory, we feed it into an electricity system model (PyPSA), which can then calculate for a given set of cost assumptions around wind and solar, a split into wind versus solar and the associated capacity requirements.

The following section further summarises the method. For a detailed overview, please see the methodology paper released in 2023.

We use a step-by-step method to calculate our benchmarks

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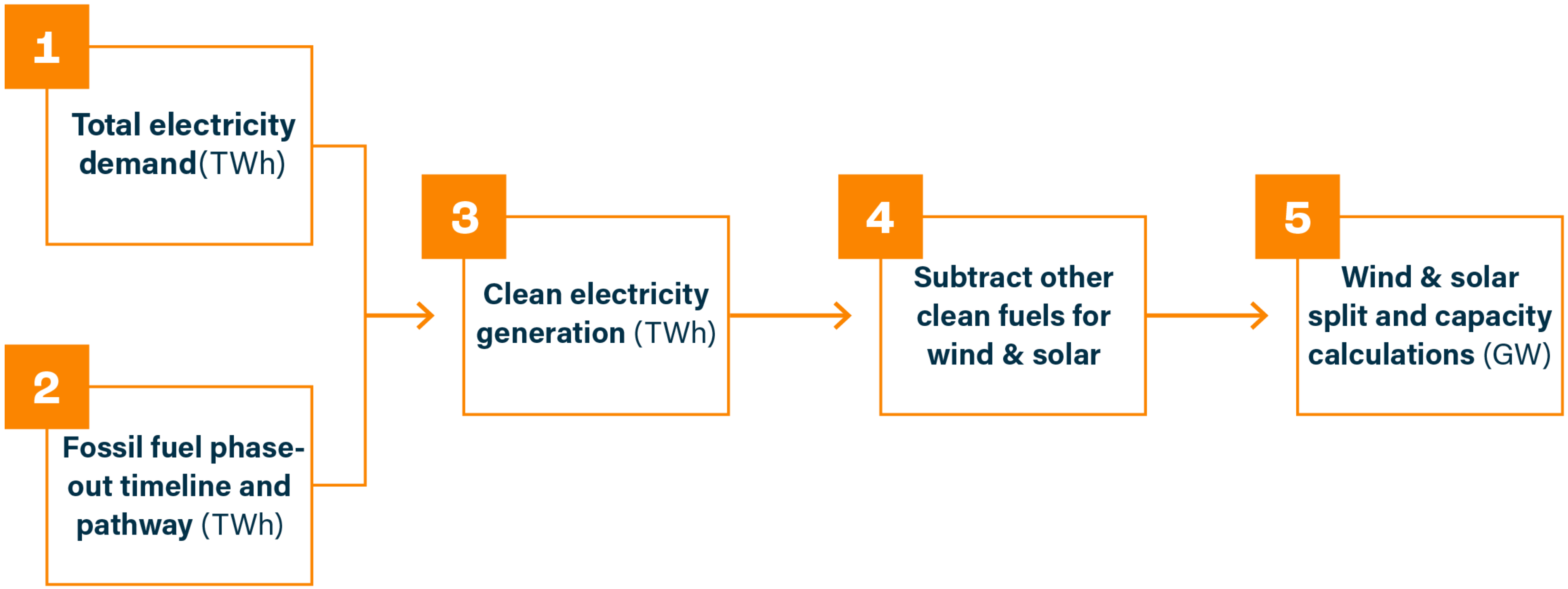
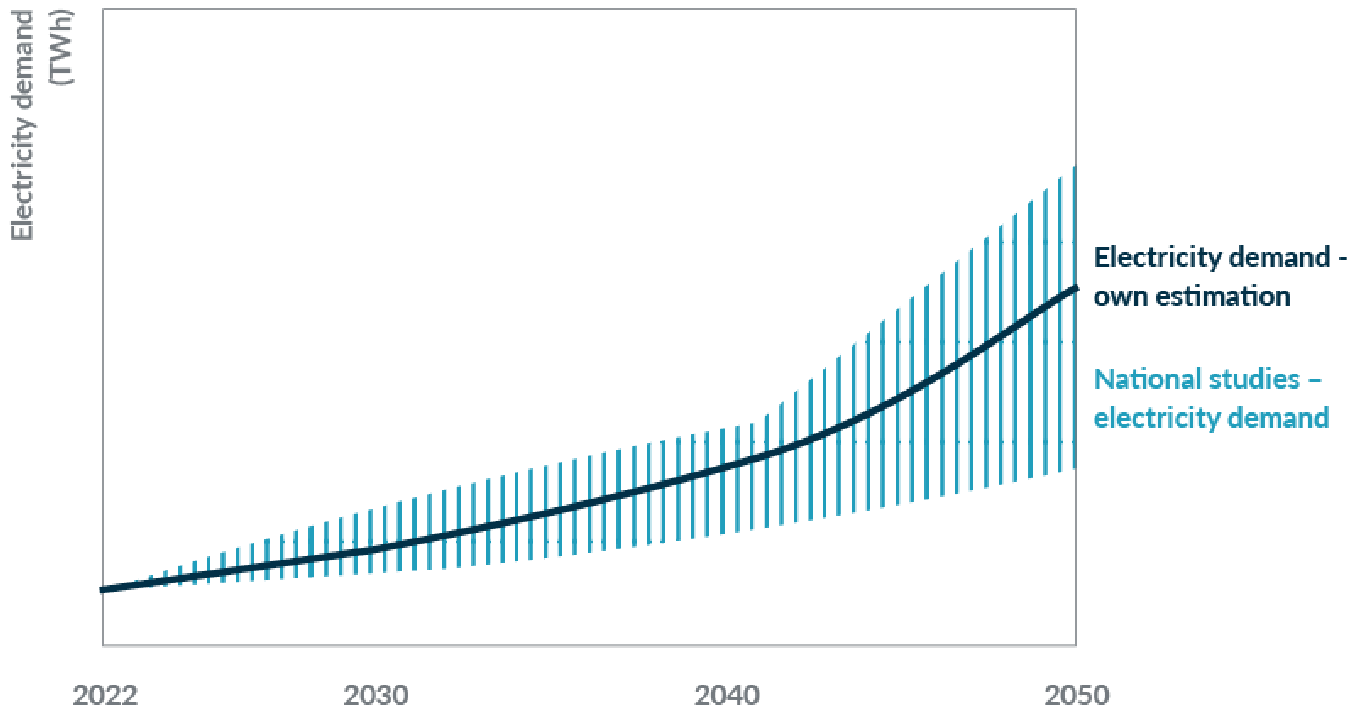


For more details see the Methods Annex

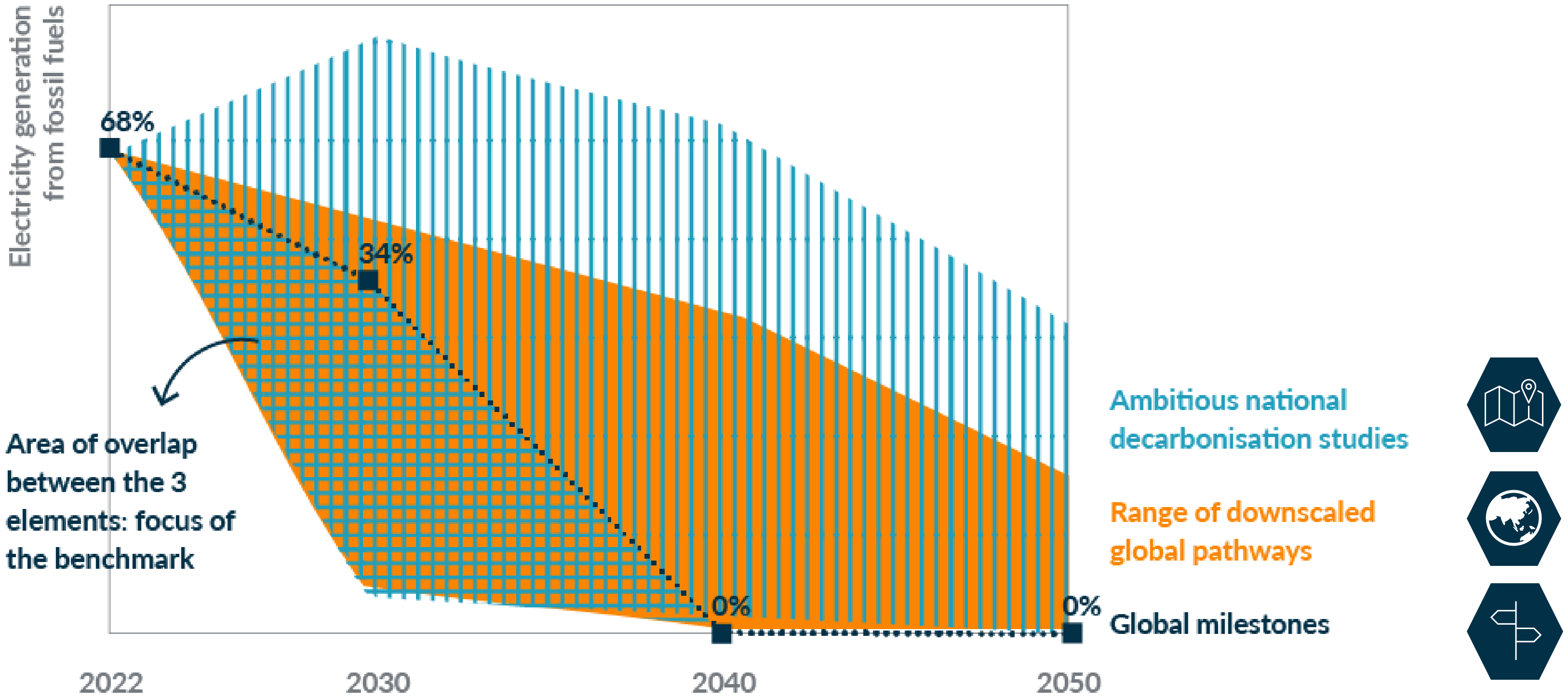
1 Total electricity generation

1. We extract electricity generation projections for 2030, 2040, and 2050 from **ambitious country-level studies**.
2. We then identify an electricity generation projection from a scenario to use for our analysis. We focus on identifying studies which capture key elements of the transition, including **high electrification**, and which have been conducted using **detailed energy system models** by **country-level experts**. We incorporate feedback from stakeholders to identify these studies which inform the electricity demand trajectory.



2 Fossil fuel phase-out

1. We calculate a range of electricity generation pathways from fossil fuels based on **ambitious country-level studies**
2. We produce a similar range from **downscaled 1.5°C compatible global scenarios**.
3. We identify the intersection of these two ranges, representing the speed and scale of decarbonisation pathways that aligns with the goals of the Paris Agreement while capturing local circumstances in countries.
4. We integrate differentiated timelines for phasing out fossil fuel electricity generation, applied as **global milestones** (2035 for advanced economies, 2040 for China, and 2045 for emerging economies).



3 4 Calculate wind and solar generation

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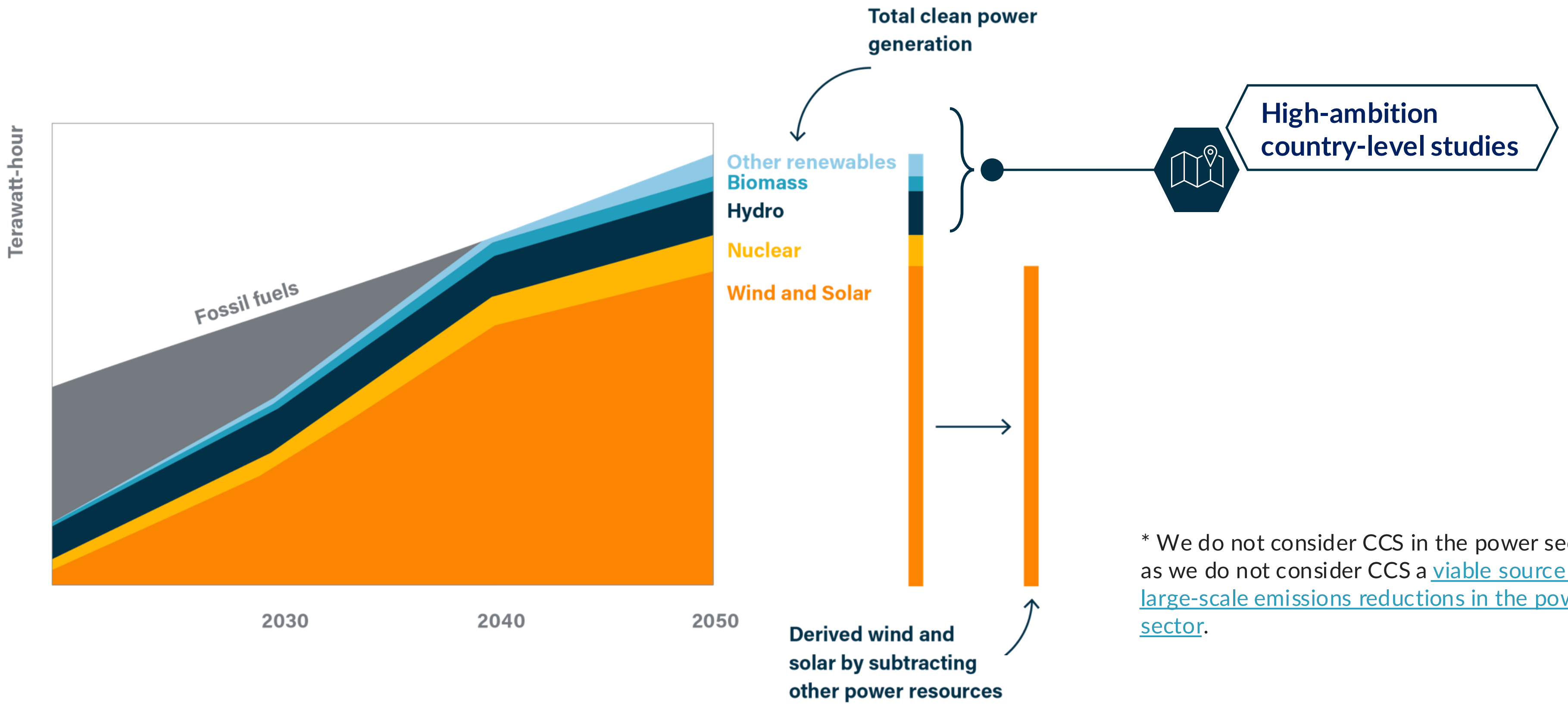
1. We obtain electricity generation from carbon-free resources: from total electricity generation (step 1), subtracting fossil-fired generation (step 2).
2. We then subtract estimates of electricity generation attributed to hydroelectricity, biomass, other renewable resources, and nuclear power – informed from **country-level studies'** estimates – from the total clean electricity generation* to infer the wind and solar generation.

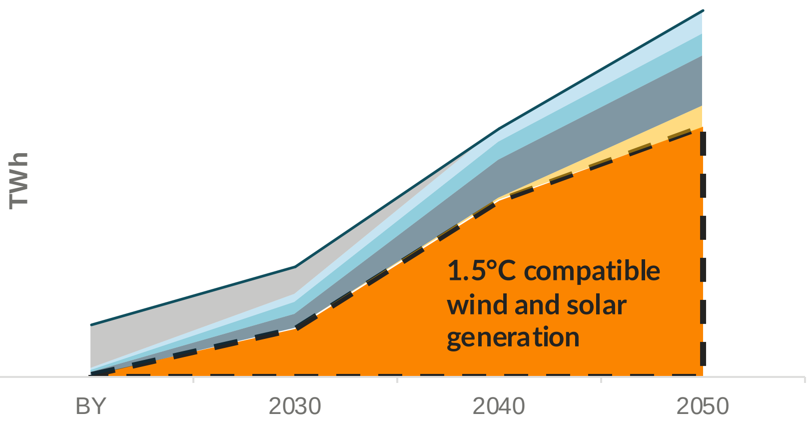


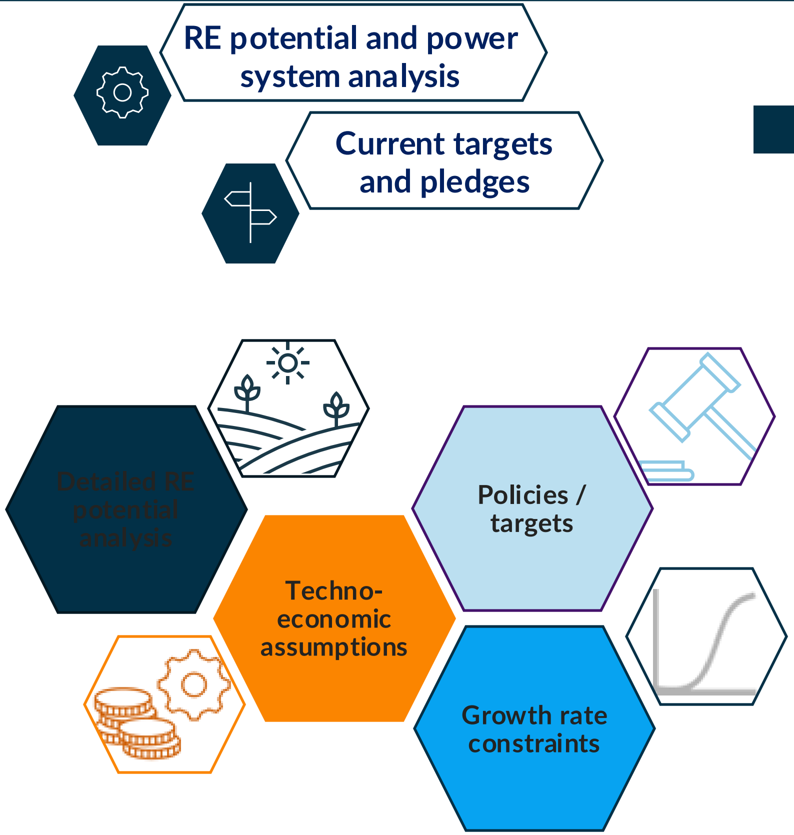
* We do not consider CCS in the power sector, as we do not consider CCS a [viable source of large-scale emissions reductions in the power sector](#).

5 Wind and solar breakdown

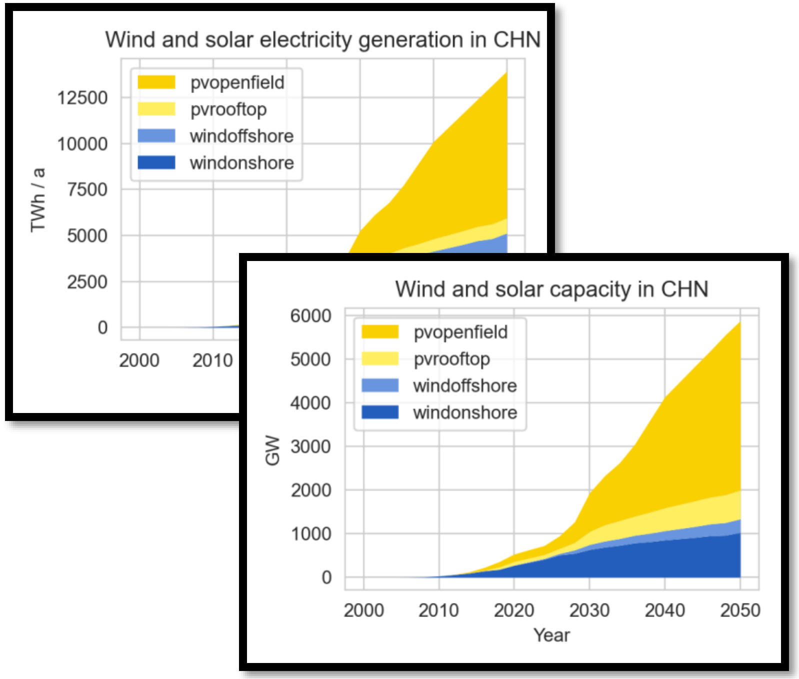
1. We use a detailed geospatial **renewable potential analysis** to calculate the technical potential of each technology in the country. We then feed the wind and solar generation required into a power system model calibrated to these potentials
2. We force the model to deploy at least the level of solar and wind seen in countries' **current targets and pledges**.
3. The power system model then gives a split of wind and solar in the country and the resulting capacity requirements.

1.5°C compatible wind and solar generation (steps 1-4)





Generation and capacity of wind and solar



Key modelling parameters in the analysis

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The following table highlights some of the most relevant parameters which influence the PyPSA modelling used to help estimate the split into wind versus solar

Model feature	Details
Cost resolution	Detailed cost curve for wind and solar produced based on geospatial weather data
Growth rates	Solar and wind growth rates constrained to technology specific growth rates set based on analysis of past technology rollout. Current default growth rates are set as • Wind = 33% per year • Solar = 41% per year These constraints are applied to both total capacity and capacity additions.
Adequacy factor	In addition to the total annual electricity generation from wind and solar having to be met, we require that at a certain proportion of the hourly load is always met by wind and solar. The default value for this constraint in Germany is 50%. This factor captures the level of storage and dispatchable generation available to meet electricity demand. A higher factor means that wind and solar need to more closely match hourly loads, without the use of storage/dispatchable generation to smooth out mismatches between generation and demand. This would generally lead to an overbuild of wind and solar to ensure adequate power supply at all times, and greater curtailment. Meanwhile a factor of 0% would mean that wind and solar generation can fall to zero for significant periods of time, as long as over the whole year, total wind and solar generation needed is provided. This would imply that there is greater availability of batteries and other dispatchable zero-carbon generation to meet demand in times of low wind and solar output.
Wind and solar costs	We produce a range of different cost curves for wind and solar in each country, based on IRENA data. For more details see the technical annex.