Wind and solar benchmarks for a 1.5°C world

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

United States of America

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Executive Summary

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Context

- US is the second-highest global emitter, with per capita emissions double the global average in 2023.
- Electricity accounts for about a quarter of total GHG emissions (excl. LULUCF), with 60% of electricity coming from fossil fuels (42% from fossil gas). US power sector emissions peaked in 2007 and have steadily declined since 2010 due to coal-to-gas shifting and renewables deployment.
- In 2022, electricity supply from renewables overtook coal and nuclear power for the first time, making them the second largest source of electricity generation after fossil gas.
- The Biden Administration set a carbon-free electricity system target for 2035, which aligns with our benchmarks. Power sector emissions must rapidly reduce to reach this target.
- This report examines the wind and solar capacity installation the US needs for a 1.5°C compatible pathway, aligning with the goal of tripling global renewables capacity by 2030.

Key findings

- To meet the 1.5°C benchmark, the US needs to increase wind and solar capacity by 3x and 6x respectively by 2030, on the road to phasing out fossil fuels in the power sector by 2035.
- Beyond ambitious targets, the main gap is in the actual build-up of wind and solar capacity. Wind and solar generation needs to increase 4-5x from 2022 levels by 2030 to be 1.5°C compatible. This means almost 1400 TWh of solar and 1600 TWh of wind. Policies at federal and state levels are needed to drive build up at the scale and speed required.
- The period until 2030 is crucial to stay on track for a 1.5°C compatible pathway. Despite recent progress, the pace of annual capacity installations must accelerate significantly in the remainder of this decade – to reach our benchmarks, wind and solar capacity additions need to more than triple compared to the last three years.
- While historical wind and solar capacity additions are below what is required, the Inflation Reduction Act (IRA) may boost wind and solar deployment in the remainder of this decade.

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 **the United States of America.**

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

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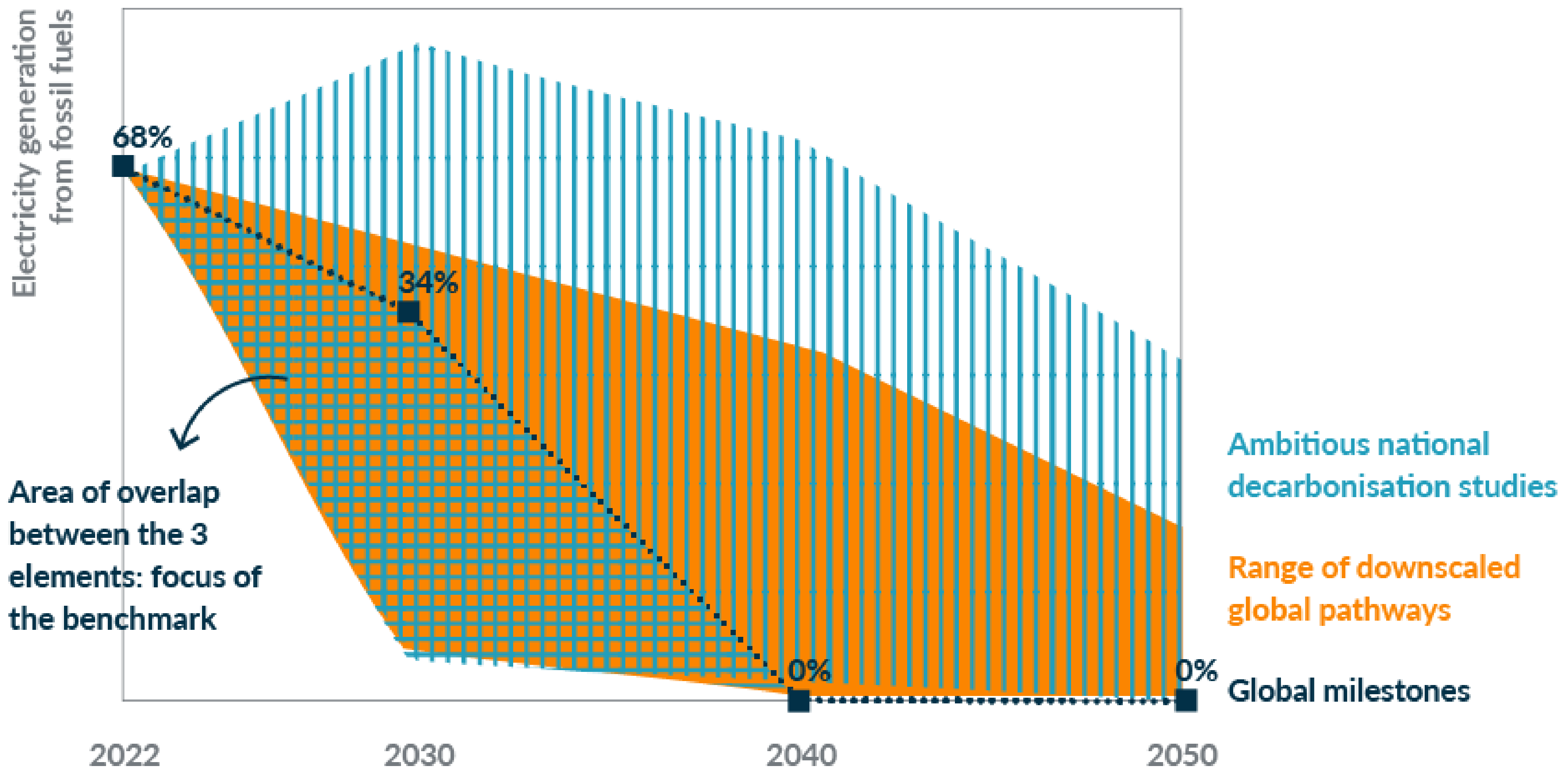


National enabling factors

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

The United States' current NDC is to reduce emissions to 50-52% below 2005 levels by 2030. The US has also set a target to achieve net zero GHG emissions by 2050. GHG emissions in the power sector must rapidly reduce to reach this targets.

The United States' current renewable targets are to reach **468 GW of solar and 369 GW of wind by 2030**, as per a National Renewable Energy Laboratory study published in 2023. Under current policies and market conditions, the IEA estimates that **solar capacity will reach 383 GW in 2028**, up from 141 GW of solar in 2022. Meanwhile, **wind capacity is projected to reach 232 GW in 2028**, up from 141 GW in 2022.

The Biden Administration set a carbon-free electricity system target for 2035. Achieving this goal is contingent on the US stopping building new fossil fuel power plants, particularly gas-fired plants. Policies at federal and state levels are needed to drive the build up at the scale and speed required.

Results

Future electricity demand

Electricity demand is taken from the Princeton University Net Zero America study exploring net zero pathways for the United States. We take demand from the E+ (high electrification) pathway, which achieves net zero GHG emissions by 2050, and nearly full electrification of buildings and transport.

Total electricity generation in the US more than doubles by 2050 relative to 2022 levels, reaching 9800 TWh. This is driven mainly by increased electrification.

However, there is a significant range in the studies in terms of the expected electricity generation in 2050 ranging from 5400 TWh to 16800 TWh. This would affect the expected growth of RE significantly. Our demand estimate is at the lower end of that range estimated by country-level studies.

Pace of fossil phaseout needed

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

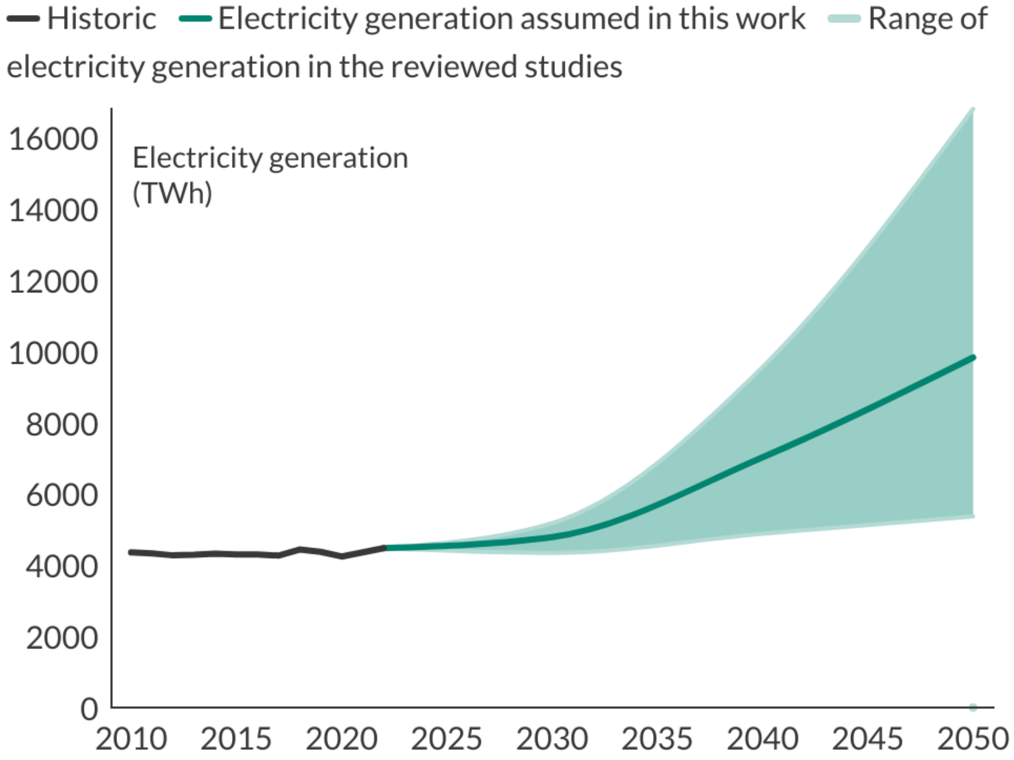
To align with 1.5°C, fossil fuels must exit the US power sector during the 2030s.

The time frame until 2030 is critical. Fossil fuel generation must fall by 65-75% by 2030, compared to 2022 levels.

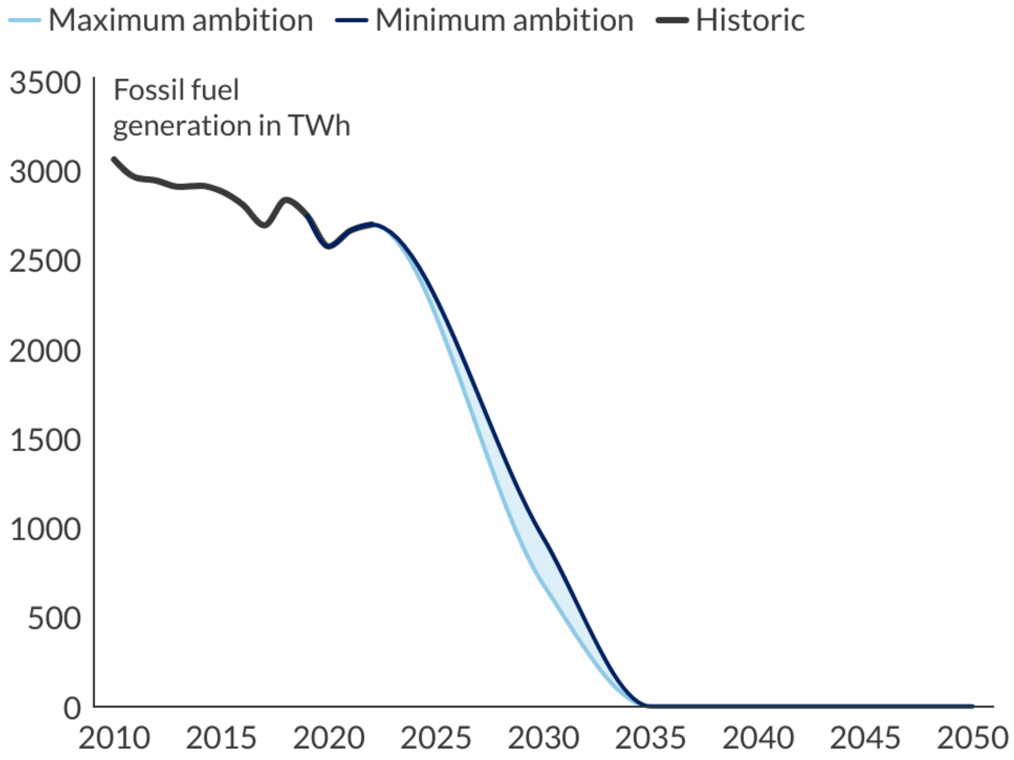
The fastest rate of fossil phase-out is set by the REPEAT Project Rapid Energy Policy Evaluation and Analysis Toolkit.

To align with 1.5°C, fossil fuels must exit the power sector in the United States by 2035, even as electricity demand grows

Electricity generation doubles in the United States over 2022–2050



United States 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 the United States would reach 1100 TWh by 2030, before falling back to 900 TWh by 2050. This is provided by nuclear, hydropower, 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 meet electricity demand growth and to drive the phaseout of fossil fuels.

To align with 1.5°C, wind and solar generation in the United States would need to reach between 2750 and 3000 TWh by 2030. Generation from these sources in 2022 was 627 TWh. **This is a 4-5x growth in wind and solar power generation by 2030** relative to 2022.

Wind and solar provides 57–63% of overall electricity generation in 2030, and 91% of overall generation in 2050.

To align with 1.5°C, wind and solar generation needs to grow rapidly in the United States

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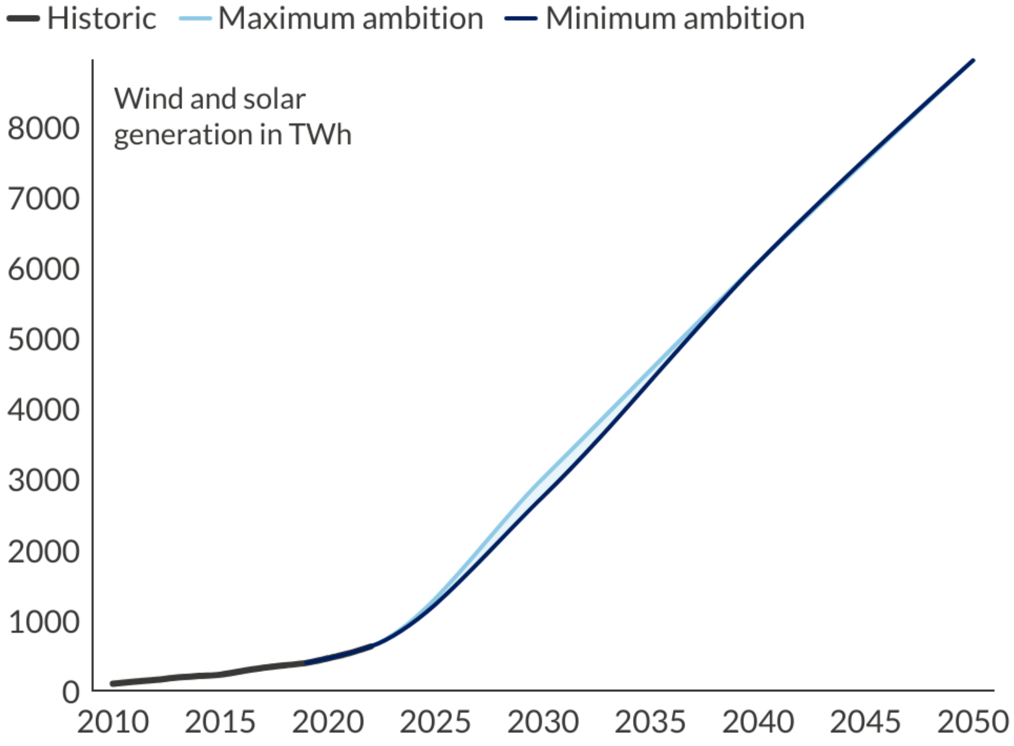
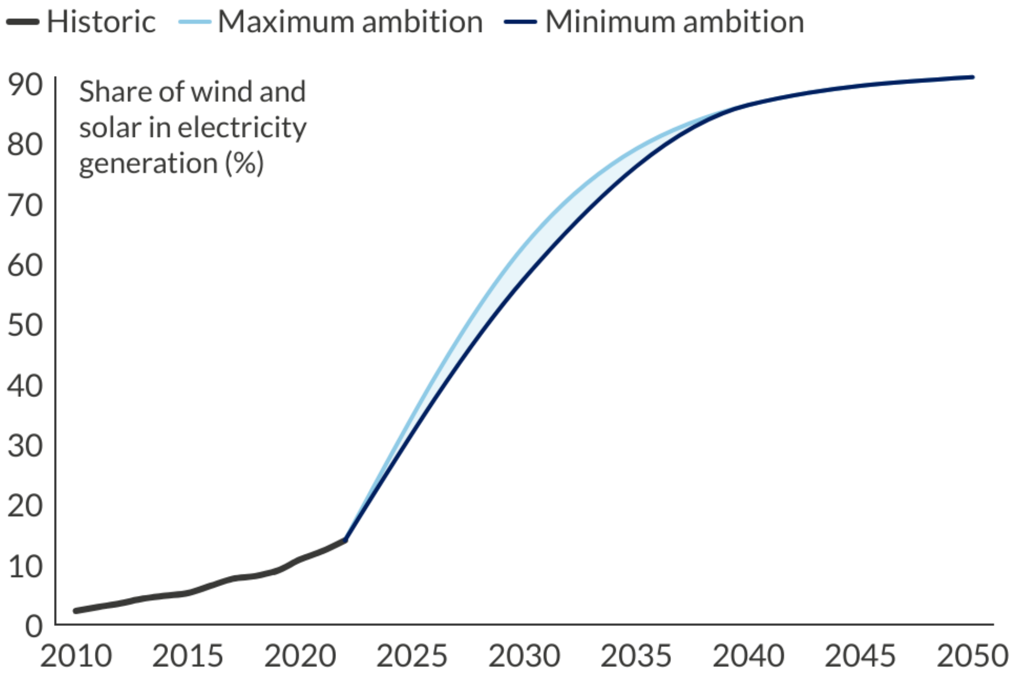
Wind and solar generation needs to grow 4-5x by 2030 relative to 2022 in the United States



Wind and solar would need to provide around 90% of electricity generation in the United States by 2050



Possible splits into wind and solar

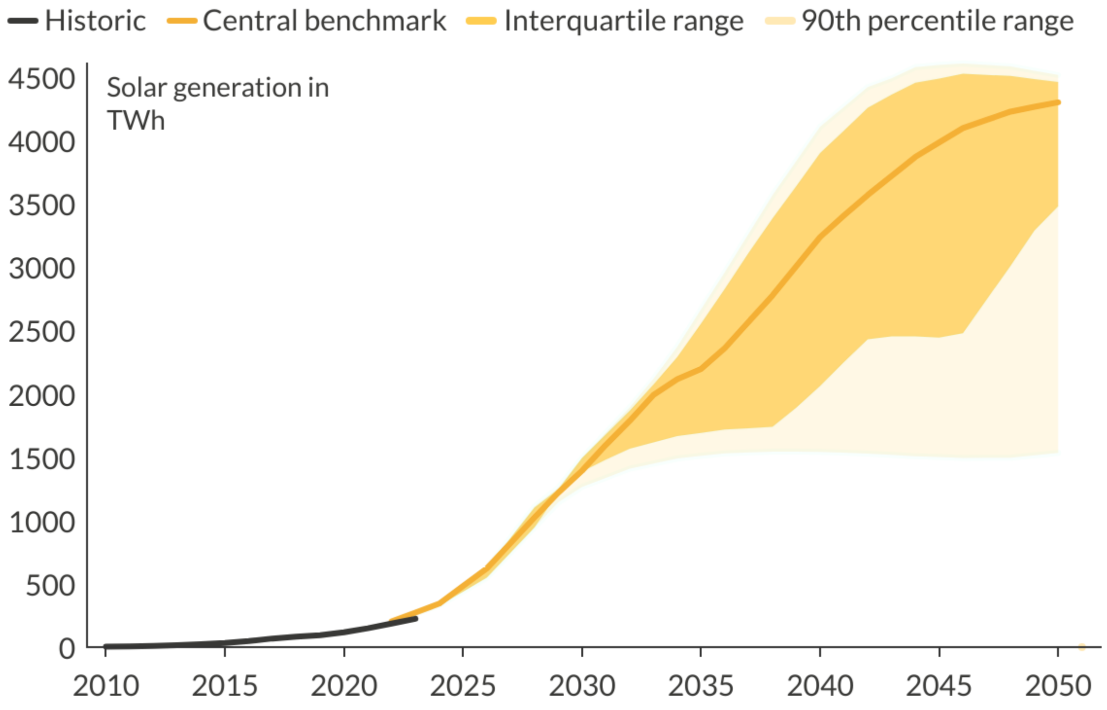
The relative share of wind and solar deployment will vary depending on how various factors develop in the future. We explore one key uncertainty, the relative cost of solar and wind electricity generation (see methods). When accounting for this uncertainty, we see a range of possible future generation 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, there is a relatively even contribution of wind and solar to total electricity generation in 2050. However, there are other scenarios in which wind provides a much greater contribution, with wind generating four times as much electricity as solar.

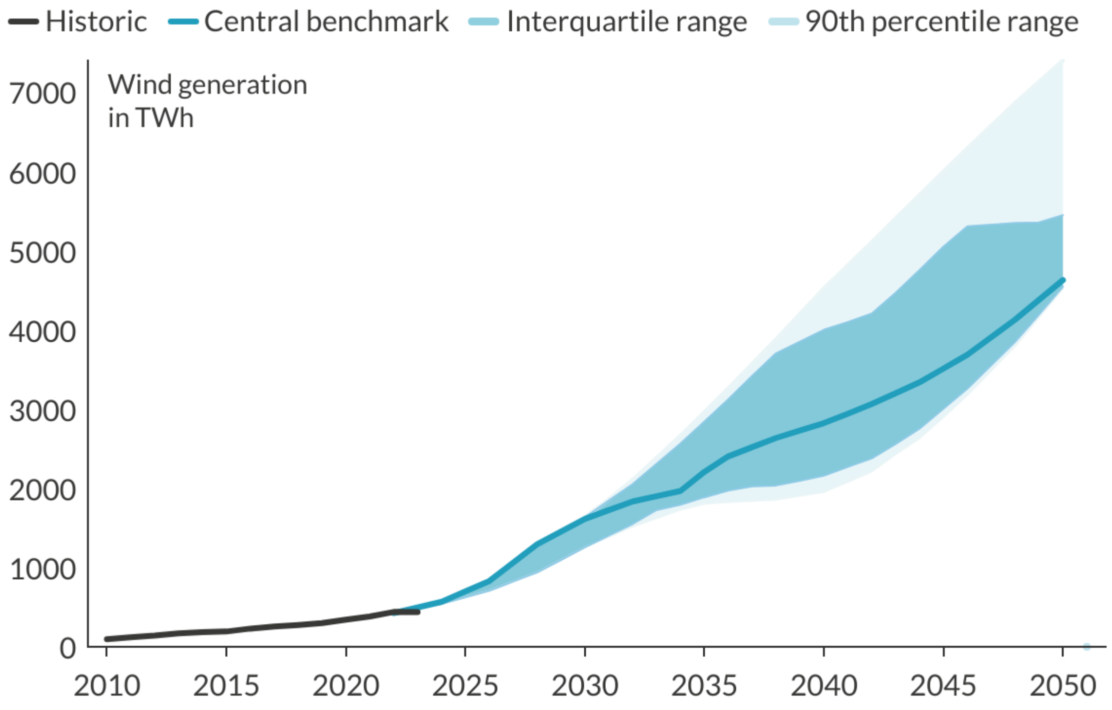
In the central benchmark scenario, **the United States would need to deploy over 1300 GW of wind and solar by 2030 to limit warming to 1.5°C**. By 2050, total wind and solar capacity would need to reach towards **3900 GW**. Due to its higher capacity factor, greater wind deployment would reduce total capacity requirements.

On average, wind and solar generation are broadly equal in 2050 in the United States

Solar generation in the United States would reach around 4500 TWh by 2050 in a 1.5°C-aligned transition

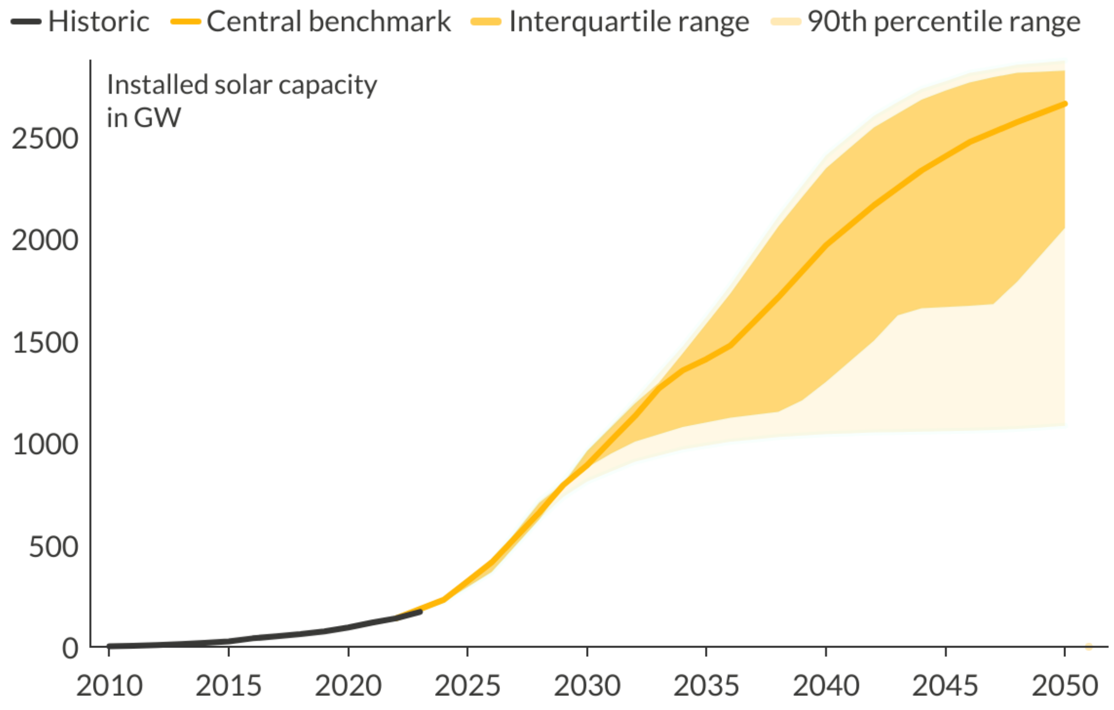


Wind generation in the United States would reach just over 4500 TWh by 2050 in a 1.5°C-aligned transition

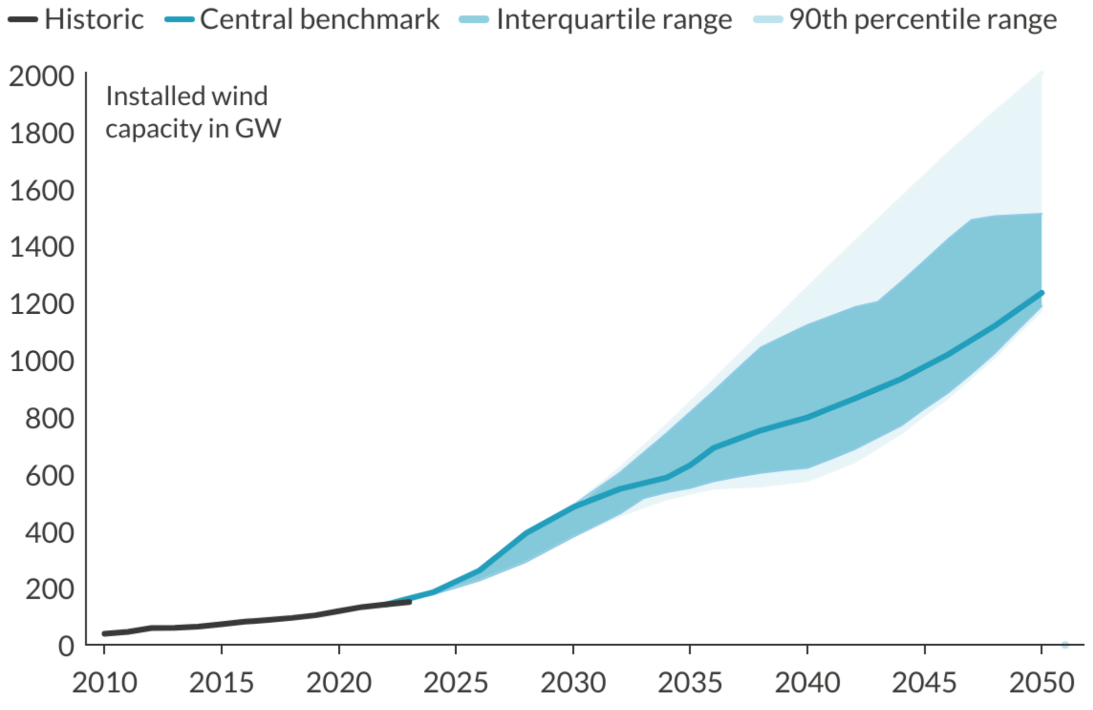


The United States needs to install over 1300 GW of wind and solar by 2030 to align with 1.5°C

Solar capacity would reach 890 GW in United States by 2030 in a 1.5°C-aligned scenario



Wind capacity would reach 480 GW in United States by 2030 in a 1.5°C-aligned scenario



Comparison to current rollout

We extend the IEA capacity forecasts for wind and solar from 2028 to 2030 to compare with the benchmarks presented in this report.

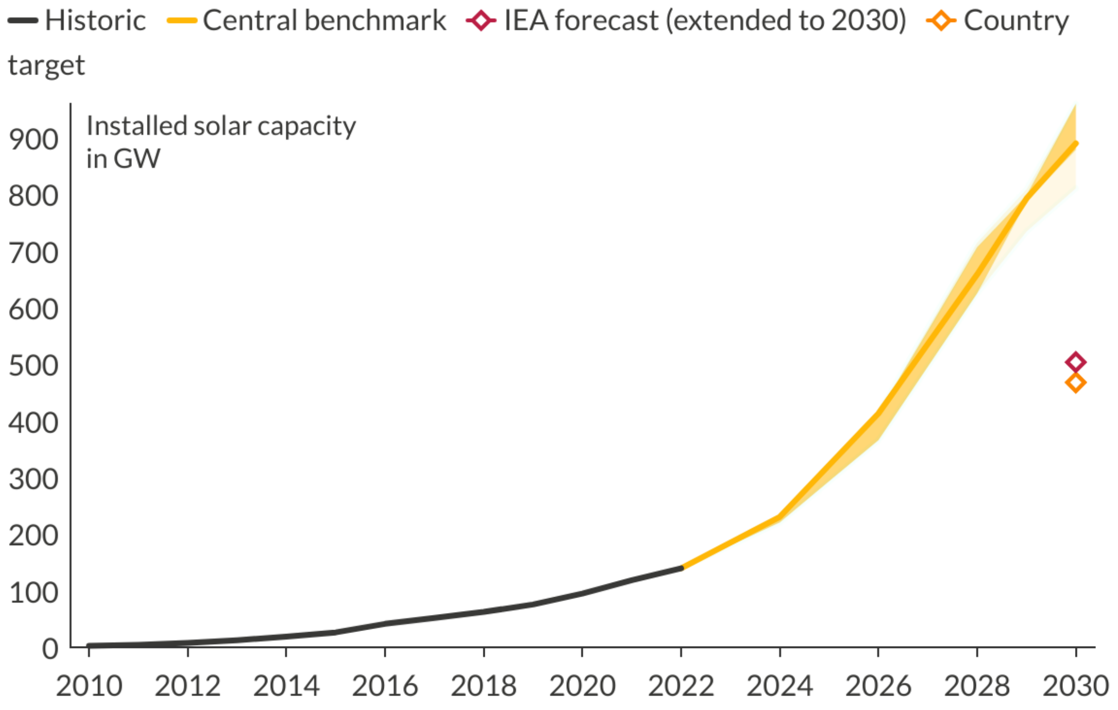
While the Biden Administration's 2035 target is aligned with our benchmarks, the main gap in the country lies in the actual build-up of wind and solar capacity. The current target for wind is close to aligned with 1.5°C, but actual rollout is lagging behind. Solar rollout also needs accelerating to align with 1.5°C.

The period until 2030 is crucial to stay on track for a 1.5°C compatible pathway. Despite recent progress, the country must significantly accelerate its pace of annual capacity installations over the remainder of this decade. According to our benchmarks, annual capacity additions for wind and solar in the remainder of this decade need to more than triple compared to the last three years.

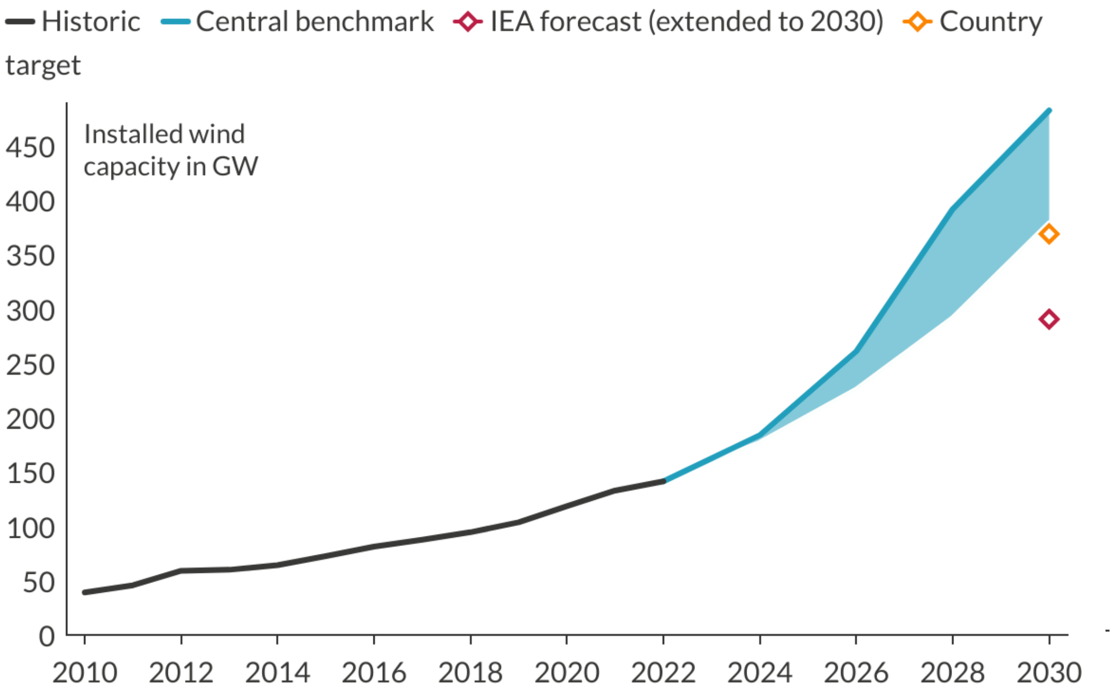
Although historical capacity additions are short of what is required, the impact of the Inflation Reduction Act (IRA) on clean manufacturing is likely to become evident in the remainder of this decade.

The United States' wind and solar rollout needs to accelerate to be aligned with 1.5°C

In United States, current rollout of solar is lagging behind 1.5°C-aligned levels

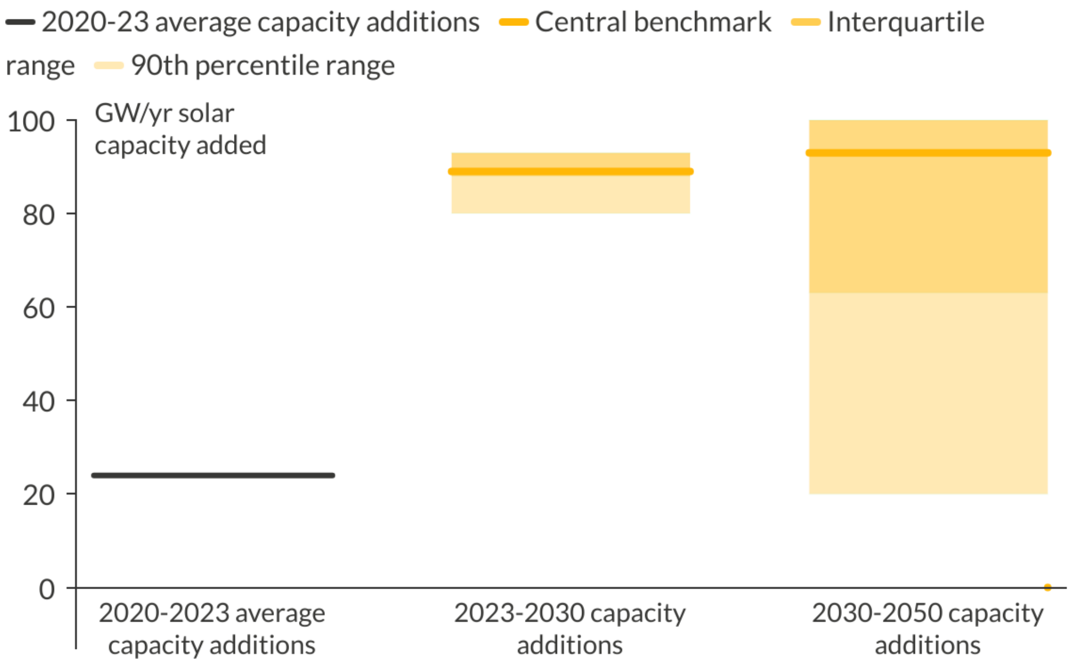


The current wind capacity target in United States almost aligns with 1.5°C, but current rollout lags behind

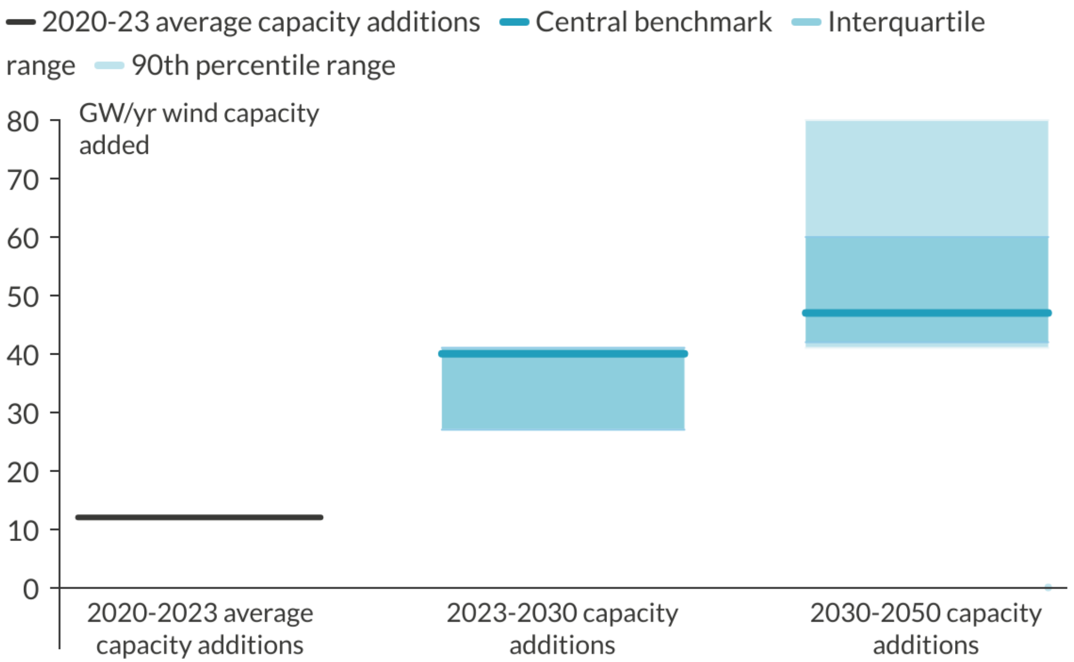


To align with 1.5°C, wind and solar capacity additions in the United States need to more than triple over 2023–30

United States would need to add on average 89.0 GW/yr of solar capacity until 2030, and 93.0 GW/yr by over 2030–2050.



United States would need to add on average 40.0 GW/yr of wind capacity until 2030, and 47.0 GW/yr by over 2030–2050



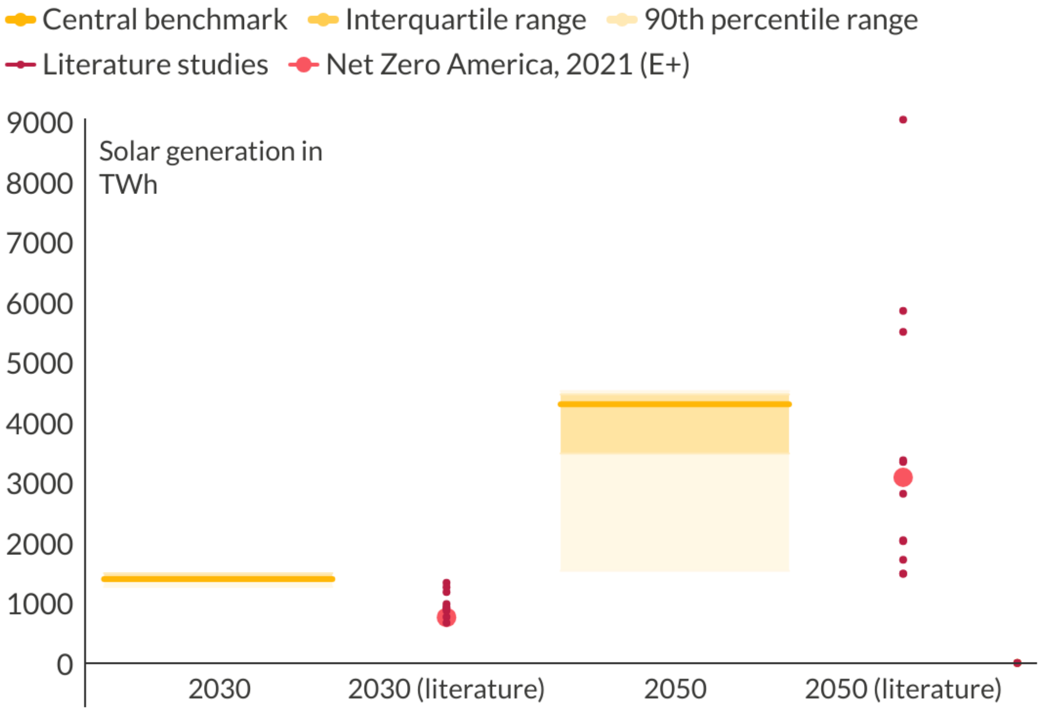
Comparison with other studies

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 Net Zero America study, exploring net zero pathways for the United States. We focus on the high electrification (E+) scenario.

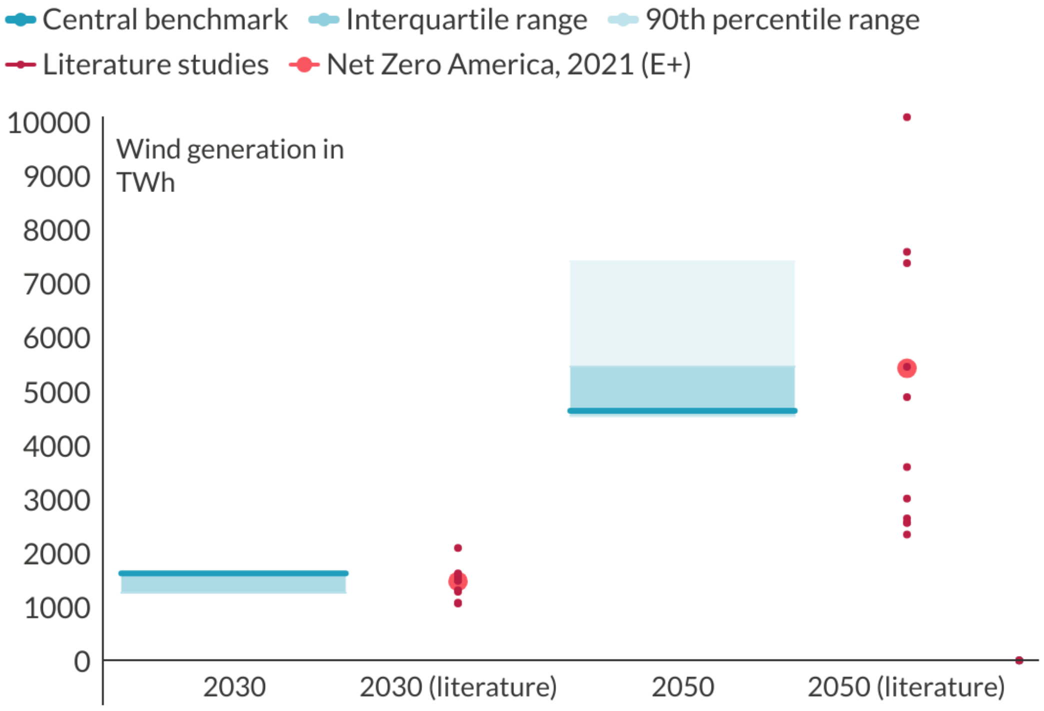
We see that the wind and solar generation that our method produces is broadly comparable to the Net Zero American modelling in 2030, however, our benchmarks envisage a faster rollout of solar. In 2050, our benchmarks align with the E+ scenario, though are much less than the E+RE+ scenario.

Wind and solar generation in our benchmarks broadly aligns with the literature

Electricity generation from solar: comparison with literature in United States



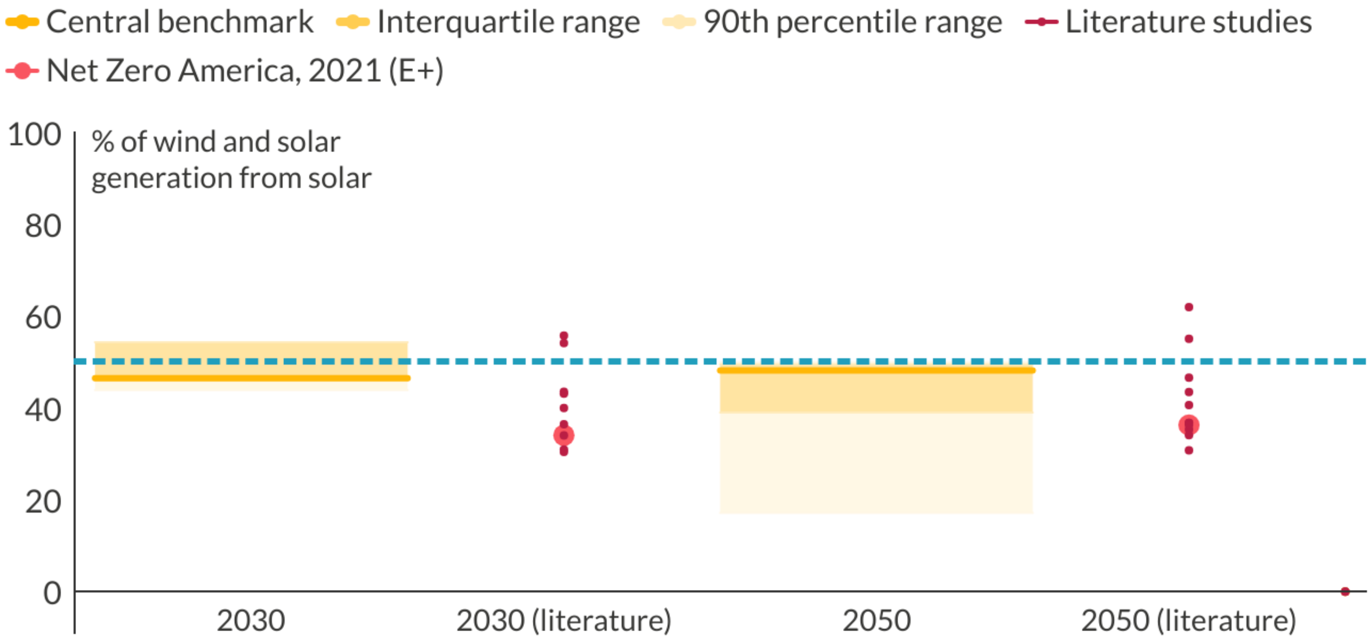
Electricity generation from wind: comparison with literature in United States



Our benchmarks generally suggest that wind will provide more generation than solar in the US

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

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	202	1400	2200	3200	4300
Central 1.5°C benchmark	Wind generation	TWh	425	1600	2200	2800	4600
Central 1.5°C benchmark	Solar capacity	GW	140	890	1400	2000	2700
Central 1.5°C benchmark	Wind capacity	GW	141	480	630	800	1200

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. North America) 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 (1/2)

Study	Publication	Scenarios Selected
Bistline *et al.*, 2022	Implications of variations in renewable cost projections for electric sector decarbonization in the United States	Low
Cole *et al.*, 2021	Quantifying the challenge of reaching a 100% renewable energy power system for the United States	100%
Evolved Energy Research, 2023	Annual Decarbonization Perspective 2023: Carbon-neutral pathways for the United States	• 100% RE • High Hydrogen
Ewing *et al.*, 2022	Pathways to Net-Zero for the US Energy Transition	Princeton High Electrification
Larson *et al.*, 2021	Net-Zero America: Potential Pathways, Infrastructure, and Impacts	• E+ • E+RE+

Country-level studies

List of scenarios selected (2/2)

Study	Publication	Scenario Selected
NREL, 2022	2022 Standard Scenarios Report: A U.S. Electricity Sector Outlook	• Mid-case with 100% decarbonization by 2035 • Low renewables energy costs with 100% decarbonization by 2035
REPEAT, 2023	Rapid Energy Policy Evaluation and Analysis Toolkit	Net-Zero Pathway Benchmark
Williams *et al.*, 2021	Carbon-neutral pathways for the United States	• Central Case • 100% Renewables

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

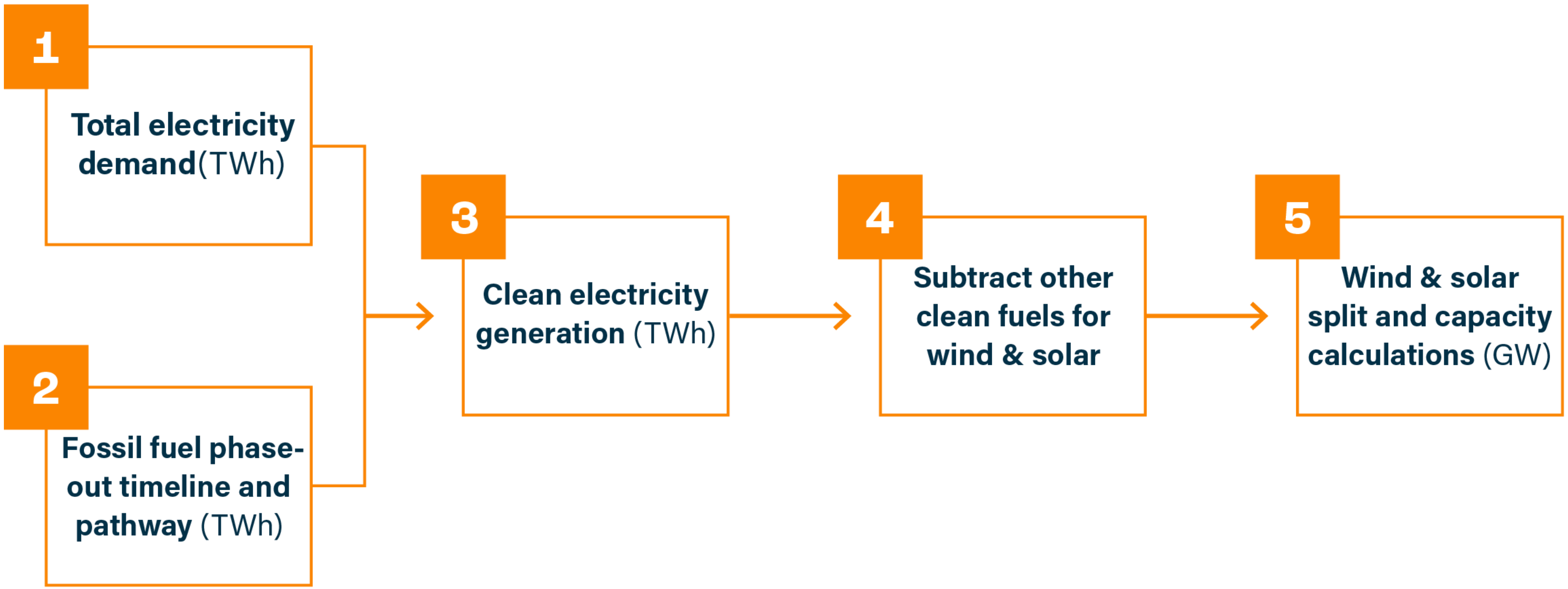
Our method takes a series of steps to calculate the wind and solar generation needed for 1.5°C, and the resulting capacity deployment.

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.

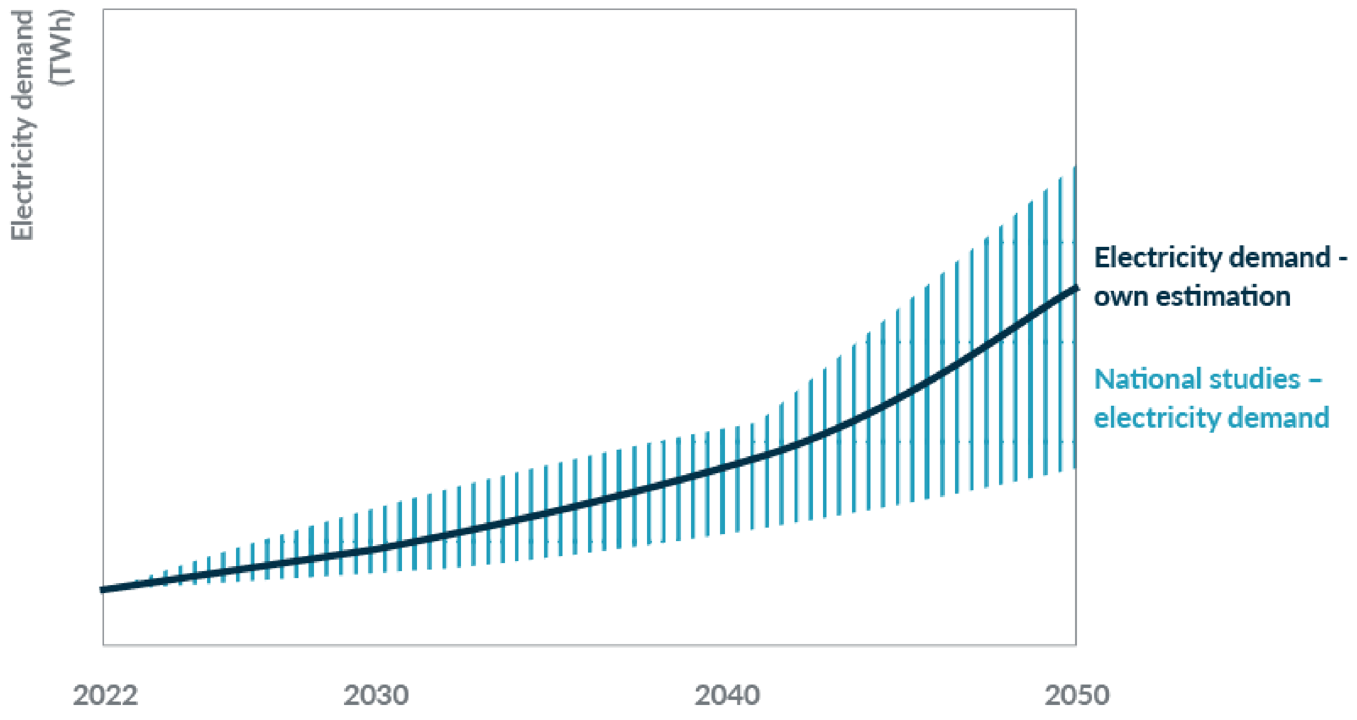
The following section further summarises the method. For a detailed overview, please see the methodology paper released in 2023.

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



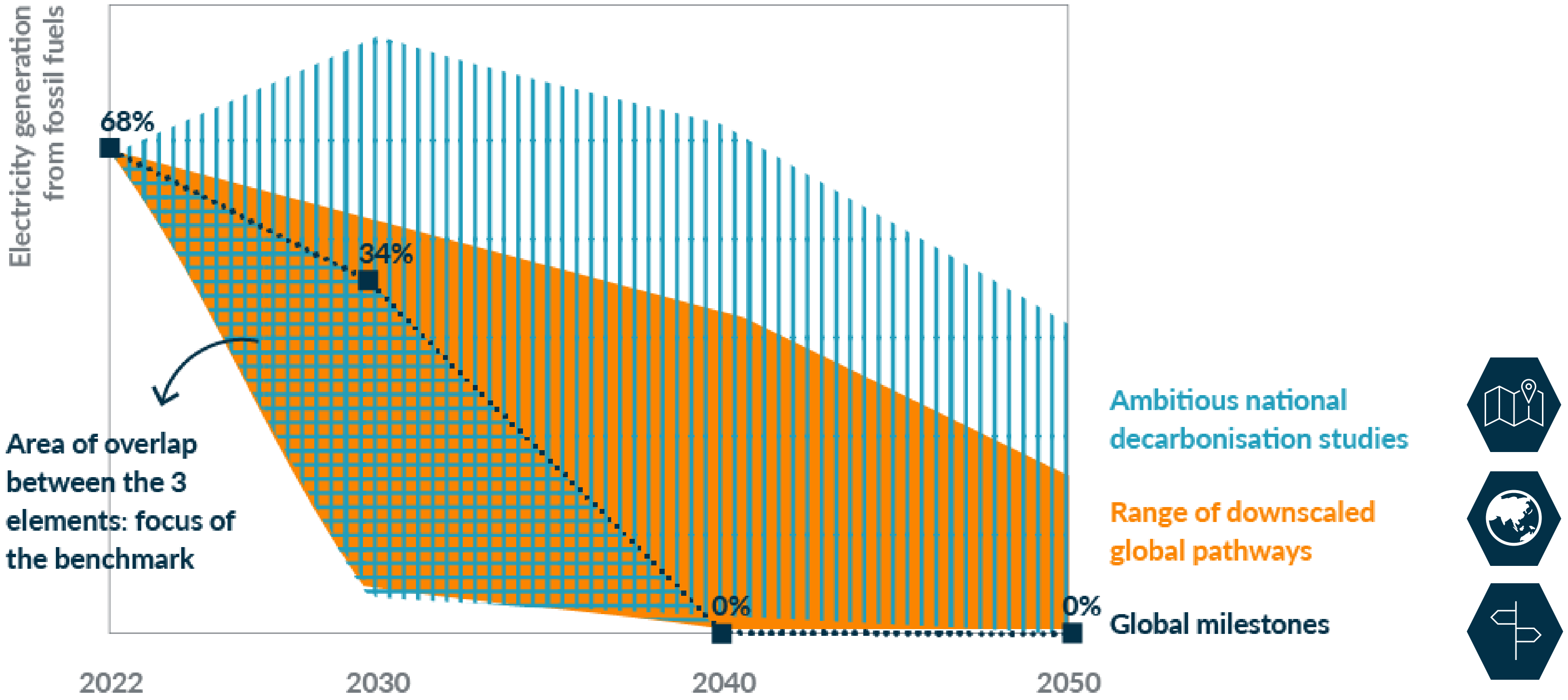
1 Total electricity generation

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.



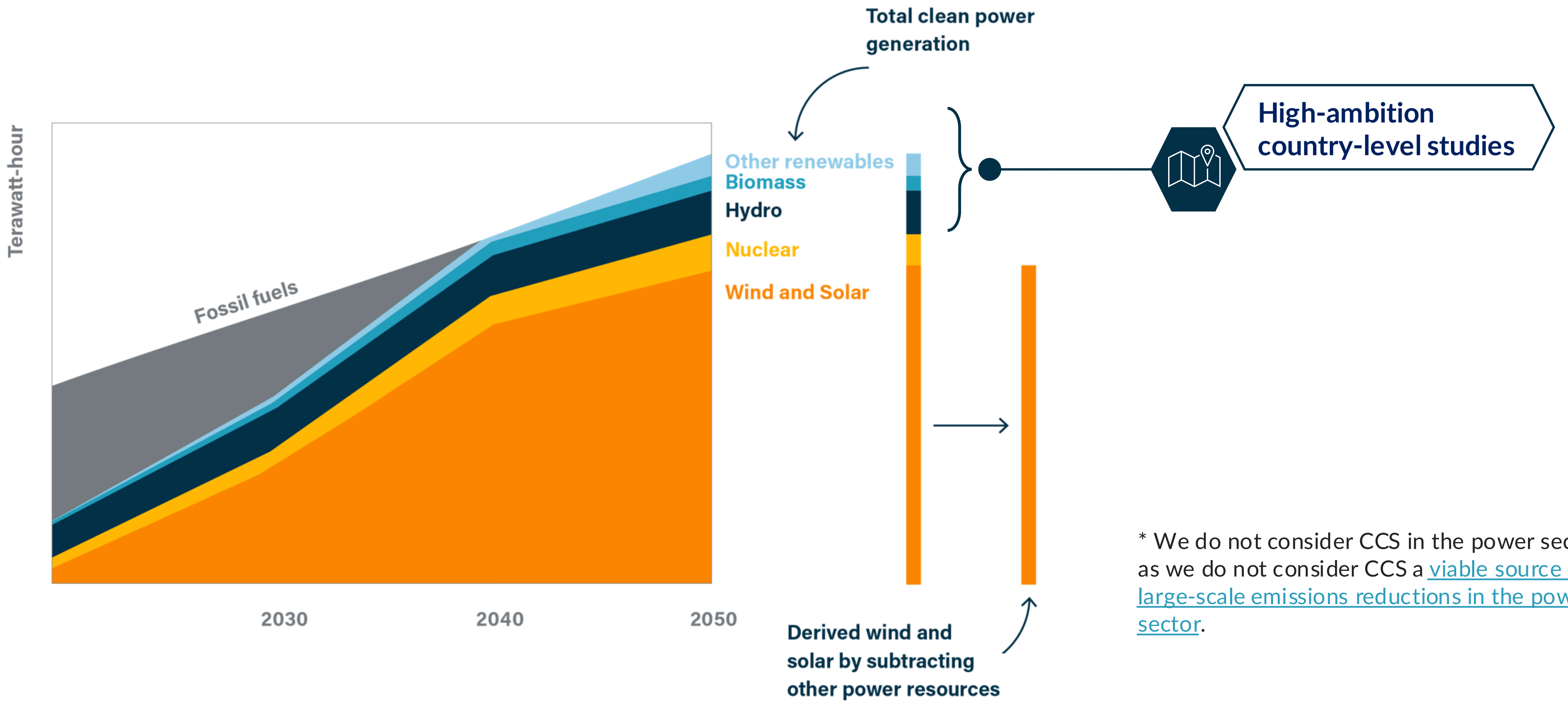
2 Fossil fuel phase-out

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

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

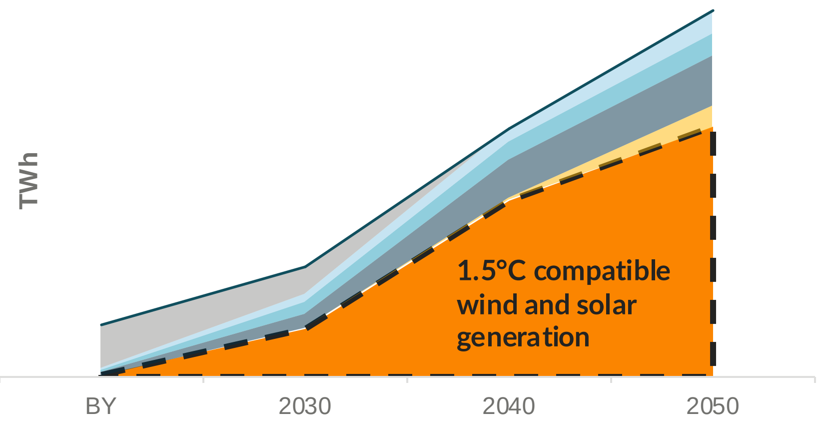
1. We use a detailed geospatial **renewable potential analysis** to calculate the technical potential of each technology in the country. We then feed the wind and solar generation required into a power system model calibrated to these potentials
2. We force the model to deploy at least the level of solar 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.

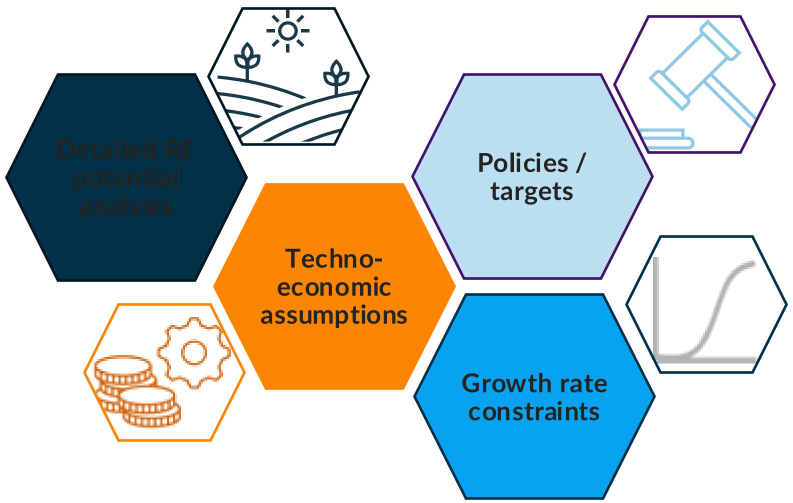
1.5°C compatible wind and solar generation (steps 1-4)

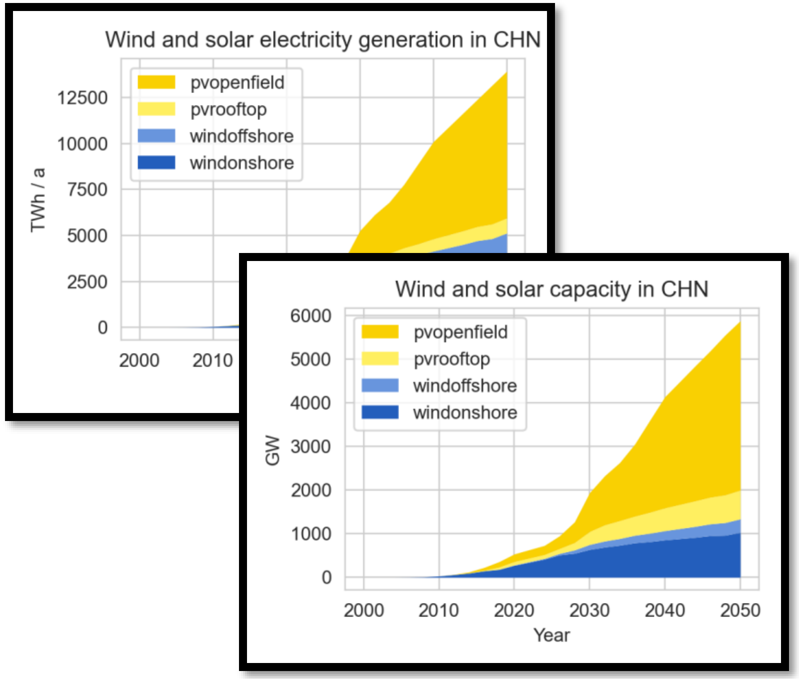
RE potential and power system analysis

Current targets and pledges

Generation and capacity of wind and solar







Key modelling parameters in the analysis

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 value for this constraint in the United States 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.