Wind and solar benchmarks for a 1.5°C world

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

India

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Executive Summary

Context

- Wind and solar are accelerating in India. However, electricity demand is growing even faster. As a result, wind and solar are still growing alongside coal, rather than displacing fossil fuels from the mix.
- India's power sector remains heavily dependent on coal, which provided 75% of electricity generation in 2023. Further action will be necessary to transform the Indian electricity system into one powered predominantly by renewables.
- In this report, we explore the level of wind and solar that India would need to install as part of a global 1.5°C compatible pathway. Our benchmarks are also compatible with tripling renewables capacity by 2030.

Key findings

- India's wind and solar generation needs to grow five to six times by 2030 to align with 1.5°C, reaching 900–1200 TWh of wind and solar.
- Just over 600 GW of wind and solar would be needed by 2030 (460 GW of solar and 150 GW of wind).
- Current rollout of wind and solar would need to further accelerate to align with 1.5°C. At the current pace of rollout, India would fall short of the needed capacity in 2030 by 140 GW of solar and 70 GW of wind.
- India will require large-scale investment to help phase down coal power, accelerate renewables deployment, and drive grid expansion. International support will be key in supporting the energy transition via climate finance.

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 **India.**

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

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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

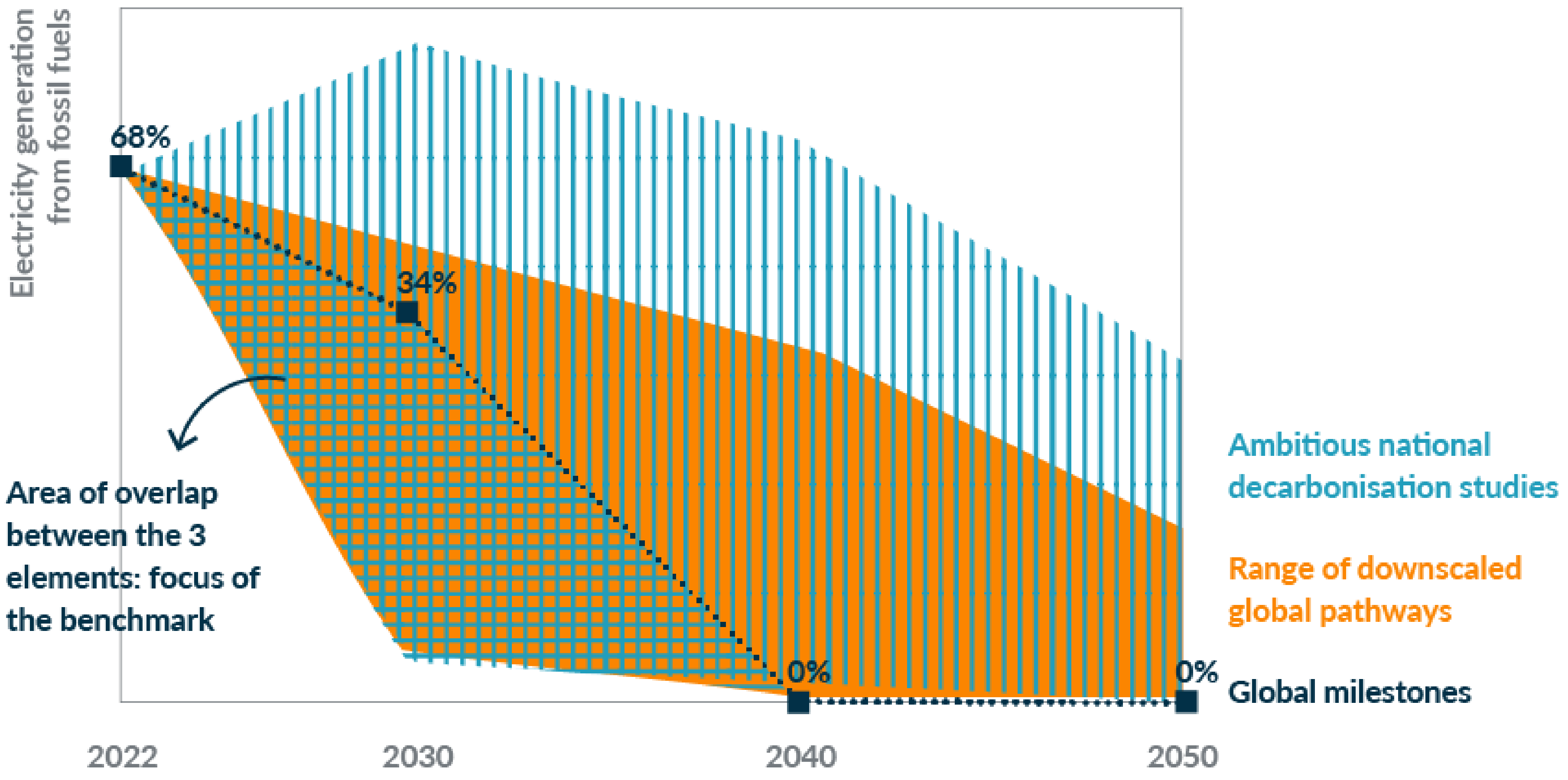
For more details see the Methods Annex

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)

International support

The key analytical elements (high ambition country-level studies and downscaled 1.5°C compatible global pathways) do not consider financing requirements.

Significant global resource transfers will be required in line with 'common but differentiated responsibilities and respective capabilities' to achieve these benchmarks.

We do not quantify the technical and financial support needed to achieve the wind and solar rollout presented in this report. This should be a country driven exercise and some countries have already initiated such processes, including under the JETP umbrella.

High-income countries will need to provide substantially increased climate finance to support emissions reduction abroad, in line with their 'fair share' of climate action.

Achieving these benchmarks in lower-income countries is therefore a global responsibility, rather than a domestic responsibility.

Policy context

India's current NDC is to cut emissions intensity by 45% below 2005 levels in 2030. This is estimated to represent an emissions level of ~4.6 $GtCO_2e$ in 2030 excluding LULUCF. The country has pledged to become net zero by 2070.

India's current renewable targets are to reach **319 GW of solar and 110 GW of wind by 2030**, as of the Indian National Electricity Plan 2022-32.

Under current policies and market conditions, the IEA estimates that **solar capacity will reach 238 GW in 2028**, up from 83 GW of solar in 2022. Meanwhile, **wind capacity is projected to reach 69 GW in 2028**, up from 42 GW in 2022.

Results

Future electricity demand

Electricity demand is taken from the TERI's study exploring India's electricity transition pathways out to 2050. This conducts a detailed estimate of future electricity demand in India, based on a bottom-up review of electrification trends by sector, and economic and demand-growth.

In this study, total electricity generation in India almost triples by 2050 relative to 2022 levels, reaching 5200 TWh.

However, there is a significant range in the studies in terms of the expected electricity generation in 2050 ranging from 5200 TWh to 9200 TWh. This would affect the necessary growth of wind and solar significantly. Our demand estimate is at the lower end of that 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 India achieves a clean power system by 2045.

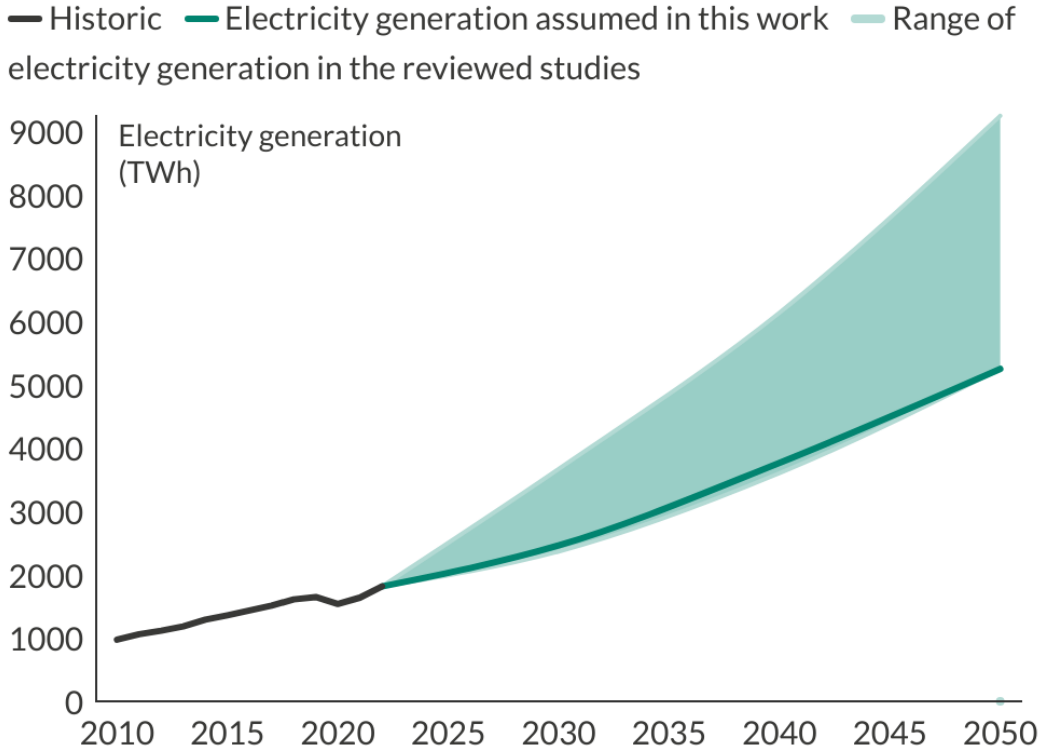
To align with 1.5°C, fossil fuels must exit the Indian power sector before 2045

Fossil fuel generation falls by 20 to 44% between 2022 and 2030 in our benchmarks. Phasing out fossil fuels while simultaneously meeting rapidly growing electricity demand will require substantial international support, including climate finance to help with the early retirement of existing coal-fired power plants.

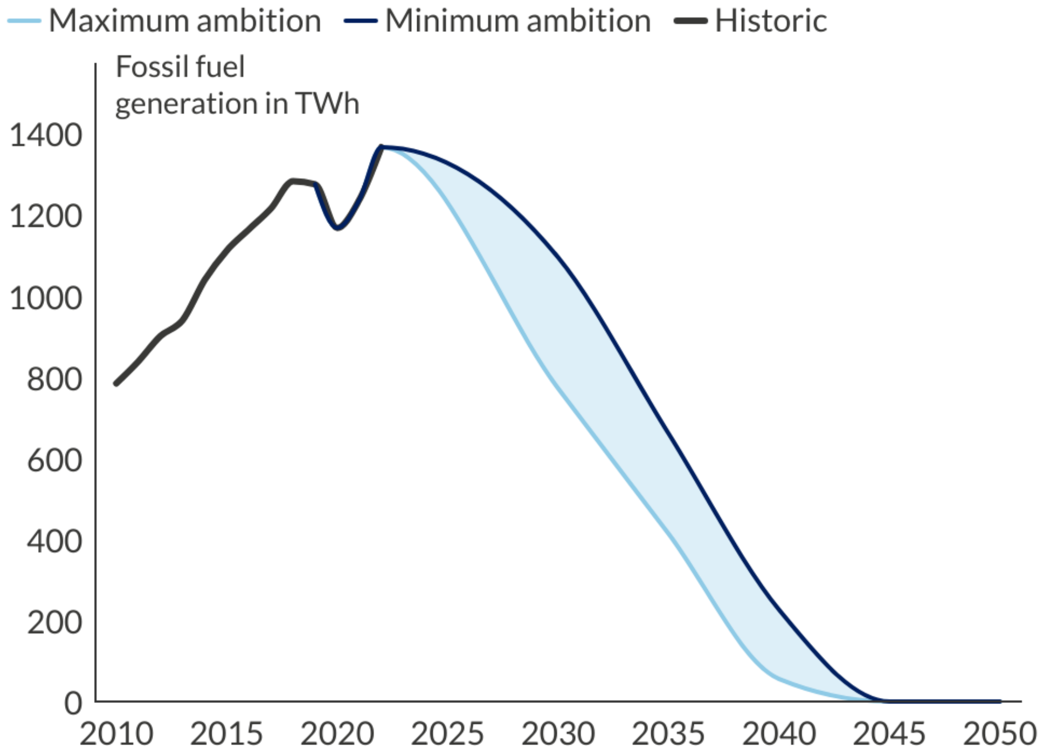
The fastest rate of fossil phase-out is set Teske et al., 2019's 1.5°C aligned pathway for India.

To align with 1.5°C, fossil fuels must exit the power sector in India by 2045, even as electricity demand grows rapidly.

Electricity generation almost triples in India over 2022–2050



India would need to achieve clean electricity by 2045



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 India would reach almost 500 TWh by 2030 and over 1000 TWh by 2050. This is provided largely by a mix of hydropower, biomass and geothermal, with limited nuclear 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.

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

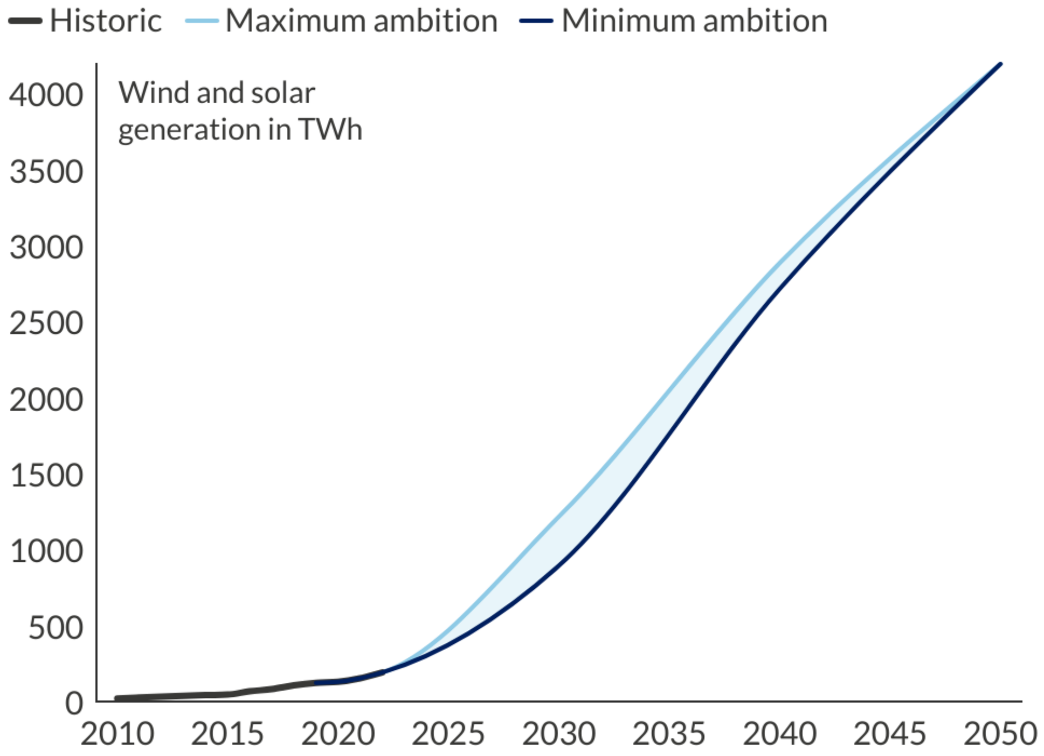
The wind and solar rollout necessary is then calculated by combining projected electricity demand growth, the fossil phase-out necessary to align with 1.5°C, and the assumed generation from other clean technologies.

To align with 1.5°C, wind and solar generation in India would need to reach between 900 and 1200 TWh by 2030. Generation in 2022 was 191 TWh. This is therefore a 5 to 6-fold growth in wind and solar over 2022–2030.

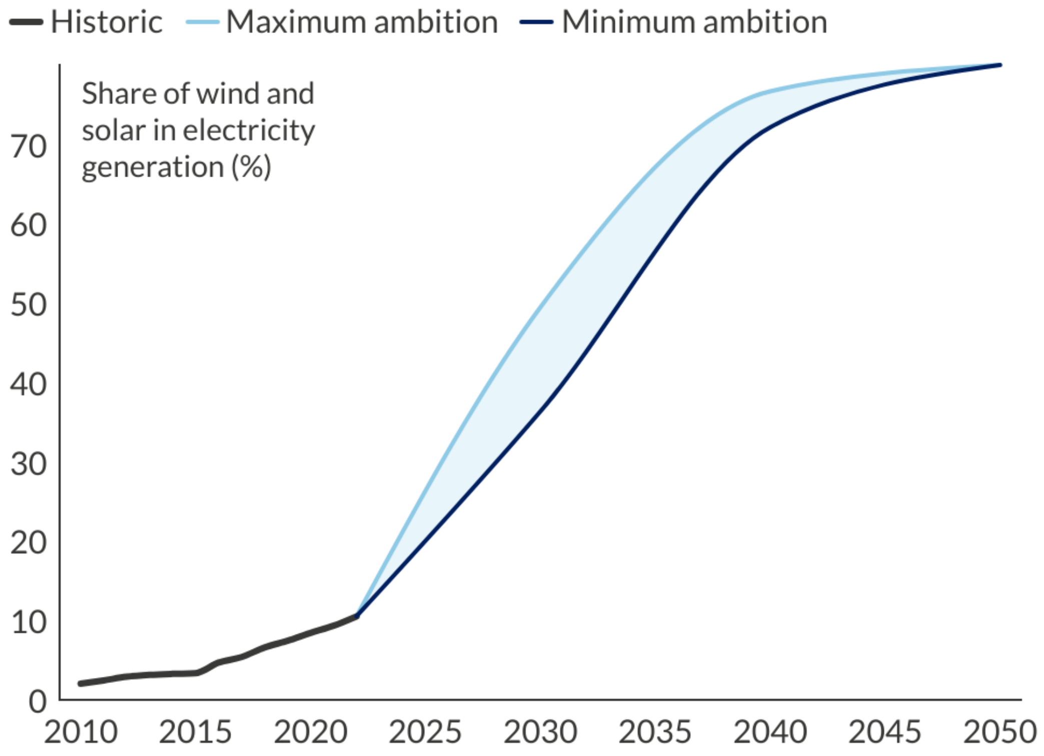
Wind and solar provides 36–49% of overall electricity generation in 2030, and 80% of overall generation in 2050.

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

Wind and solar generation needs to grow 5-6x by 2030 relative to 2022 in India



Wind and solar would need to provide around 80% of electricity generation in India 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.

In India, the level of uncertainty seen in our benchmarks across wind and solar costs is small. This does not mean that there is no uncertainty in the possible split of wind and solar, as a range of other uncertainties could also impact on the split, including grid capacity, supply chains, national policies and more.

We highlight the median of the range as our **central benchmark**, but do not suggest that this is the only possible breakdown into wind vs. solar. In the central benchmarking scenario, solar becomes the main source of generation, providing on average 70% more generation as wind in the electricity mix by 2050. This will require a rapid uptake of non-fossil flexibility options.

In this scenario, **India would need to deploy around 600 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 2.6 TW. Due to its higher capacity factor, greater wind deployment would reduce total capacity requirements.

On average, solar provides nearly twice as much electricity as wind by 2050 in India

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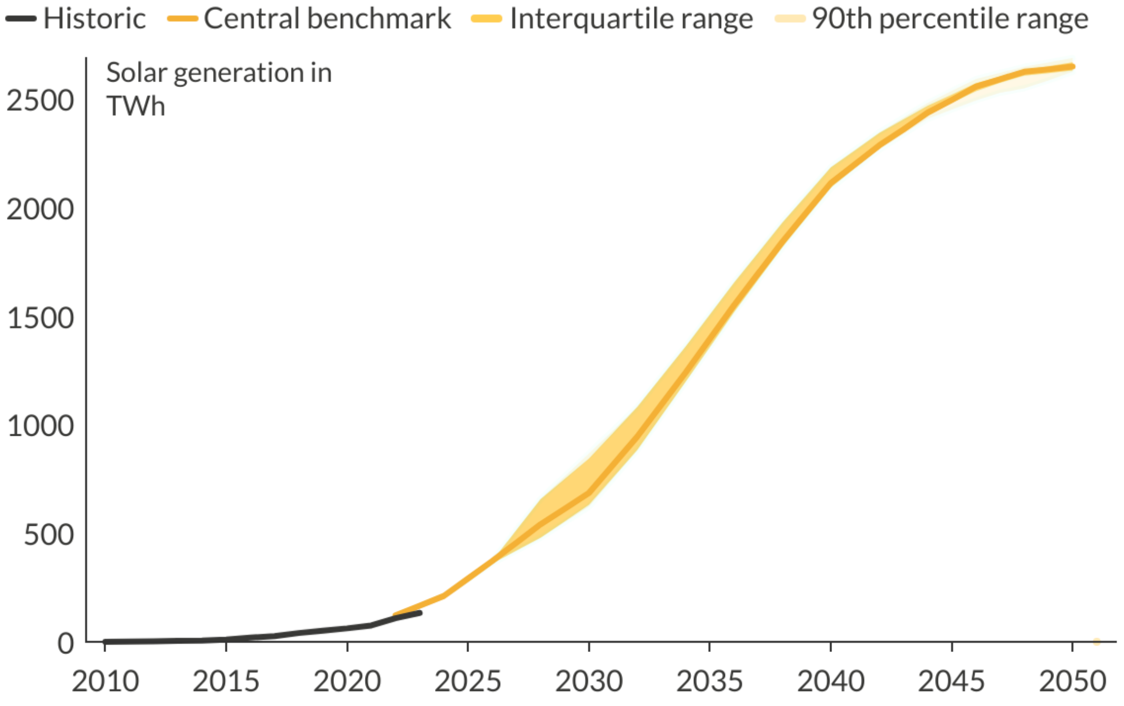
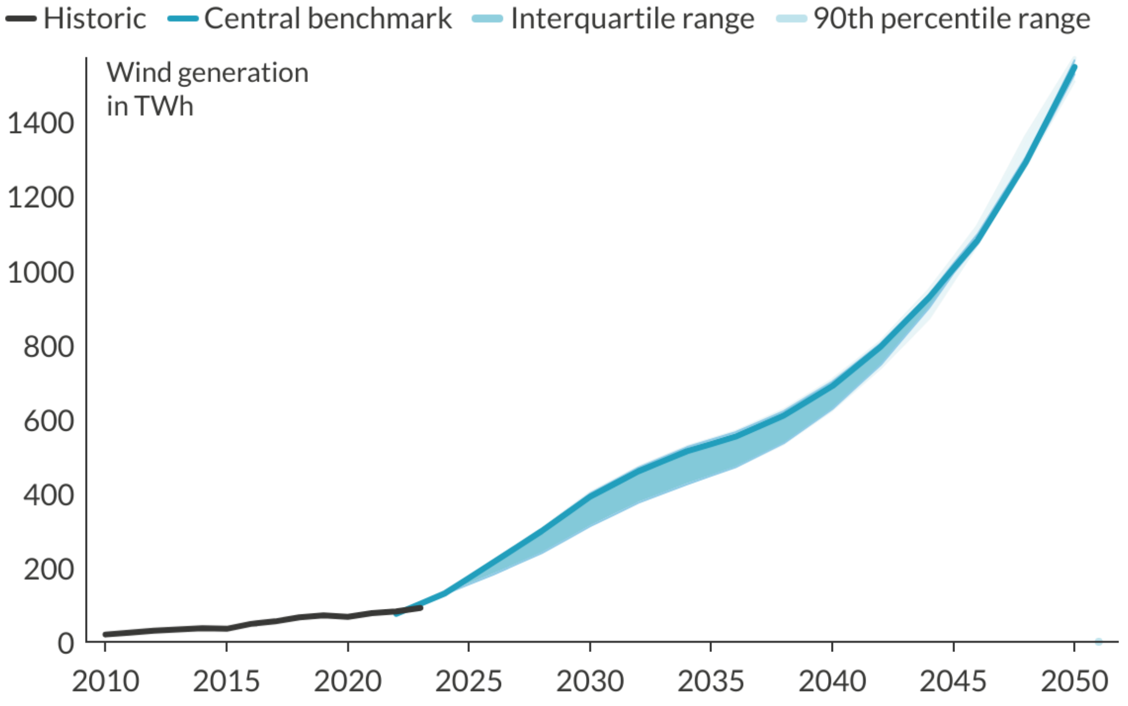
Solar generation in India would reach around 2500 TWh by 2050 in a 1.5°C-aligned transition



Wind generation in India would reach around 1500 TWh by 2050 in a 1.5°C-aligned transition



India needs to install around 600 GW of wind and solar by 2030 to align with 1.5°C

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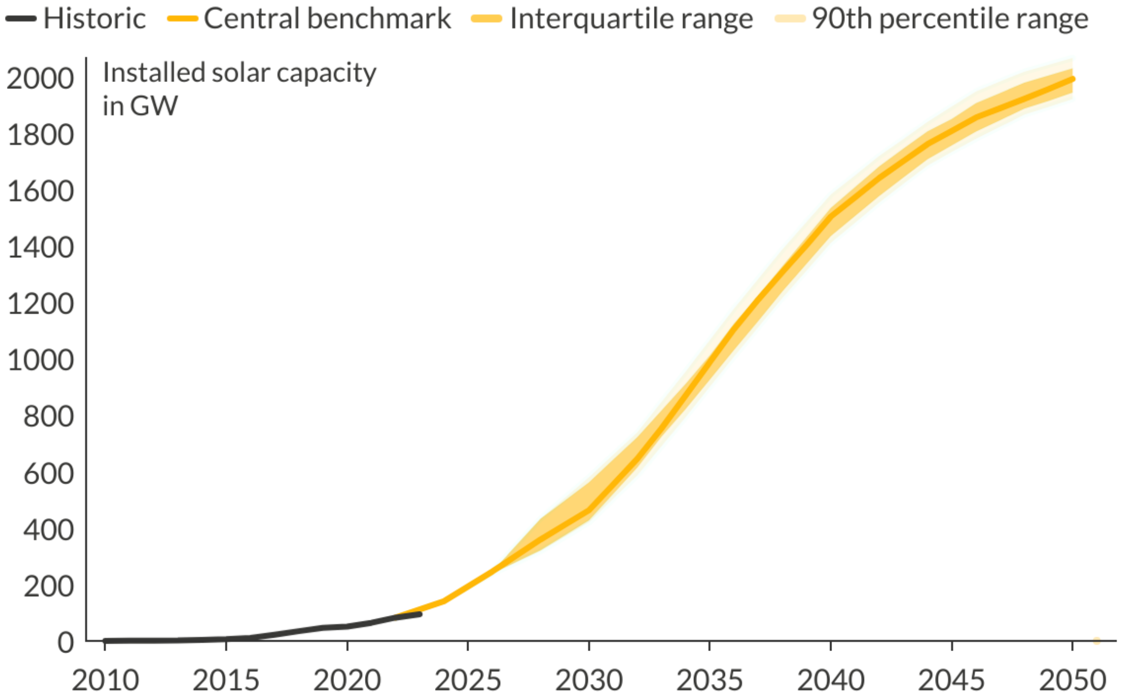
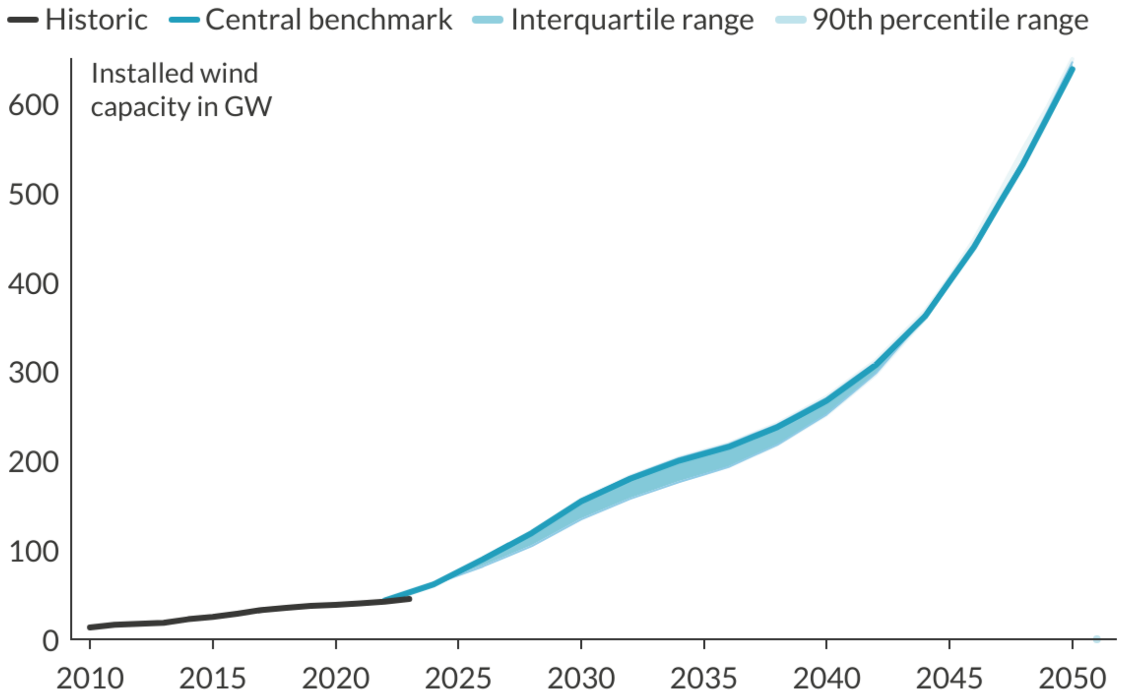
Solar capacity would reach 460 GW in India by 2030 in a 1.5°C-aligned scenario



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



Comparison to current rollout

We extend the IEA's capacity forecast for wind and solar (which is provided out to 2028) to 2030 and compare to the benchmarks presented in this report.

This highlights that currently India is on track to achieve its 2030 target for solar of just over 300 GW but is not on track to install the 110 GW of wind targeted in the National Electricity Plan 2022-2032.

Both current targets and current policy rollout would need to be further accelerated to align with the 1.5°C compatible benchmarks presented in this report.

India’s rollout of wind and solar is lagging behind 1.5°C- aligned level

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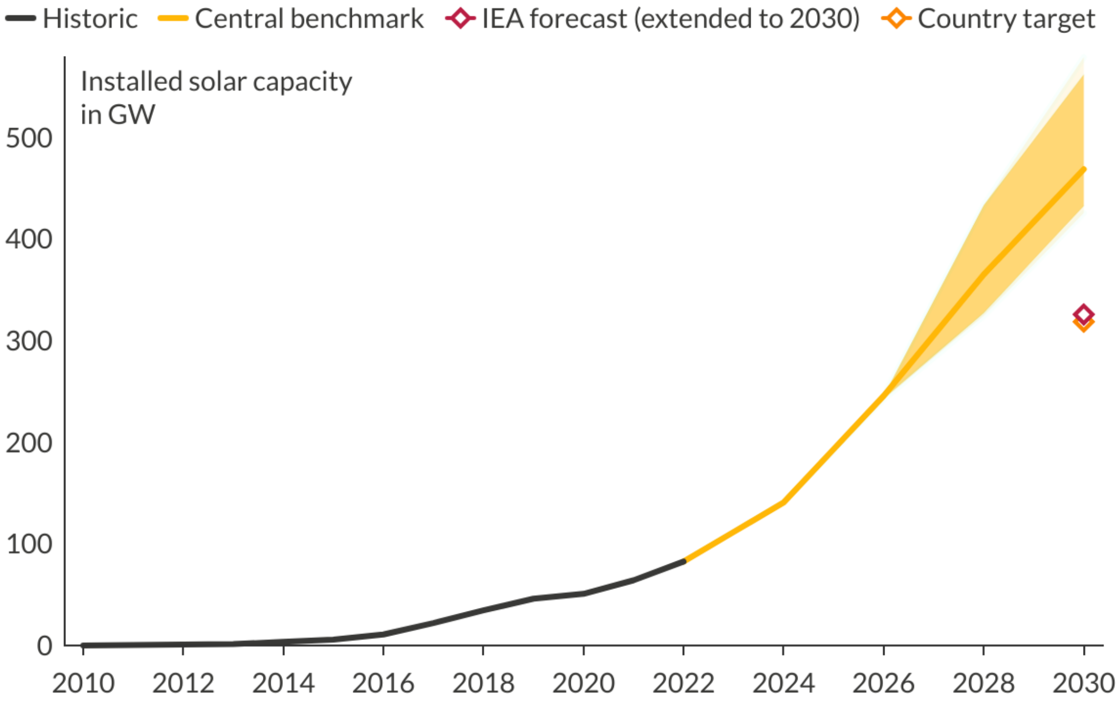
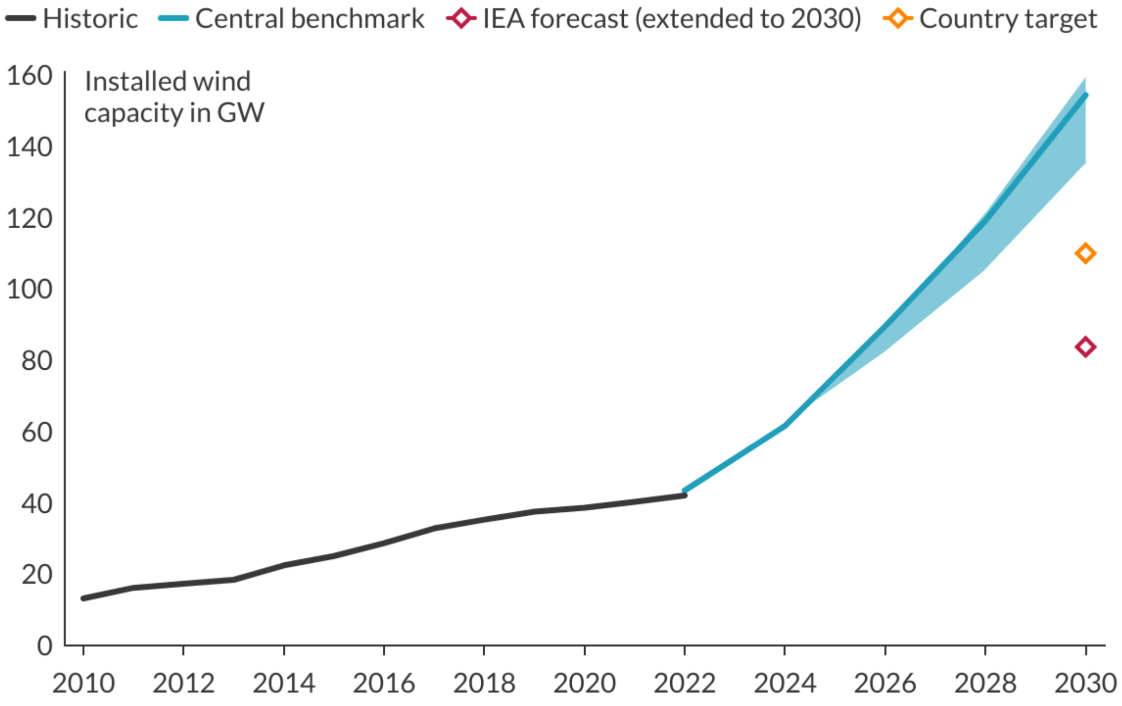
In India, current rollout of solar is lagging behind 1.5°C-aligned levels

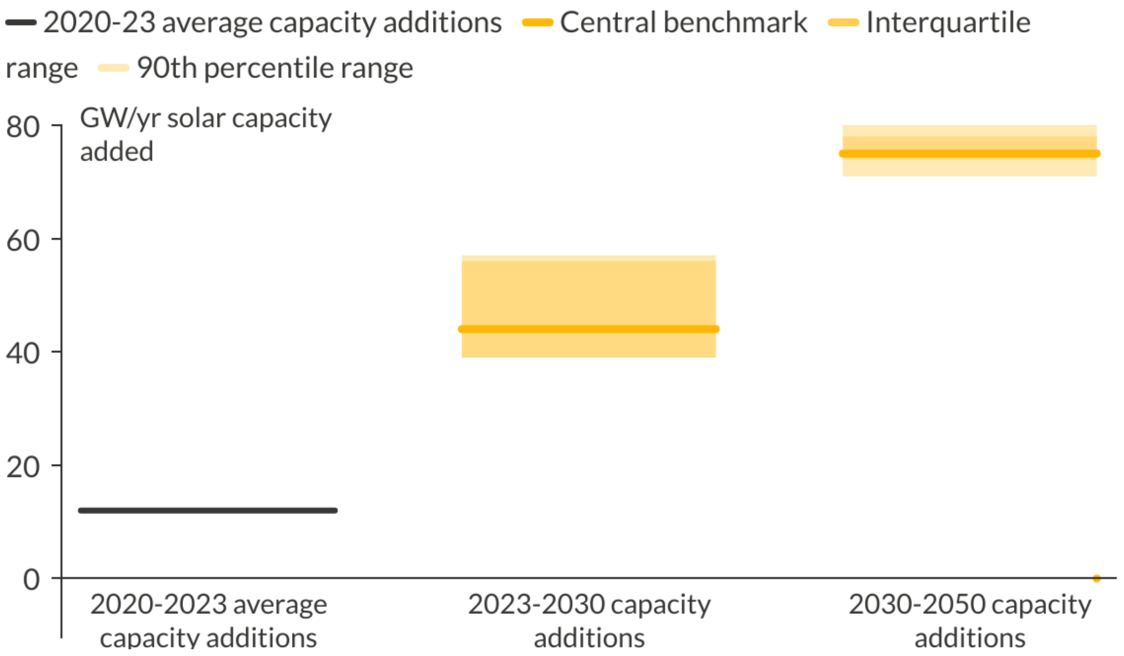


In India, current rollout of wind is lagging behind 1.5°C-aligned levels

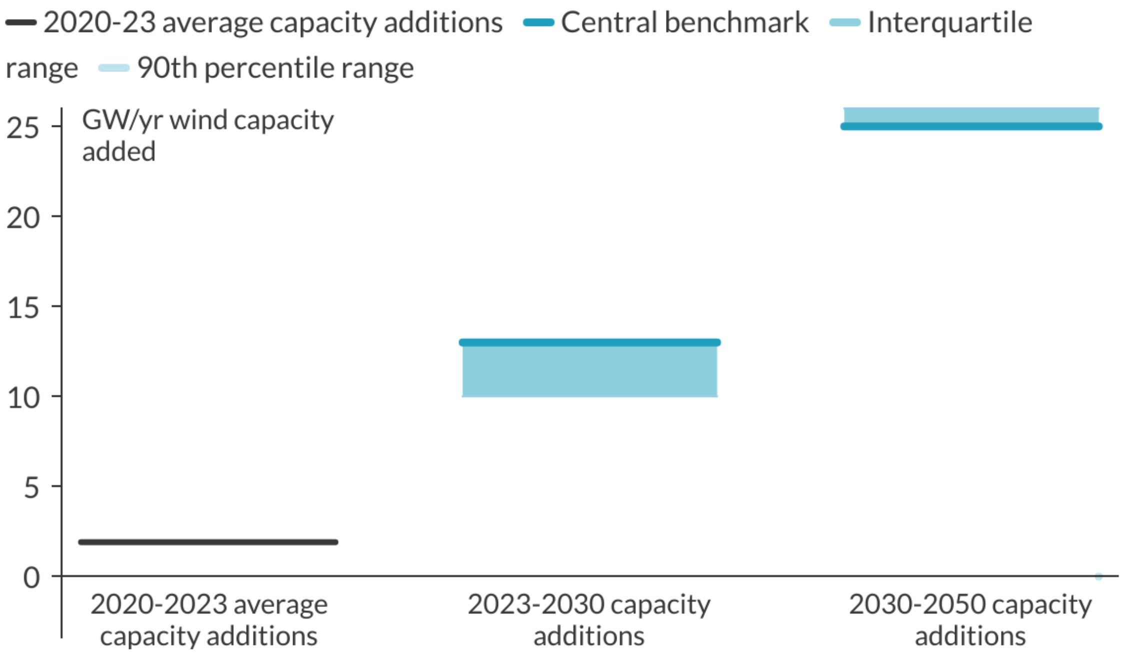


Wind and solar capacity additions in India need to accelerate to align with 1.5°C

India would need to add on average 44.0 GW/yr of solar capacity until 2030, and 75.0 GW/yr by over 2030–2050.



India would need to add on average 13.0 GW/yr of wind capacity until 2030, and 25.0 GW/yr by over 2030–2050



Comparison with other studies

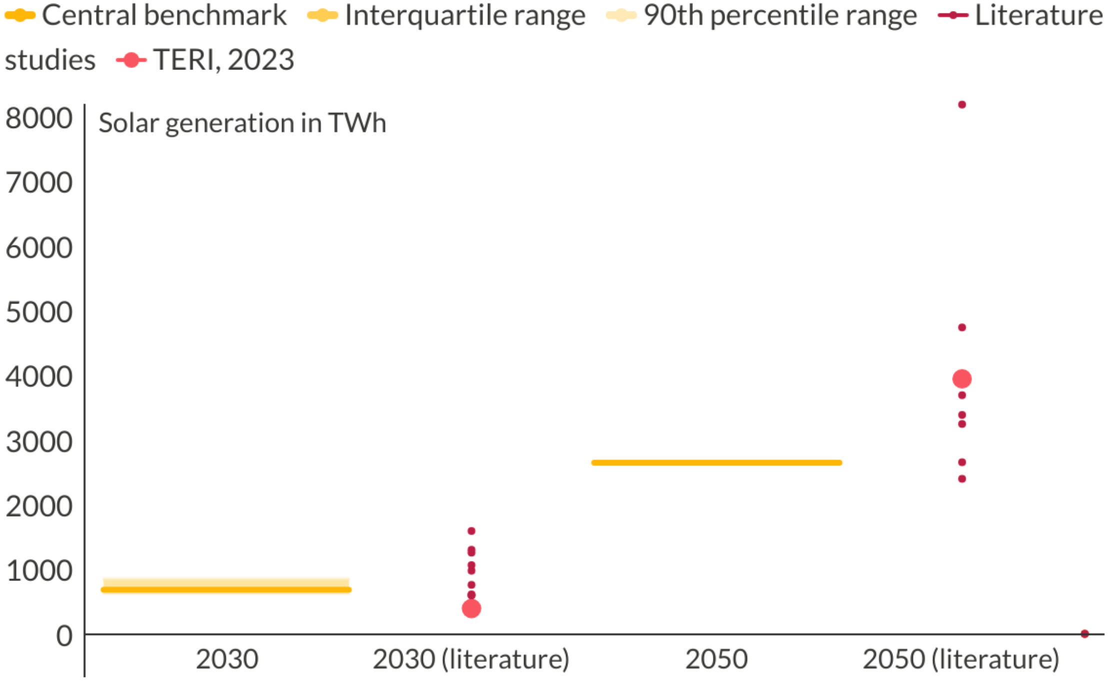
We compare the wind and solar generation seen in our analysis to that in the literature review of country-level studies. In particular, we highlight the results from TERI's modelling of a net zero power sector in which there is no new fossil fuel capacity added after 2025.

Our modelling suggests that **solar will be the dominant source of electricity generation** in future zero-carbon electricity grids for India. The majority of the literature agrees with this, with solar providing the majority of electricity generation in most country-level studies exploring deep decarbonization of the Indian power sector.

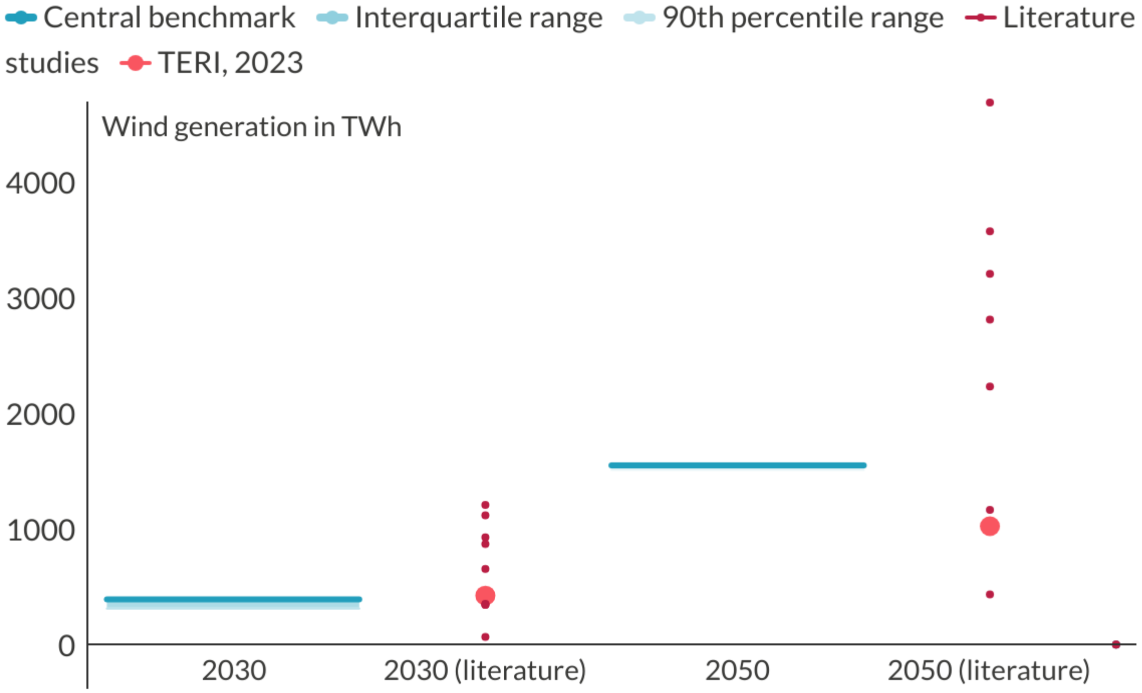
In general, our analysis is broadly aligned with the results of country-level studies, although is at the lower end of solar generation in 2050.

Our benchmarks are broadly aligned with the literature

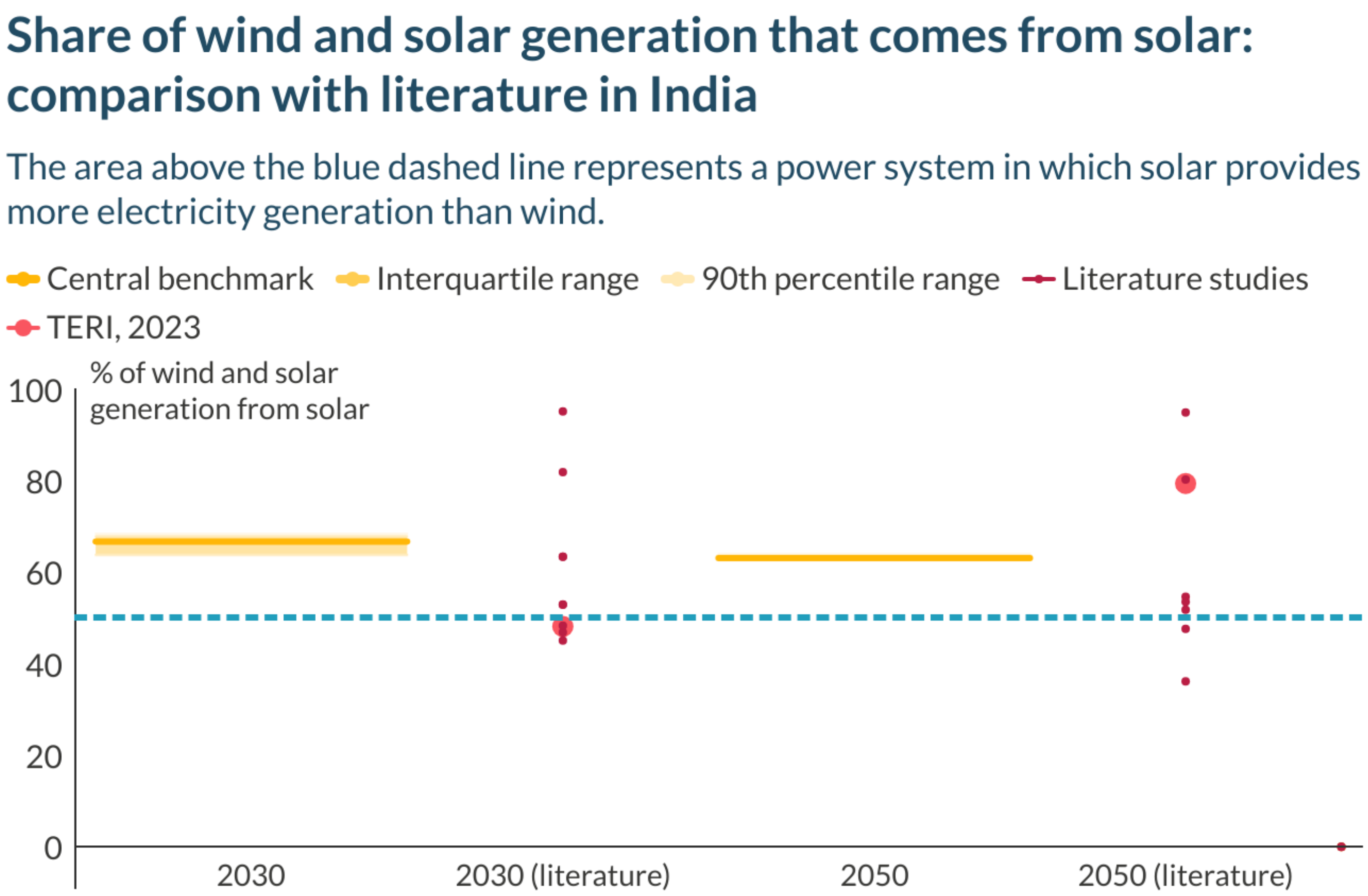
Electricity generation from solar: comparison with literature in India



Electricity generation from wind: comparison with literature in India



In India, our benchmarks generally suggest that solar will provide more 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	121	690	1400	2100	2600
Central 1.5°C benchmark	Wind generation	TWh	75	390	530	690	1500
Central 1.5°C benchmark	Solar capacity	GW	83	460	990	1500	2000
Central 1.5°C benchmark	Wind capacity	GW	43	150	210	270	640

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

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

Study	Publication	Scenario Selected
Gulagi et.al., 2017	The role of storage technologies in energy transition pathways towards achieving a fully sustainable energy system for India	Integrated scenario
Lawrenz et.al., 2019	Exploring energy pathways for the low-carbon transformation in India--A model-based analysis	limited emissions only (LEO)
Teske, 2015	A Sustainable World Energy Outlook 2015	Advanced Energy [r]evolution scenario
Teske, 2015	A Sustainable World Energy Outlook 2015	Energy [r]evolution scenario
IEA, 2021	India Energy Outlook 2021	Sustainable Development Scenario
Teske, 2019	Achieving the Paris Climate Agreement Goals	1.5 °C
Teske, 2019	Achieving the Paris Climate Agreement Goals	2 °C
TERI, 2023	India's Electricity Transition Pathways to 2050: Scenarios and Insights	No fossil fuel scenario
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

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

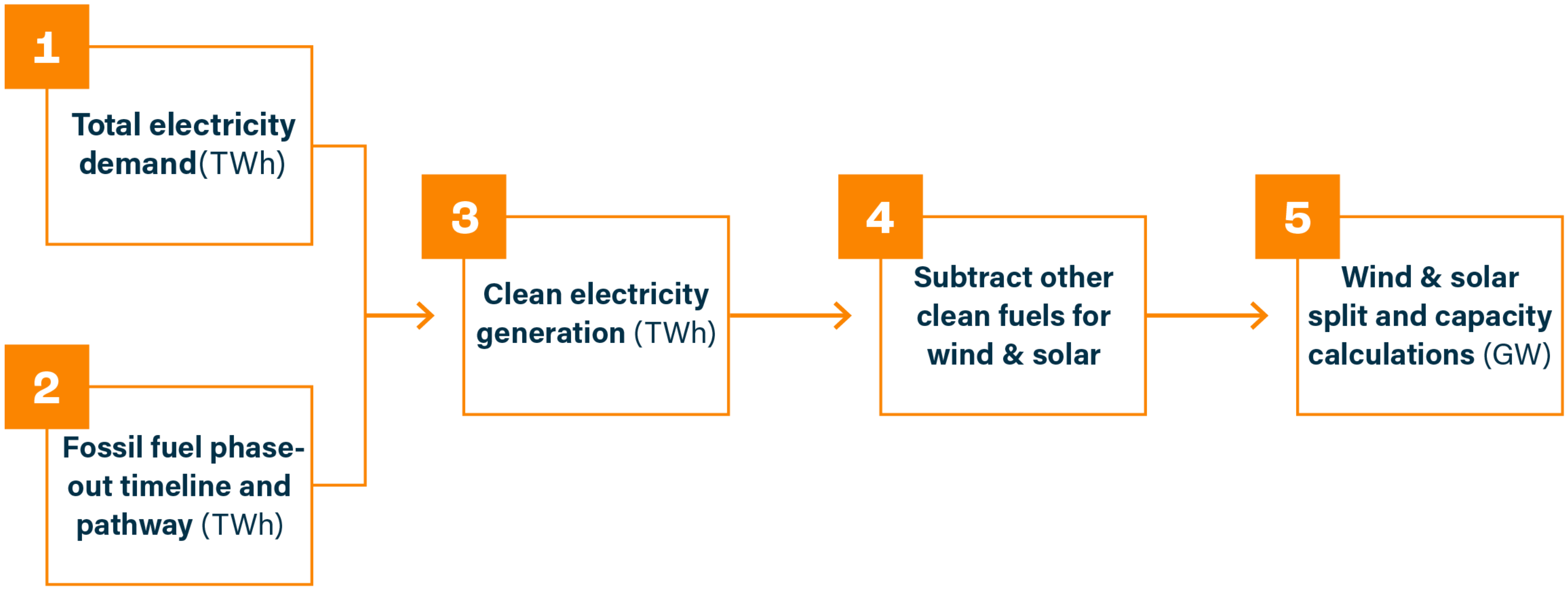
Our method takes a series of steps to calculate the wind and solar generation needed for 1.5°C, and the resulting capacity deployment.

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



For more details see the [Methods Annex]

1 Total electricity generation

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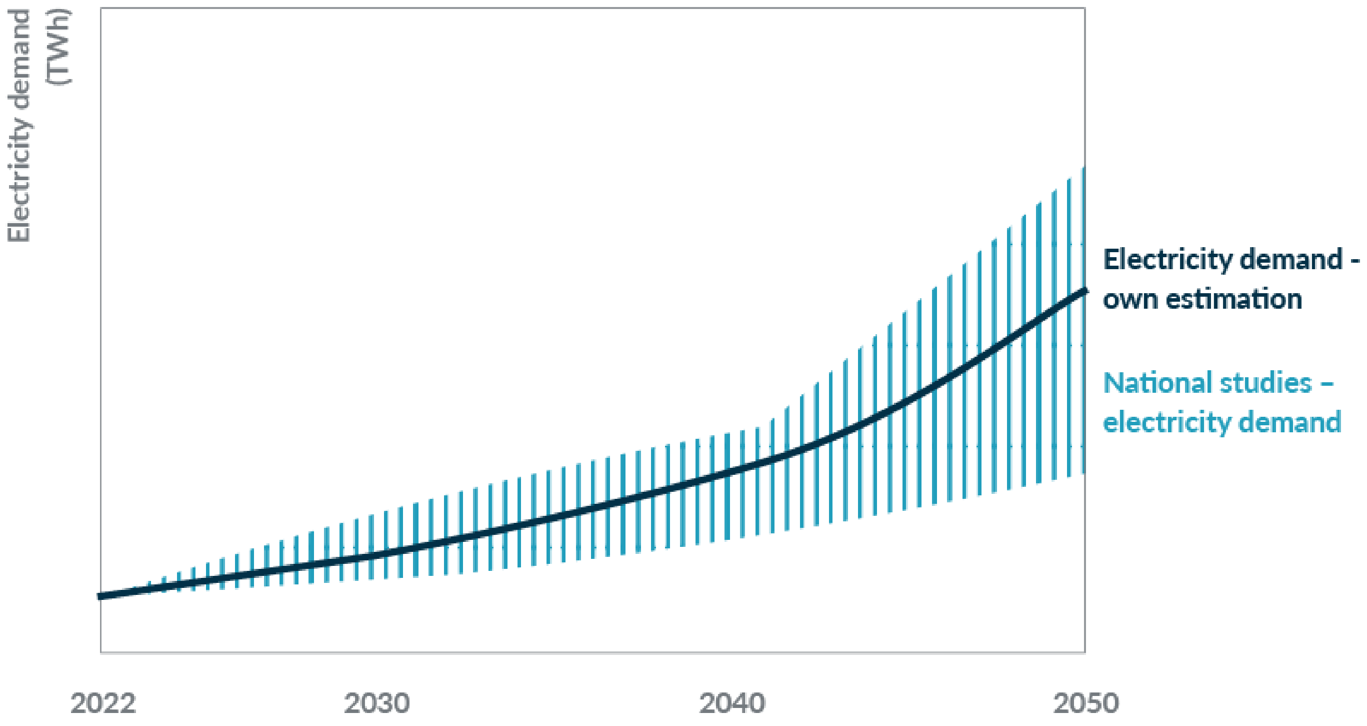
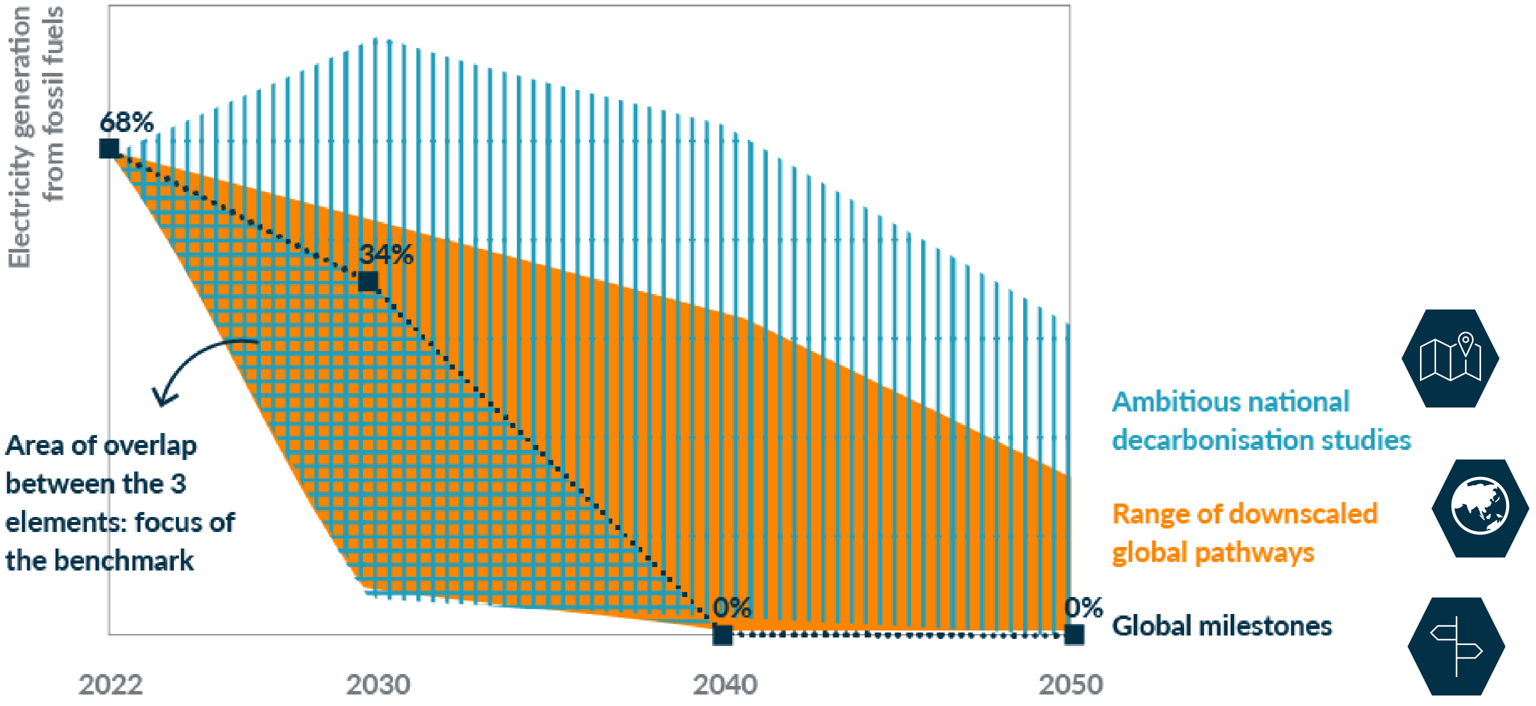
1. We extract electricity generation projections for 2030, 2040, and 2050 from **ambitious country-level studies**.
2. We then identify an electricity generation projection from a scenario to use for our analysis. We focus on identifying studies which capture key elements of the transition, including **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.



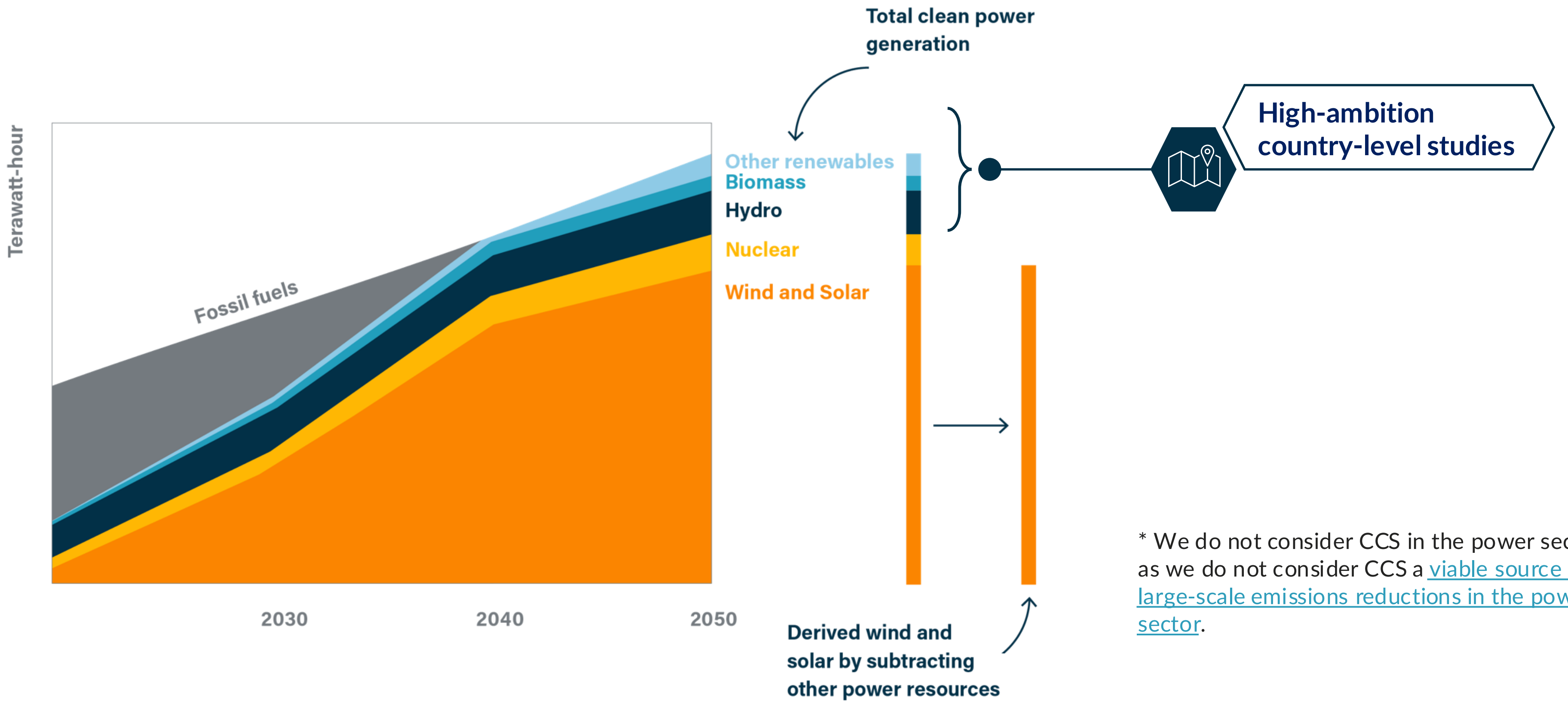
2 Fossil fuel phase-out

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.

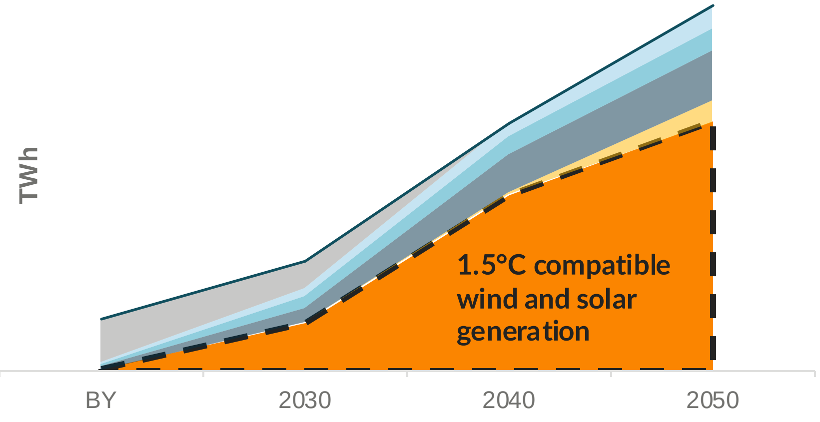


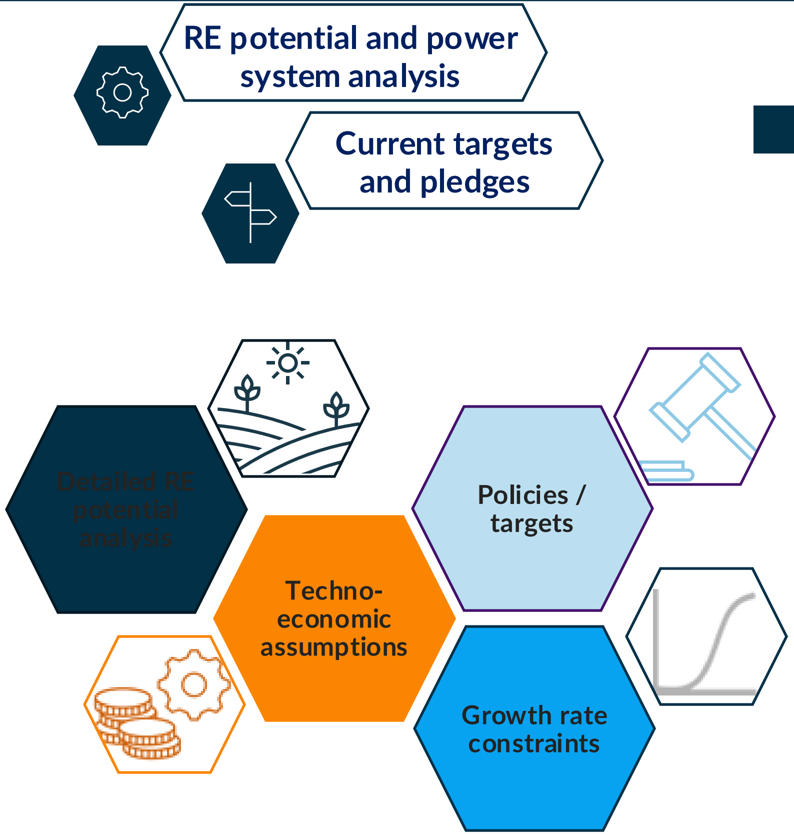
* We do not consider CCS in the power sector, as we do not consider CCS a viable source of large-scale emissions reductions in the power sector.

5 Wind and solar breakdown

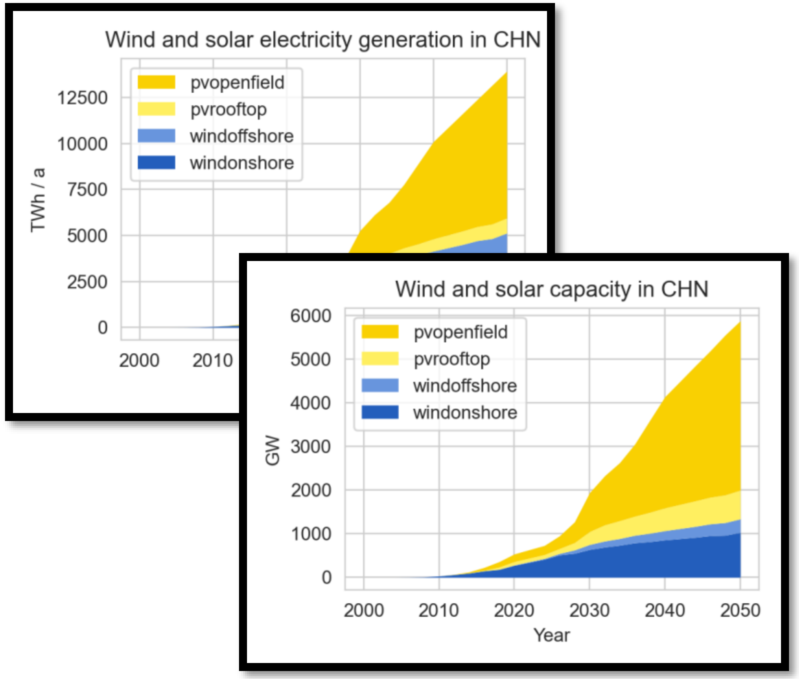
1. We use a detailed geospatial **renewable potential analysis** to calculate the technical potential of each technology in the country. We then feed the wind and solar generation required into a power system model calibrated to these potentials
2. We force the model to deploy at least the level of solar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





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 = 16% per year • Solar = 33% 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 is 25%. 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.