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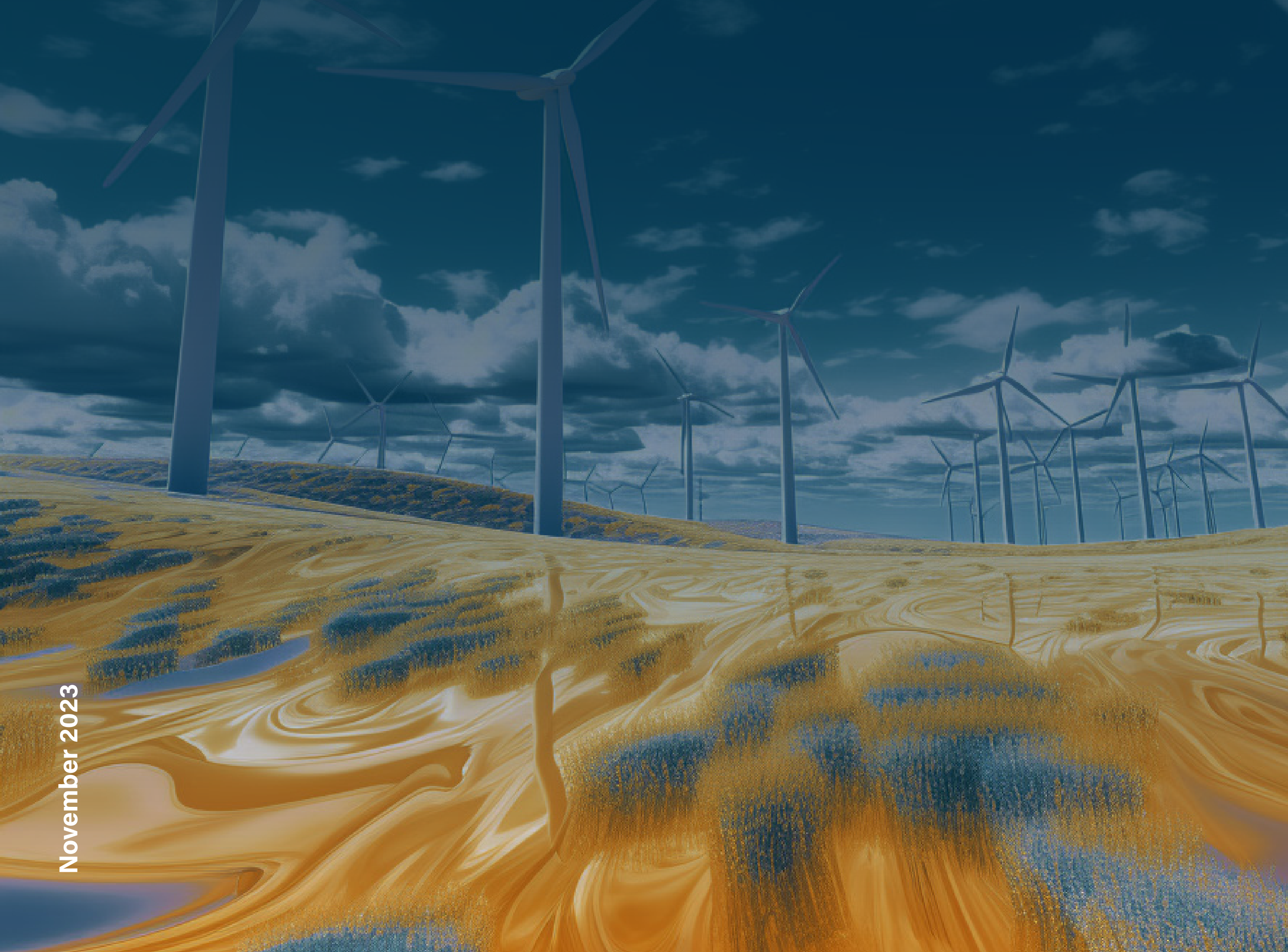
Wind and solar benchmarks for a 1.5°C world

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



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01 Background

The global power sector is critical in mitigation efforts against climate change, as it is both a major contributor to greenhouse gas emissions and the foundation for decarbonising other sectors through electrification and sector coupling. Emissions from the power sector—generated by the burning of fossil fuels such as coal, natural gas, and oil—have generally been on an upward trend in the last decade despite strong renewable deployment meeting the bulk of growth in global electricity demand in 2022 (IEA, 2023a). As electricity demand continues to rise with growing populations, urban centres and economies, the need to transform the power sector is becoming increasingly urgent, starting with a tripling of renewable energy capacity by 2030 from today's levels. The clean energy transition not only holds the key to mitigating climate change but also presents opportunities for innovation, economic growth, and improved energy access worldwide.

Wind and solar technologies have experienced the most promising growth in clean electricity fuels, driven by technological advancements, favourable economics and policy developments that improve financial conditions, regulatory structure, and market stability. This development has also highlighted the potential of these clean industries to stimulate economic growth, create jobs, and improve energy security. Wind and solar have been major drivers of the imminent peak emissions in global electricity supply (Ember, 2023) and will experience the largest growth in low-carbon energy supply on the road to global net zero (IEA, 2023b).

But wind and solar capacity deployment under current and planned policies continues to fall short of the required speed and scale. The bulk of clean power expansion is concentrated in a few regions, notably China the US, Europe, and India. The main factors contributing to the limited global reach and holding back investment in many other countries are attributed to higher financial costs, ambiguous policy frameworks, and failure to recognise and harness the transformative potential of renewable investments in promoting and aligning with countries' development priorities (IEA, 2023d; IRENA, 2023a). These technologies need to be scaled up sufficiently in all regions to decarbonise the global economy, however there is limited research until now on the levels of wind and solar needed to be installed over time, and in which geographies, to safeguard the 1.5°C limit of the Paris Agreement.

In this document, we provide a stepwise methodology for defining credible, replicable, and transparent 1.5°C compatible benchmarks for wind and solar capacity expansion and generation at the country level while accounting for national circumstances.

In → **Section 2**, we outline the considerations and lines of evidence employed to construct the methodology and detail the novel stepwise approach. In → **Section 3** we present indicative 2030, 2040, and 2050 benchmark results for a subset of countries (Brazil, China, India, Indonesia, Germany, South Africa) and conclude in → **Section 4** with a discussion of the results and areas of future research.

02 Methodology

This section presents the different building blocks of the methodology and how they are combined in a step-by-step method to quantify wind and solar capacity benchmarks. The methodological framework presented here is not intended to provide forecasts of what wind and solar capacity might be installed under current efforts, but rather a picture of the global power sector decarbonisation needs translated to the national level.

2.1 Guiding principles

The scope and design choices of a method differ significantly depending on the intended purpose, application, and the resources available, with trade-offs existing at every element. Broadly, on one end of the spectrum, a method could employ various “simple” approaches to estimate capacity growth like global deployment growth rates or stylised technological adoption curves to serve as proxies for renewable installation pathways at the country level or citing selected results from the literature based on a systematic review. These simple approaches have the advantage of being able to calculate benchmarks for many countries in a less resource-intensive and transparent manner but are also unlikely to be precise or reflect real-world circumstances. On the other end of the spectrum, an approach could employ the use of advanced power and energy systems modelling at the national (and sub-national) level, which would lead to detailed results but would be resource-intensive, inaccessible to general audiences and policymakers, and be highly sensitive to the inputs of one modelling team.

As a first step, we established a catalogue of guiding principles to inform and steer our design of an approach. The final methodology to calculate wind and solar capacity benchmarks should ensure:

- → **1.5°C compatibility**, meaning the aggregated benchmarks of all countries and regions are derived from and consistent with global levels sufficient to limit global warming to under 1.5°C by the end of the century.
- → **Capture of local circumstances**, reflecting the characteristics of national energy systems, geographies, and renewable resource potentials.
- → **Capture of fundamentals and nuances in power sector transitions**, such as economy-wide electrification needs, energy efficiency gains, and renewable grid integration and flexibility challenges.
- → **Clean fuel inclusive**, to recognize the availability and viability of other low-carbon sources (excluding wind and solar) in existing national energy systems.

- → **Robustness**, to provide accurate benchmarks that are reviewed, validated, and sense-checked across other high-quality sources of evidence.
- → **Common but differentiated responsibilities**, to reflect equity considerations that those historically responsible and with greater capabilities decarbonise their power systems more rapidly.
- → **Transparency**, where the data sources and lines of evidence used to apply the methodology can be derived from publicly available sources, and the method itself is published.
- → **Communicability**, so a wide range of stakeholders can easily and intuitively understand the method, the lines of evidence it draws from, and its guiding principles.
- → **Replicability and consistency**, so the approach can be applied without bias to a range of countries with diverse characteristics and still stay aligned with other guiding principles.

To ensure the principles above, we identified the need for a more nuanced and balanced approach as neither a simple approach nor a modelling approach was appropriate **(see → Figure 1)**. The approach proposed, labelled as a "step-by-step method", resorts to employing different lines of evidence **(see → Section 2.2)** to inform all relevant features of the methodology in the construction of wind and solar benchmarks for the power sector while respecting the guiding principles defined above **(see → Section 2.1)**.

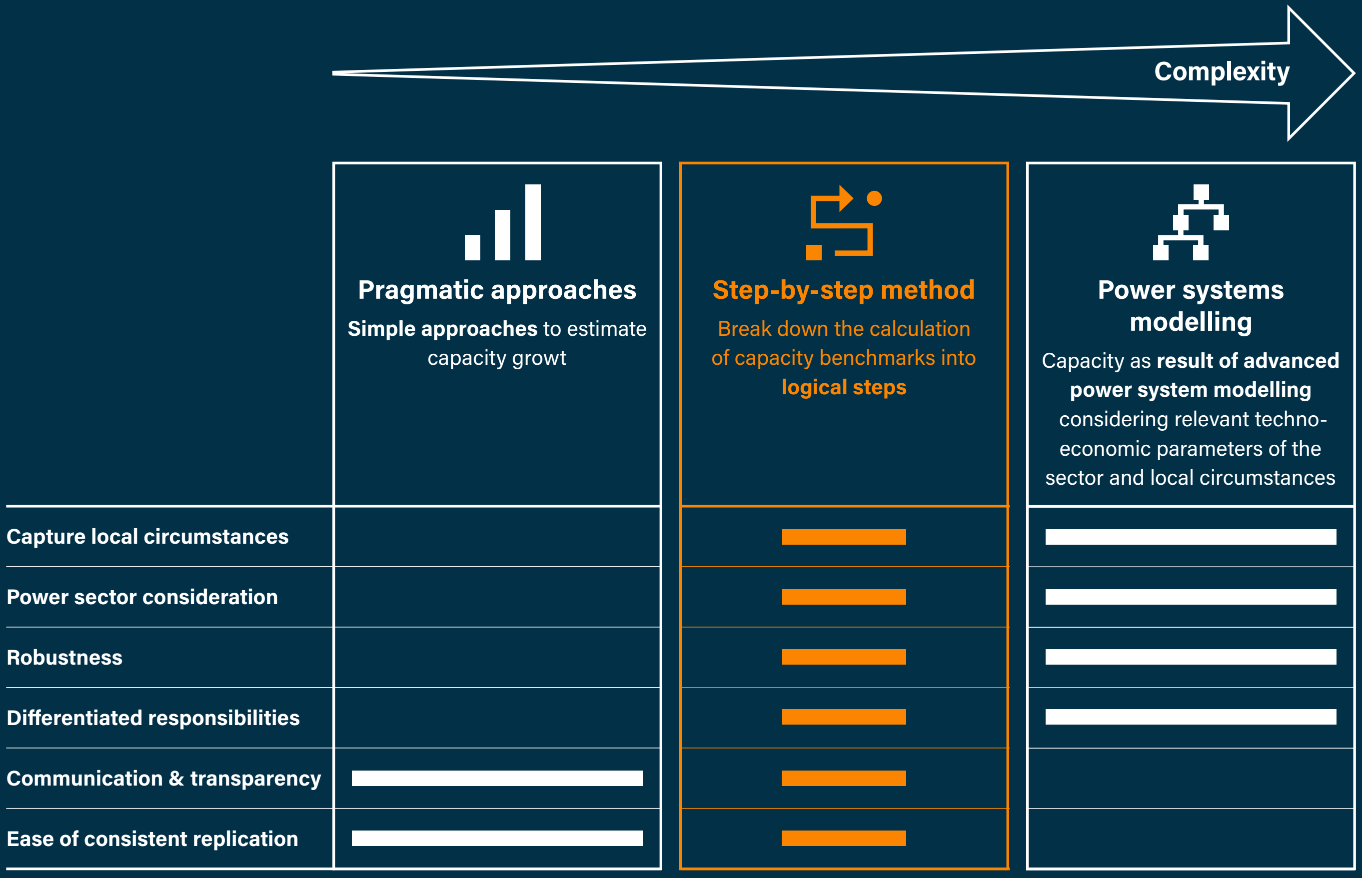
2.2 Integrating multiple lines of evidence

We use multiple lines of evidence in our "step-by-step method" approach. The first three lines of evidence are used to calculate the level of electricity generation from wind and solar required in each country for 1.5ºC compatibility. The remaining lines of evidence are used to split this generation into different wind and solar technologies and calculate the corresponding capacity requirements.

Figure 1

Informing scope of methodological approach based on guiding principles

The stylised diagram illustrates how the guiding principles inform the scope of the methodology along a spectrum of complexity.



	Pragmatic approaches **Simple approaches** to estimate capacity growt	**Step-by-step method** Break down the calculation of capacity benchmarks into **logical steps**	**Power systems modelling** Capacity as **result of advanced power system modelling** considering relevant techno-economic parameters of the sector and local circumstances
Capture local circumstances		▬	▬
Power sector consideration		▬	▬
Robustness		▬	▬
Differentiated responsibilities		▬	▬
Communication & transparency	▬	▬	
Ease of consistent replication	▬	▬	

Bar length in each column represents how much the guiding principle can be accounted by each approach

High-ambition national studies

The first line of evidence includes high-ambition national studies that examine the full and rapid decarbonisation of the power sector within national contexts. These studies serve as essential anchors, incorporating locally informed assumptions regarding economic growth, energy efficiency potentials, and the evolving landscape of electrification, including indirect electrification through green hydrogen production. These studies serve as links to our guiding principles of 1.5 °C ambition and capturing local circumstances; while the local context serves as a proxy for feasibility, they are not a hard determinant of feasibility as the studies do not test for the maximum possible pace of decarbonisation.

We identified relevant studies by consulting review articles mapping national modelling studies investigating 100% renewable systems (Khalili and Breyer, 2022) and supplemented them through our own research to ensure a comprehensive and up-to-date pool.

We scanned over 200 studies from the original pool and filtered the literature across a set of criteria determining the robustness of the methodology used and the decarbonisation ambition of the scenario(s). The filtering criteria aimed to analyse how studies incorporate relevant parameters and assumptions in the analysis of a power system with high wind and solar penetration, including national contexts, integration challenges, investment barriers, and others. We classified models based on type (Optimisation, Accounting, Simulation, General Equilibrium, Other) and name (while some are existing and well-documented modelling tools, others are created solely for the study).

The criteria used to determine the robustness and level of ambition of the national studies assessed included the following indicators and model details:

→ **High ambition:** This criterion evaluates whether the scenarios within national studies reflect ambitious goals for power sector decarbonisation. A direct way to determine this is whether studies defined a decarbonisation scenario (e.g., full decarbonisation or 1.5°C compatible scenarios). Alternatively, we look into the level of decarbonisation achieved (e.g., the share of fossil fuels or renewables in 2050). Scenarios that explicitly aim for full decarbonisation of the power sector by 2060 at the latest or achieve a fossil fuel share of less than 10% by 2050 are considered. Studies that don't meet these ambitious levels, or don't have clear information about decarbonisation levels, are filtered out to ensure that selected studies align to the development of meaningful benchmarks.

→ **Modelling approach:** Modelling approaches are classified into different types, including optimisation, accounting, simulation, general equilibrium, and others. These classifications help in understanding the methodology employed in the study. Some studies make use of well-established and documented modelling tools, while others create custom models specifically for the study's unique requirements. This criterion helps ensure that the selected national studies provide robust and relevant data that can effectively contribute to the development of the methodology.

→ **Sectoral scope:** This criterion examines the depth of the studies in the different dimensions of the energy sector. We prioritise studies that offer a comprehensive, system-wide analysis of the power sector transformation. Such studies provide detailed insights into the intricate workings of the power sector, its evolution, and the transition towards cleaner energy sources. Furthermore, we also consider studies that adopt a broader perspective by examining the wider energy supply transition, encompassing not only the power sector but also the end-use sectors. These studies explore the interconnected dynamics, trade-offs, and potentials associated with the electrification of end-use sectors, offering a more holistic view of the energy landscape.

→ **Temporal dimension:** This dimension evaluates how a study addresses the temporal aspect in its modelling and analysis. It scrutinises whether the study models a single year, over multiple years through individual runs or time-step intervals, or encompasses a full-time horizon that models the transition from a base year to an end year. The choice of the temporal approach allows us to understand the focus of the study and the extent to which it goes into the decarbonisation process. In the case of studies that adopt a single-year model or short-term analyses, they tend to provide a snapshot of a potential future or scenario. We prioritise studies with a full-time horizon that provide a comprehensive pathway for decarbonisation, tracking the evolution of the system over time, offering a broader perspective, allowing for an exploration of the transition process rooted in current conditions.

- **Power system nuances:** It underscores the need for a thorough understanding of the technical challenges associated with integrating higher shares of variable and less predictable energy sources, such as wind and solar, into the power grid. It looks at how the studies have incorporated flexibility considerations into their models, such as the representation of the grid, geographical granularity, and the temporal granularity of the analysis (e.g., whether it's performed at an hourly or seasonal level). Furthermore, we also assess if other flexibility options were included in the analysis, including energy storage solutions and demand-side flexibility measures.

We filtered out studies that lacked the ambition to achieve deep decarbonisation in the power sector and those that failed to offer a comprehensive representation of the energy system based on the criteria outlined above, encompassing modelling approach, sectoral scope, temporal dimensions, and power system nuances. Additionally, we excluded studies that lacked the data required for the development of our methodology.

From the remaining studies, we extracted the following datasets for our step-by-step method:

- Generation mix (%): shares of different energy sources in the power mix in the base year, 2030, 2040, and 2050.
- Installed capacity (GW): installed capacity of different energy sources in the base year, 2030, 2040, and 2050.
- Electricity demand:
  - Total electricity generation and total electricity demand (TWh), to account for losses;
  - If available: additional demand from sector coupling (TWh), additional electricity demand from hydrogen and synthetic fuels production (TWh).

Downscaled global pathways

Limiting warming to 1.5ºC will require collective action to reduce emissions across all countries and sectors. As national power system studies do not generally model the emissions reductions that would be required in other sectors and other countries to limit warming to 1.5ºC, their compatibility with the Paris Agreement's long-term temperature goal is less certain.

We therefore complemented these national studies with evidence produced by global 1.5ºC compatible pathways. For this line of evidence, we used the latest downscaled global pathways assessed by the IPCC in its Sixth Assessment Report (AR6) (IPCC, 2022). These pathways show how emissions reductions in different regions and sectors can combine to produce a globally consistent pathway which limits warming to 1.5ºC.

In developing this line of evidence, we made three key steps: selecting, downscaling, and adjusting downscaled global pathways. We briefly summarise these steps here. For more details, see the Annex.

First, we selected pathways. While the IPCC AR6 contains around 100 pathways which limit warming to 1.5ºC, some of these pathways use unsustainable levels of carbon dioxide removal, and others are not consistent with the Paris Agreement's goal of achieving net zero greenhouse gas emissions. We filtered the pathways to consider a subset of 32 pathways which are compatible with 1.5ºC, avoid unsustainable CDR deployment, and are consistent with achieving net zero GHGs.

Having selected these 32 pathways, we then downscaled them to the national level. IAMs provide results at the regional, not national, level. In the IPCC AR6, downscaled global pathways are broken up into 10 major world regions, or "macro-regions". To convert these macro-region pathways to national-level pathways, we used the Simplified Integrated Assessment Model with Energy System Emulator (SIAMESE) (Sferra et al., 2019). SIAMESE takes energy consumption and emissions at the macro-region level and allocates energy consumption to each country in a way that sets fuel prices to be equal across all countries in the region. This is equivalent to maximising the welfare of the macro-region as a whole or finding the most cost-effective allocation of energy consumption – replicating the cost-optimising logic of the global models. This results in 32 possible future electricity mixes for each country. Each electricity mix is part of a downscaled global pathway which, across all countries and all sectors, limits warming to 1.5°C.

Finally, we made some minor adjustments to the downscaled pathways. We accelerated the pace of emissions reductions in advanced economies and used this additional emissions headroom to slow the pace of emissions reduction in emerging economies while conserving the global carbon budget. These adjustments address the call in the Paris Agreement for developed countries to take the lead in reducing emissions, the challenges related to stranded assets in emerging economies, and the current geopolitical context in the aftermath of the fossil gas price crisis.

These three steps ensure that we extract robust information from the downscaled global pathways, providing a key line of sight back to the 1.5ºC goal. These downscaled pathways can then be combined with high-ambition national studies to create benchmarks which incorporate both global consistency with 1.5ºC and account for national circumstances which could guide the energy transition.

Evidence-based safeguards

We further employed a series of "evidence-based safeguards"—defined exogenous inputs based on globally peer-reviewed evidence and real-world developments—as an additional line of evidence to ensure the step-by-step method stays consistent and coherent with the original guiding principles. This line is employed as a simple and transparent solution to ensure certain conditions are met in the methodology, where there is no reasonable alternative. We use these safeguards only to ensure consistency of the narrative in the benchmarks with no intended bias on final benchmark results. We use three types of the safeguards in the methodolgy, which are described in the following sections.

High electrification to capture energy transition nuances

High electrification levels are a key feature of any 1.5°C scenario as electrification is one of the most important strategies for reducing CO_2 emissions from energy consumption due to the replacement of fossil fuel-based energy sources with renewable ones. Electricity demand is expected to rise in the pursuit of national and global net zero emissions, with significant shifts towards electrification in the transport, industry, and buildings sectors.

To remain consistent with our guiding principles of capturing the nuance of energy transitions, we employ safeguards of minimum economy-wide electrification rates consistent with the global average benchmark (51-55% electrification by 2050), informed by IRENA's World Energy Transition Outlook (IRENA, 2023b) and IEA's 2023 update of the Net Zero Roadmap (IEA, 2023b). This is to ensure that countries' 1.5°C-compatible pathways assessed under our methods accurately reflect an electrified future.

Common but differentiated responsibilities in phasing out fossil fuels in the power sector

The drivers for, impacts from, and ability to tackle anthropogenically induced climate change are not distributed equally around the world. While there is no universally established method to define an equitable national or regional contribution to a worldwide goal, the Paris Agreement (Article 4.3) recognises that Parties' contributions should reflect "common but differentiated responsibilities and respective capabilities" with advanced economies to "continue taking the lead" (UNFCCC, 2015). This leadership includes setting more ambitious climate targets, taking the brunt of the costs in research and incubating new technologies, and accelerated implementation of clean energy technologies. Emerging economies, which have historically contributed less to global greenhouse gas emissions and thus bear a lesser responsibility for mitigation, can then benefit from financial support, technology sharing, and technical assistance.

Our safeguards are based on the IEA's 2023 update of the Net Zero Roadmap to ensure countries' differentiated fossil fuel phaseout timelines in the power sector—the latest year when countries' fossil fuel mix in power generation needs to decline to zero—are informed by pathways from global energy modelling studies. To conform to global imperatives, the safeguards implemented are: advanced economies must achieve full decarbonisation of the power sector by 2035, China by 2040, and emerging economies by 2045.

Renewable energy targets and policies

Renewable energy targets and policies are an accurate reflection of a country's unique techno-social, political, and economic circumstances. Technological capabilities, value chains, and social attitudes towards sustainability can drive the adoption of certain types of renewables, while political will and economic feasibility determine the pace and scale of the transition domestically. Although a country may have abundant solar or wind resources that can produce safe and affordable power, differing attitudes, capabilities, and alternative resources mean technologies may not be determined solely by these factors.

To produce benchmarks that are reflective of national circumstances we use national and regional-level renewable energy targets and policies as a line of evidence to inform the minimum levels of wind and solar capacity installed split by technology. As no major economy is currently on track to achieve power sector transformation with the requisite speed and scale necessary for 1.5°C compatibility, benchmarks for wind and solar will outpace any current national policy target, so using these targets and policies helps to infer the split of the technologies in-line with national circumstances.

For this line of evidence, we use pathways and projections for wind and solar deployment based on optimistic government targets and policies, such as implied levels of installations for long-term carbon neutrality or net-zero targets.

Renewable potential analysis

National-level benchmarks for wind and solar deployment should reflect the national potential for wind and solar. Some countries may have greater resource potential for solar, while others may be better suited to wind deployment. While the high-ambition national studies may be based on a detailed assessment of wind and solar potential in different countries, this is not guaranteed. Therefore, we also produce our own assessment of the wind and solar potential in different countries to guide the development of national-level benchmarks. In addition to guaranteeing a thorough evaluation of resource potential in all countries, this approach also ensures a uniform approach across all countries.

To do this, we use a Python-based simulation pipeline. This pipeline uses two open-source packages, GLAES (Severin Ryberg et al., 2022) and RESkit (Severin Ryberg et al., 2019). We use these packages to calculate the technical potential for onshore wind, offshore wind, open-field PV, and residential rooftop PV.

The pipeline works as follows. First, GLAES uses geospatial gridded datasets to identify the land that would be eligible for wind or solar deployment in the given country. To do this we use a range of exclusion criteria to eliminate land that is unsuitable for renewables deployment. The range of exclusion criteria applied and their stringency can be varied as part of the analysis, but they cover infrastructural (proximity to roads, railways, airports, human habitation), environmental (avoiding wildlife-protected areas and forests) and topographical (elevation, slope, water depth etc.) criteria. For full details on the exclusion criteria applied in this work, and more details on the land available for renewable placement, see the Annex.

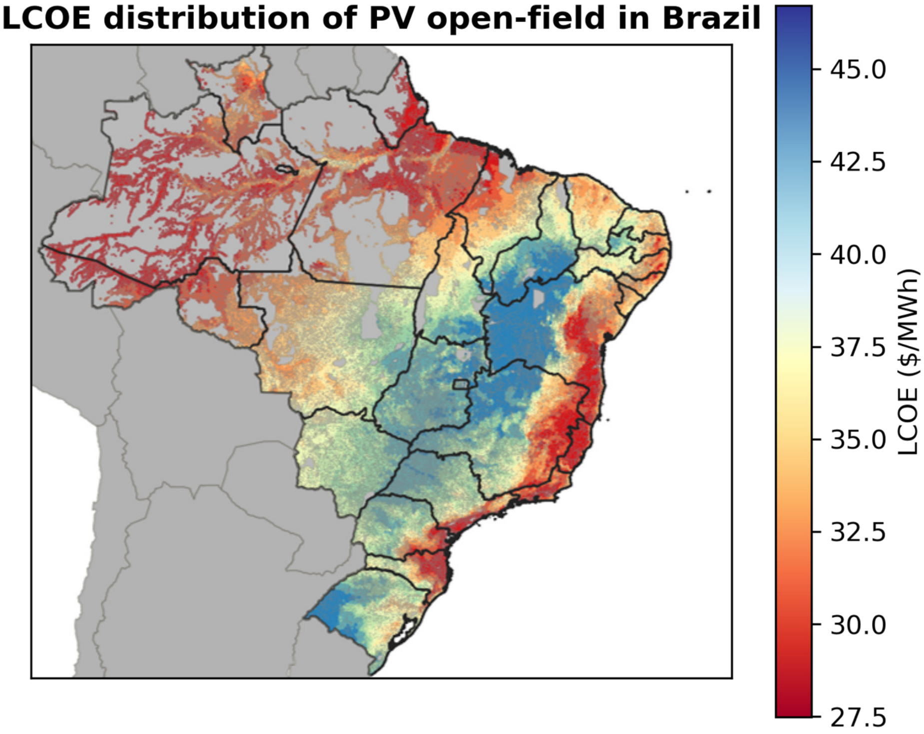
Having defined the land available for placement of solar and wind turbines, we then use RESkit to evaluate the implications of this for total renewable potential. RESkit conducts a site-by-site optimisation to calculate the wind and solar potential that could be deployed at a site, the capacity factor achievable, and the capital costs of installation by utilising globally available data on solar irradiance and wind speeds and input cost assumptions for a baseline turbine/solar panel design. It then conducts a simulation of the wind turbine/solar panel operating under these weather conditions and calculates the renewable potential that could be accessed if the eligible land was used for solar and wind deployment and the associated capacity factor. In the case of wind turbines, it also optimises the size of the turbine (e.g. hub height) and adjusts the capital costs from the baseline costs where necessary.

When providing initial capital cost (CAPEX) trajectories to RESkit, we provide three variants, which we label as high, medium and low. These CAPEX costs are calculated using IRENA data (IRENA, 2020, 2022) and capture the differentiated CAPEX of renewables in different countries. For more detail on this, see the technical annex.

Having run RESkit, we get the capacity potential, costs and capacity factors achievable at each site in the country. By aggregating up across all placements in a country, a cost-supply curve can be generated for each technology (rooftop PV, open-field PV, onshore wind, and offshore wind), which shows how the levelized cost of electricity (LCOE) varies as increasing capacity of wind/solar is deployed. Example outputs of the renewable potential analysis are shown in → **Figure 2**.

Figure 2

LCOE distribution of PV open-field in Brazil



Note: This figure shows the spatially distributed potential for open-field PV in Brazil, showing how the LCOE varies from site to site. The area which is excluded (not suitable for PV) is shown in grey.

Simplified power system analysis

Our final line of evidence is the use of a simplified power system model to produce the final benchmarks. This model takes the 1.5ºC compatible generation trajectory for wind and solar in a country (produced using the first three lines of evidence) and calculates a cost-optimal split of this generation into onshore wind, offshore wind, rooftop solar PV, and open-field PV based on the country-level resource potentials (the fourth line of evidence), and subject to a range of user-defined constraints. The model provides as an output the capacity deployment and generation trajectories on a technology-specific basis, which form the final benchmarks.

We conduct our power system analysis using the PyPSA modelling framework. For more details, see the section below.

2.3 Step-by-step method

The methodology presented in this document offers a pragmatic and structured approach to determine wind and solar power generation capacity through 2050, in 10-year intervals. It does so by breaking down this complex task into manageable, comprehensible, and effective steps, aiming to facilitate an effective communication of the process and outcomes.

Rooted in the guiding principles defined in → **Section 2.1**, the step-by-step method adheres to the fundamental principles governing the expansion of power systems in the context of deep decarbonisation: an ever-increasing electricity demand boosted by electrification needs, the gradual but sustained decline in fossil fuel generation, compliance with national policies and targets, and the efficient utilisation of available resources for electricity generation. Each of these elements is systematically incorporated into the methodology.

To ensure the robustness and coherence of the methodology, various lines of evidence are integrated and aligned throughout the step-by-step progression **(→ Section 2.2)**. These lines of evidence capture essential elements, such as national relevance, minimum ambition levels, and consistent narratives across countries. By embracing a holistic perspective and anchoring the methodology in a strong technical foundation, we aim to provide a comprehensive framework to define 1.5°C-compatible wind and solar power generation capacity benchmarks.

Overview of the step-by-step method

The overview below provides a concise summary of the sequential steps in the methodology for obtaining wind and solar power generation capacity benchmarks **(see → Figure 3)**.

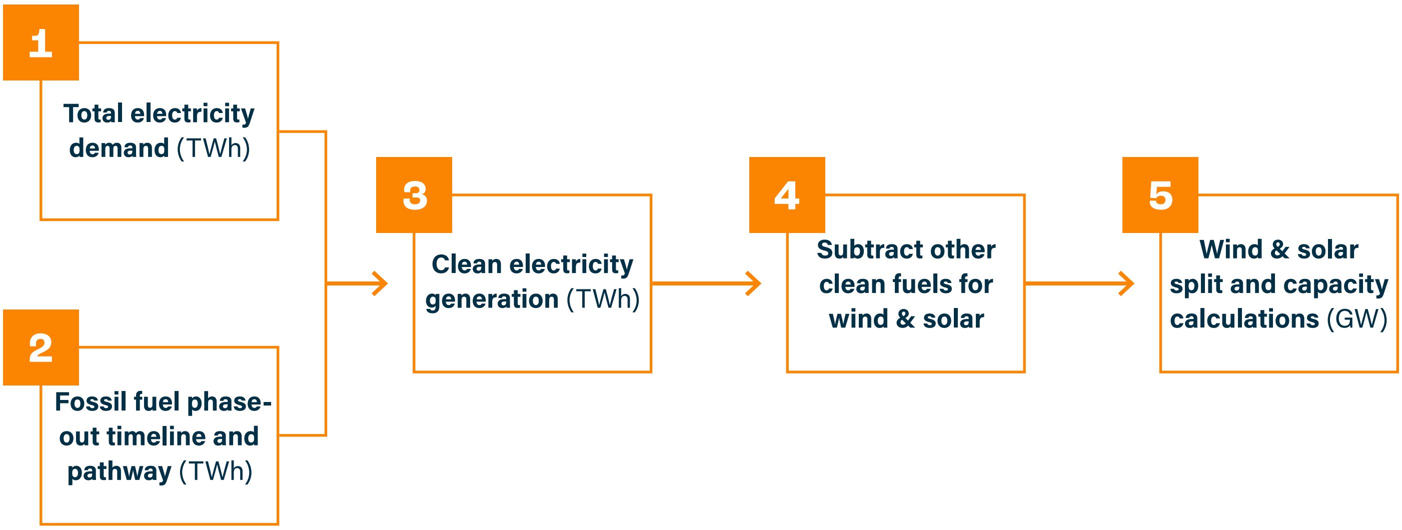
1. **Estimate total electricity demand:** Initially, we calculate the total electricity demand for each target year, considering factors such as economic development, increased electrification of various sectors, and improvements in energy efficiency.
2. **Determine fossil fuel phase-out:** The next step involves determining the gradual phase-out of electricity generation from fossil fuel sources. This process considers national circumstances, differentiated countries' responsibilities, and the minimum level

of ambition required to align with the global target of limiting the temperature increase to 1.5°C by the end of the century.

3. **Calculate carbon-free electricity generation:** Using the figures obtained from the previous steps, we determine the electricity that must be generated from carbon-free technologies to meet the demand.
4. **Isolate wind and solar:** Subsequently, we subtract the electricity generated from non-wind-and-solar technologies (i.e., hydro, biomass, and other renewables, and nuclear) from the total clean electricity generation. The result of this subtraction represents the electricity that needs to be generated from wind and solar technologies.
5. **Calculate technology-specific capacities:** Lastly, based on the outcomes of the previous step, the methodology computes the total power capacity required for each wind and solar technology to generate the specified electricity.

Figure 3

Overview of step-by-step method for calculating wind and solar generation and capacity benchmarks



In essence, the step-by-step structure of our methodology ensures that every step can be rigorously examined and refined as needed, guaranteeing that critical factors, including national representation, alignment with the Paris Agreement climate goals, and adherence to the techno-economic features of power systems, are addressed. Each method within these steps has been developed taking into account consistency throughout the process and alignment with the overarching guiding principles, such as transparency, communicability, replicability, and robustness. This methodological framework is not intended to provide accurate forecasts, but rather an interpretation of the global needs for decarbonisation of the electricity sector translated to the national level.

Electricity demand

Power system expansion hinges on the imperative to meet electricity demand at all times. Following this logic, the first step is to estimate the electricity demand in the target countries for the benchmark years (2030, 2040, and 2050). This initial phase is critical as it sets the cornerstone for all subsequent calculations.

Estimating future electricity demand usually requires robust assumptions rooted in economic development trajectories and a thorough understanding of electricity consumption patterns, including increased access to electricity in rural areas. Furthermore, other drivers beyond the electricity sector, which are key in driving the global shift towards decarbonisation of the economy in accordance with the Paris Agreement goals, also have a direct influence on electricity demand. In particular, the electrification of various end-use sectors, which drives electricity demand growth, and the enhancement of energy efficiency, which conversely reduces demand, are both principal decarbonisation strategies. These multifaceted considerations underline the complexity of estimating total electricity demand and underscore the significance of this initial step in our methodology.

Guiding principles and lines of evidence

The following table summarizes the key guiding principles and relevant elements for the estimation of **electricity demand**, and how they are handled in the methodology, including the lines of evidence used.

Guiding principles & other elements	Line of evidence	Methodology handling
Capture of local circumstances	High ambition national studies	Extract electricity demand from national studies. This is the starting point of the methodology.
Capture of elements and nuances in power sector transitions (including high electrification, energy efficiency, and others)	High ambition national studies Evidence-based safeguards	Uplift electricity demand from national studies to account for minimum levels of electrification, including indirect electrification for hydrogen production. The uplift is carried out with a simplified calculation method based on fundamentals of power systems.
	High ambition national studies	Inherit energy efficiency assumptions from national studies. Consider additional efficiency gains from higher electrification, carried out with a simplified calculation method based on fundamentals of power systems.
	Simplified power system analysis	Incorporate fundamental elements of power systems analysis, such as grid losses.
1.5°C compatibility	Downscaled global pathways	Create a safeguard (minimum demand trajectory that is consistent with the global goal of tripling RE capacity by 2030) to compare against the resulting electricity demand.

Table 1

Estimating electricity demand: integrating guiding principles in our methodology

Method applied

We took the following steps to determine electricity demand in 2030, 2040, and 2050 **(supported by illustration in → Figure 4)**.

1. **National studies – electricity demand:** We first extract electricity demand projections for the benchmark years (2030, 2040, and 2050) from ambitious national studies **(see 'High ambition national studies' in → Section 2.2)**. By relying on national studies, this step provides a foundation rooted in the specific circumstances that will shape each country's future electricity demand. The range of electricity demand from national studies is represented by dashed blue lines in **→ Figure 4.**

2. **Demand adjusted – with high electrification & efficiency gains:** Subsequently, each national study is carefully assessed, with a particular focus on the underlying electrification rates. The electrification rate of each study is then compared against global benchmarks of the minimum electrification levels required to adhere to the 1.5°C temperature goal **(set at 51-55% electrification by 2050, see 'Evidence-based safeguards' in → Section 2.2)**. If a national study's electrification rate falls below this global benchmark, the methodology elevates the electrification level to

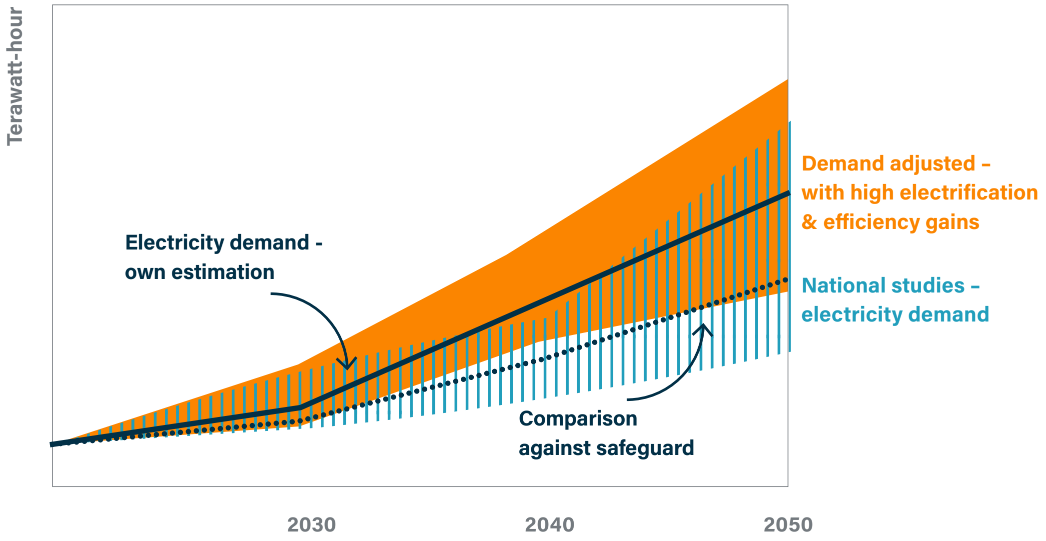
meet the global average, thereby adjusting the total electricity demand upwards. Simultaneously, the methodology acknowledges that the electrification of end-use sectors often enables energy efficiency gains (i.e., shifting from traditional forms of energy to electricity improves efficiency by using less primary energy to satisfy the rising demand for energy services). Efficiency gains associated with higher electrification are factored into the calculations. In cases where national studies lack data to quantify electrification rates, these rates are inferred through regression analysis based on electricity demand growth and the elasticity of electricity demand with respect to GDP. The adjusted electricity demand as explained above is represented by the orange range in → **Figure 4**.

3. **Electricity demand – own estimation:** After adjusting electricity demand figures from national studies to accommodate the minimum electrification levels and associated efficiency gains, a range of electricity demand projections are developed for the years 2030, 2040, and 2050. The reference electricity demand used in subsequent steps is established as the median value within this range. The final electricity demand estimates, generated through these steps, are subsequently translated into total electricity generation for each year, accounting for grid losses. The own estimation of final electricity demand is represented by the black continuous line in → **Figure 4**.

4. **Comparison against safeguard:** In the final stage, we compare the resulting electricity demand to the country’s downscaled global pathways of electricity demand **(dotted dark blue line in → Figure 4)**. If the electricity demand projected in the preceding steps falls below the electricity demand outlined in the downscaled pathways for any given year, the methodology adjusts the electricity demand to align with the downscaled pathway as the minimum bound. The use of downscaled pathways serves as a safeguard to ensure that the underlying global electricity demand, which propels power system expansion, remains congruent with the overarching global imperative of limiting temperature increases to 1.5°C and the global target to triple renewable energy capacity by 2030.

Figure 4

Approach to estimate national electricity demand



Note: The figure above is for illustrative purposes. The y-axis represents energy units (e.g., TWh).

These four interconnected steps collectively form a comprehensive methodology for estimating electricity demand, rooted in local circumstances while striving to maintain global alignment with critical climate and renewable energy goals.

Within this methodology, the consideration of electricity demand for hydrogen production is contingent on whether specific national studies incorporate such assumptions within their scenarios. Our methodology does not (yet) introduce additional assumptions regarding hydrogen production, either for domestic consumption or exports. This decision assumes that national studies are better equipped to provide precise information when assessing the potential for hydrogen production. They possess an inherent advantage in capturing local nuances, circumstances, and potentialities relevant to hydrogen generation.

Other methods explored

Various alternatives for estimating electricity demand were considered in the course of this research. For example, relying solely on national studies, overlapping ranges derived from national studies and downscaled pathways, or adopting a standardized approach based on economic growth projections. Nevertheless, we selected the methodology using multiple lines of evidence to keep the significance of national studies as the primary line of evidence. The studies offer granular insights into local contexts and estimations of electricity demand, the safeguards keep the power sector in the foreground of the energy transition, and downscaled global pathways keep consistency with 1.5°C. Any other approach in isolation would not meet these conditions.

Fossil fuel phaseout pathways

In the transition to a climate-aligned power sector, the imperative to pursue ambitious goals rests not merely on the rapid expansion of renewable energy sources but critically also on the pace and depth of phasing out electricity generation from fossil fuels. Scaling up renewables alone will not suffice: what is crucial is the simultaneous and synchronized reduction of electricity generation from fossil fuels.

In this context, the proposed methodology recognises that different countries find themselves at varying stages concerning the role of fossil fuels in their energy mix. The methodology's approach to decarbonisation acknowledges that the speed and scale of this transformation are inherently linked to a country's starting point and its present reliance on fossil fuels. Moreover, it accounts for the divergent capacities and responsibilities of individual nations by defining specific timelines for achieving full decarbonisation **(see 'Evidence-based safeguards' in → Section 2.2)**. To align with global imperatives, the methodology employs safeguards where advanced economies must reach full power sector decarbonisation by 2035, China by 2040, and emerging economies by 2045 – a reflection of the latest recommendations from the International Energy Agency (IEA) regarding net-zero emissions targets (IEA, 2023b). While recognizing the different roles and responsibilities, it does not lose sight of the need for a collective effort to achieve a decarbonised energy sector. This may also mean that some countries financially support others in achieving these levels.

Guiding principles and lines of evidence

The following table summarizes the key guiding principles and relevant elements for the estimation of **electricity generation from fossil fuels**, and how they are handled in the methodology, including the lines of evidence used. The summary table is followed by a description of the method applied in this step with illustrative examples.

Guiding principles & other elements	Line of evidence	Methodology handling
1.5°C compatibility	Downscaled global pathways	Create a range of electricity generation from fossil fuels based on 1.5°C compatible downscaled global pathways.
Capture of local circumstances	High ambition national studies	Create a range of electricity generation from fossil fuels based on ambitious national decarbonisation studies.
Common but differentiated responsibilities	Evidence-based safeguards	Define differentiated timelines of fossil fuel phaseout in the power sector in each country.

Table 2

Defining fossil fuel phaseout pathways: integrating guiding principles in our methodology

Method applied

The process for determining electricity generation from fossil fuels in 2030, 2040, and 2050 is structured into the following sequential steps **(supported with → Figure 4)**:

1. **Ambitious national decarbonisation studies:** Produce a range of electricity generation pathways from fossil fuels based on ambitious national decarbonisation studies **(range formed by dashed blue lines in → Figure 5)**. These pathways are specific to each country, consider local circumstances, and aim to capture feasible yet ambitious decarbonisation scenarios specific to each country's power sector.

2. **Range of downscaled global pathways:** In parallel, establish a range of electricity generation pathways from fossil fuels derived from downscaled 1.5°C compatible global scenarios **(orange range in → Figure 5)**. This range offers a spectrum of options for reducing fossil fuel-based electricity generation in each country that are consistent with the objectives of the Paris Agreement, ensuring a trajectory consistent with limiting global temperature increases below 1.5°C.

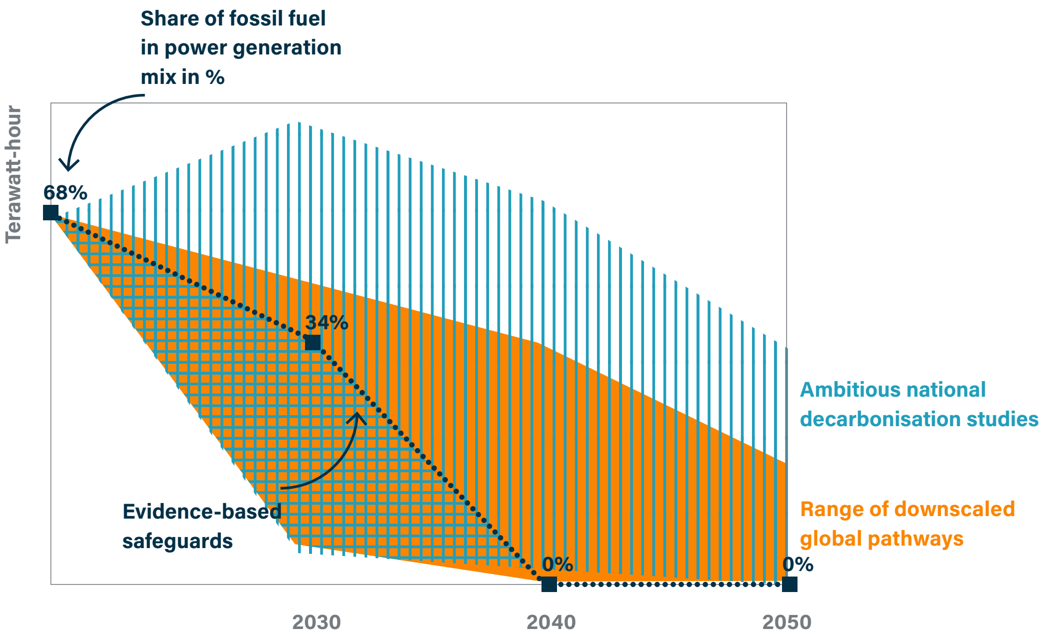
3. **Overlap of ranges:** Identify the intersection of these two ranges. This overlap represents the speed and scale of decarbonisation pathways that not only align with the goals of the Paris Agreement but also capture the local characteristics of each country.

4. **Evidence-based safeguards:** Integrate safeguards to recognise that countries possess distinct starting points, capabilities, and responsibilities in their climate action. These safeguards introduce differentiated timelines for phasing out electricity generation from

fossil fuels. For the transition period until the full fossil fuel phaseout, we apply a safeguard in the form of a linear interpolation of the share of fossil fuel electricity generation from the current share until it reaches zero in the designated phase-out year **(dotted dark blue line in → Figure 5)**. This approach serves as a minimum speed at which countries need to phase out fossil fuels in their power system, in the units of percentage share. This safeguard is applied to the overlap of ranges and removes the portion of the overlap which is less ambitious than the safeguard (slower phaseout).

Figure 5

Approach to define differentiated national fossil fuel phaseout timelines in the power sector



Note: Our methodology takes the wedge comprised in the overlap between national studies and downscaled global trajectories, limited to the part below the evidence-based safeguard.

Note: The figure above is for illustrative purposes. The y-axis represents energy units (e.g., TWh).

Other methods explored

In developing this methodology, we have also studied alternative approaches to estimating future fossil fuel electricity generation. This exploration included the examination of more sophisticated phaseout pathways to coal and fossil gas separately, as well as the consideration of simplified models, like linear or stylised trajectories leading to zero emissions by specific target dates. However, the approach presented above was ultimately prioritised to strike a balance between climate ambition and local relevance, all while upholding transparency and ensuring the method's clear and effective communication.

Clean electricity generation

Building upon the results derived from estimating total electricity generation and the electricity generated from fossil fuels above, the next logical step is to find the difference between the two to obtain electricity generated from carbon-free resources: removing fossil-fired generation from overall electricity generation provides the annual electricity output required from non-fossil sources.

Since this step is a mathematical exercise, involving no assumptions or judgments, it adheres to the overarching guiding principles and lines of evidence implemented in prior steps, ensuring consistency throughout the methodology.

Wind and solar generation

On the path towards a decarbonised power sector, it is projected that future power systems will revolve around wind and solar energy resources in most countries **(see → Section 1)**. However, it's crucial to underscore that the decarbonisation of the power sector extends beyond these two renewable sources. The availability and role of various other carbon-free technologies play a significant role in shaping the energy transition landscape. These factors not only influence the future generation mix of each country but also have an impact on the role of wind and solar in diverse geographical contexts.

The relevance of hydropower, biomass, other renewable resources, and nuclear power is largely contingent on the specific circumstances of each country. Factors such as resource availability, national priorities, and local sustainability implications play pivotal roles in determining the role of these technologies. Given this complexity, it is imperative to inform the future roles of these resources in the energy mix by drawing upon insights from national studies.

Guiding principles and lines of evidence

The following table summarizes the key guiding principles and relevant elements to define **electricity generation from other carbon-free technologies different from wind and solar**, and how they are handled in the methodology, including the lines of evidence used. The summary table is followed by a description of the method applied in this step with illustrative examples.

Guiding principles & other elements	Line of evidence	Methodology handling
Capture of local circumstances	High ambition national studies	Renewable potential analysis and electricity generation from hydro, biomass, other RE, and nuclear power is informed and extracted directly from national studies.
Capture of elements and nuances in power sector transitions	High ambition national studies	Filter out national studies that heavily shift the energy mix to nuclear, hydro or biomass based on sustainability criteria.
Clean fuel inclusive	High ambition national studies	Value the role of other carbon-free energy sources (excluding wind and solar). Inform their availability and viability from national studies.

Table 3

Deriving total electricity generation from wind and solar sources: integrating guiding principles in our methodology

Method applied

The fourth step of the methodology focuses on distinguishing electricity generation sourced from carbon-free technologies aside from wind and solar; specifically hydropower, biomass, other renewables, and nuclear power. With this information, and building on the previous step in which we determined the required electricity generation from non-fossil fuel sources, we can infer how much electricity has to be generated from wind and solar.

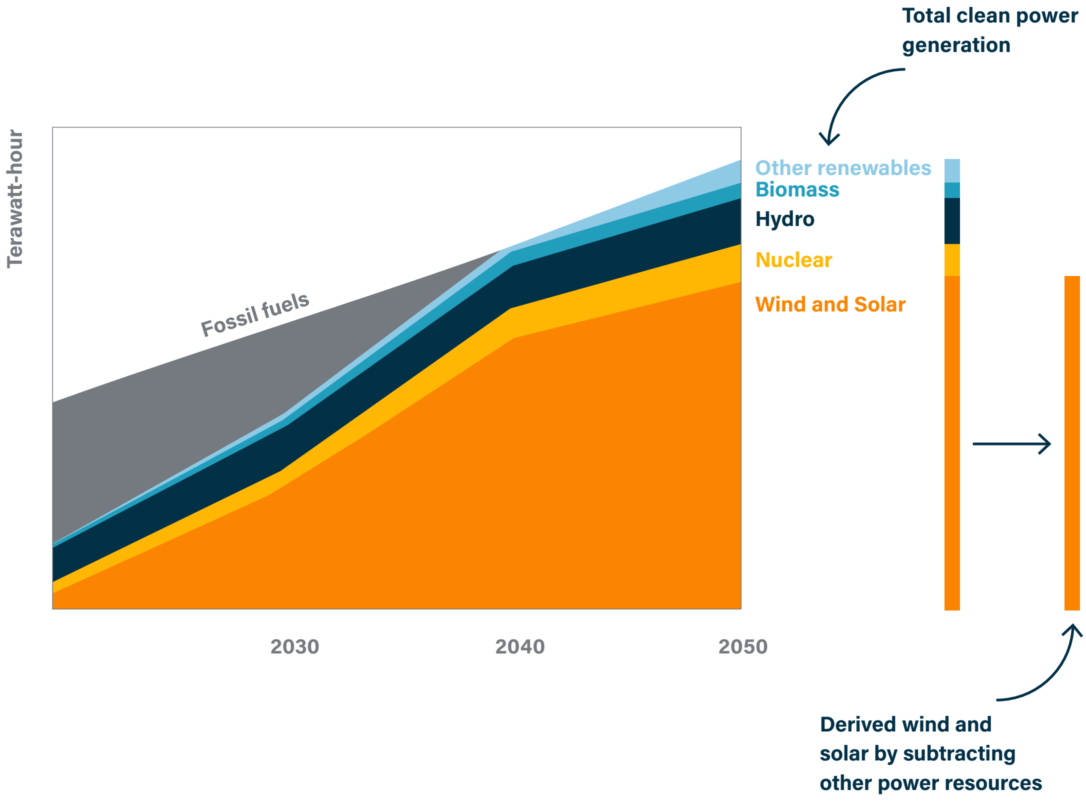
We begin by creating a range of absolute electricity generation for each of these technologies based on data from the filtered ambitious national decarbonisation studies. These national studies are assumed to be grounded in local circumstances. To ensure sustainability, national studies that indicate an excessive reliance on or expansion of any of these resources, particularly nuclear and hydro, are filtered out.

Once the range is established, we eliminate outliers by retaining data within the 10th and 90th percentiles. The median value obtained from this refined range for each fuel serves as the estimate for electricity generation for that same fuel.

Lastly, we subtract estimates of electricity generation attributed to hydroelectricity, biomass, other renewable resources, and nuclear power from the total clean electricity generation calculated in the preceding step **(see → Figure 6 for illustration)**. The outcome of this step is the quantification of electricity generation from wind and solar sources, together **(orange range in → Figure 6)**. This approach ensures that the role of these technologies is integrated into the larger picture of our energy transition strategy, accounting for the specific contexts of individual countries.

Figure 6

Deriving wind and solar generation by subtracting other non-fossil resources from total clean electricity generation



Note: The figure above is for illustrative purposes. The y-axis represents energy units (e.g., TWh).

Other methods explored

Similar to other steps in the step-by-step method, we explored alternative methods to estimate future electricity generation from hydroelectricity, biomass, other renewable resources distinct from wind and solar, and nuclear power. For example, by including in the analysis other lines of evidence such as the downscaling of global domestic pathways or trying simplified approaches such as keeping a constant share of penetration for each of these technologies or employing growth rates derived from historical data.

Nevertheless, we selected the approach above over these alternatives on the basis of prioritising a methodology grounded in national studies. This choice is based on the guiding principle of capturing local conditions in the analysis of these resources, in particular resource availability, technical potential and national policy implications, and in being inclusive of all incumbent low-carbon technologies.

Wind and solar split

In the final step in the approach, we used the simplified power system analysis to split the aggregated wind and solar generation into a cost-optimal mix of onshore wind, offshore wind, open-field PV, and rooftop PV. As an output, the power system model gives the generation split into wind and solar and the capacity requirements for each technology.

Guiding principles and lines of evidence

The following table summarizes the key guiding principles and relevant elements to split wind and solar generation into separate trajectories for onshore/offshore wind and rooftop/open-field PV, and how they are handled in the methodology, including the lines of evidence used. The summary table is followed by a description of the method applied in this step. Illustrative examples are provided in the results section **(see → Section 3)**.

Guiding principles & other elements	Line of evidence	Methodology handling
Capture of local circumstances	Renewable potential analysis	The renewable potential analysis gives a country-specific estimate of the cost and availability of different wind and solar technologies. It serves as an input into the power system modelling.
	Renewable energy targets and policies	The model deploys at least the level of countries' solar and wind current targets and pledges.
Capture of elements and nuances in power sector transitions	Simplified power system analysis	The power system model used captures some key constraints which will guide the power system transition, including capacity growth rates on different technologies and minimum capacity requirements set by current targets.

Table 4

Splitting the aggregated wind and solar generation: integrating guiding principles in our methodology

Method applied

The main inputs to the model are as follows:

- **Wind and solar generation projections:** The generation from wind and solar required in the country from 2022 to 2050. The model is harmonised to 2021 historical generation/capacity, which is taken from the IEA (IEA, 2023c).

→ **Wind and solar technical potential, capital costs and capacity factors:** We use the detailed renewable potential analysis to calculate the technical potential of each technology in the country, and the range of capacity factors available. We represent each technology in a very high level of detail, splitting the solar/wind potential into 250/500 different bins, each bin representing a section of the overall resource potential with a specific capacity factor and capital cost. This allows the model to deploy the lowest-cost segments of each resource potential, providing a balanced mix of wind and solar that captures the lowest-cost options. When producing renewable potential estimates for a country, we develop three different cost assumptions (high/medium/low), using IRENA data. The methodology uses the scenario with medium-cost assumptions for all technologies, in which the capital cost of solar falls almost 70% from 2021 to 2050 across all countries, while the cost of onshore/offshore wind falls 35%/25%. The high and low bounds are established for sensitivity analyses.

→ **Constraints on capacity deployment.** We apply two main constraints on capacity deployment:

1. **Minimum capacity bounds:** We force the model to deploy at least the level of solar and wind seen in countries' current targets and pledges. These targets/pledges can be extracted from a range of data sources (planned capacity in Global Energy Monitor databases, national strategies and policy documents). As real-world deployment does not only follow a least-cost logic this constraint ensures that the model accounts for policy drivers when country targets/pledges diverge from a purely cost-optimising logic.

2. **Capacity growth rates:** We limit the pace at which wind and solar can be deployed to avoid unrealistically high deployment levels. Post-2030, capacity growth rates are limited to 25%/y for solar PV and 20%/y for wind, although in the 2020s this constraint is relaxed to enable the very rapid deployment of wind and solar which will be necessary this decade to align with 1.5ºC and meet national targets (which sometimes require higher growth rates than 20/25%, particularly in regions starting from a low level of wind/solar installation). We apply

this growth rate constraint to both growth in total capacity and growth in capacity additions (as capacity additions are constrained by the skills/material/labour available in the supply chain).

Taken together, the model calculates a cost-optimal split of wind and solar deployment which will meet the generation projection, using the wind and solar resources provided, while meeting the capacity constraints applied. In any model, there is a trade-off between the spatial, temporal and technological detail included. Increasing the detail in one dimension requires reduced focus in another dimension. In the current modelling set-up, we focus on the technological dimension, representing the solar and wind cost curves in a region at a high level of detail. We currently limit the spatial and temporal resolution of the model, considering a single annual time slice and not representing transmission/distribution grids. In future work, this could be extended to consider these spatial and temporal aspects in more detail, as there are often spatial and temporal correlations between wind and solar which could influence the cost-optimal generation mix.

03 Results

The results presented in this section are an outcome of implementing the methodology introduced in the section above. In the next stage of the process, these outcomes will be shared with actor groups working in the affected countries to validate and cross-reference the results. The feedback collected during this phase plus the implementation of the methodology to a larger number of countries will be used to refine it. Therefore, it is important that the results presented here are seen as an illustrative overview of the method's outcomes and what national benchmarks for wind and solar power could look like and should be regarded as preliminary.

3.1 Step-by-step method

For illustration purposes, we present visual results of each stage within the step-by-step method for Brazil, China, India, Indonesia, Germany and South Africa.

Electricity demand

The results of the first step of the step-by-step method focused on estimating electricity demand up to 2050, show a clear increasing trend in all countries driven by rising energy demand and growing electrification rates. For comparative purposes, the results are presented as electricity demand growth relative to base year levels **(see → Figure 7)**.

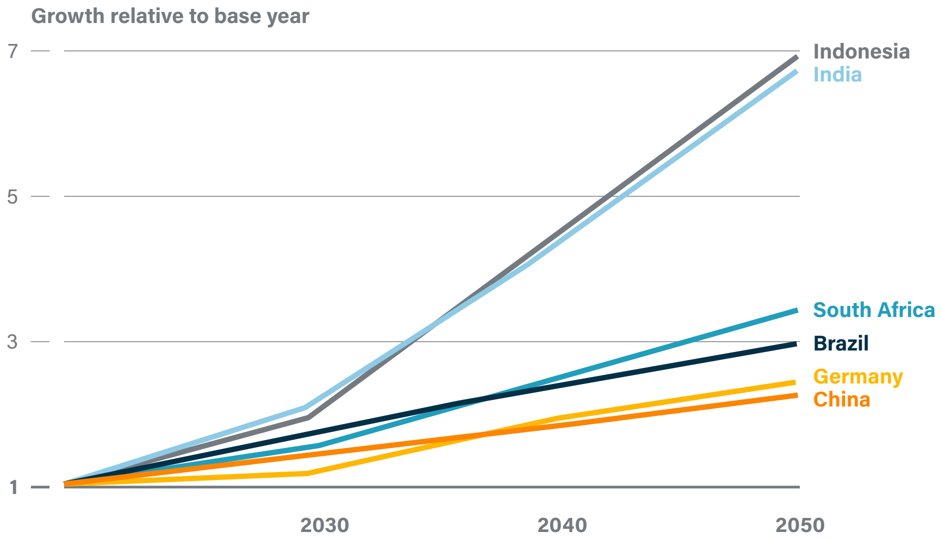


Figure 7

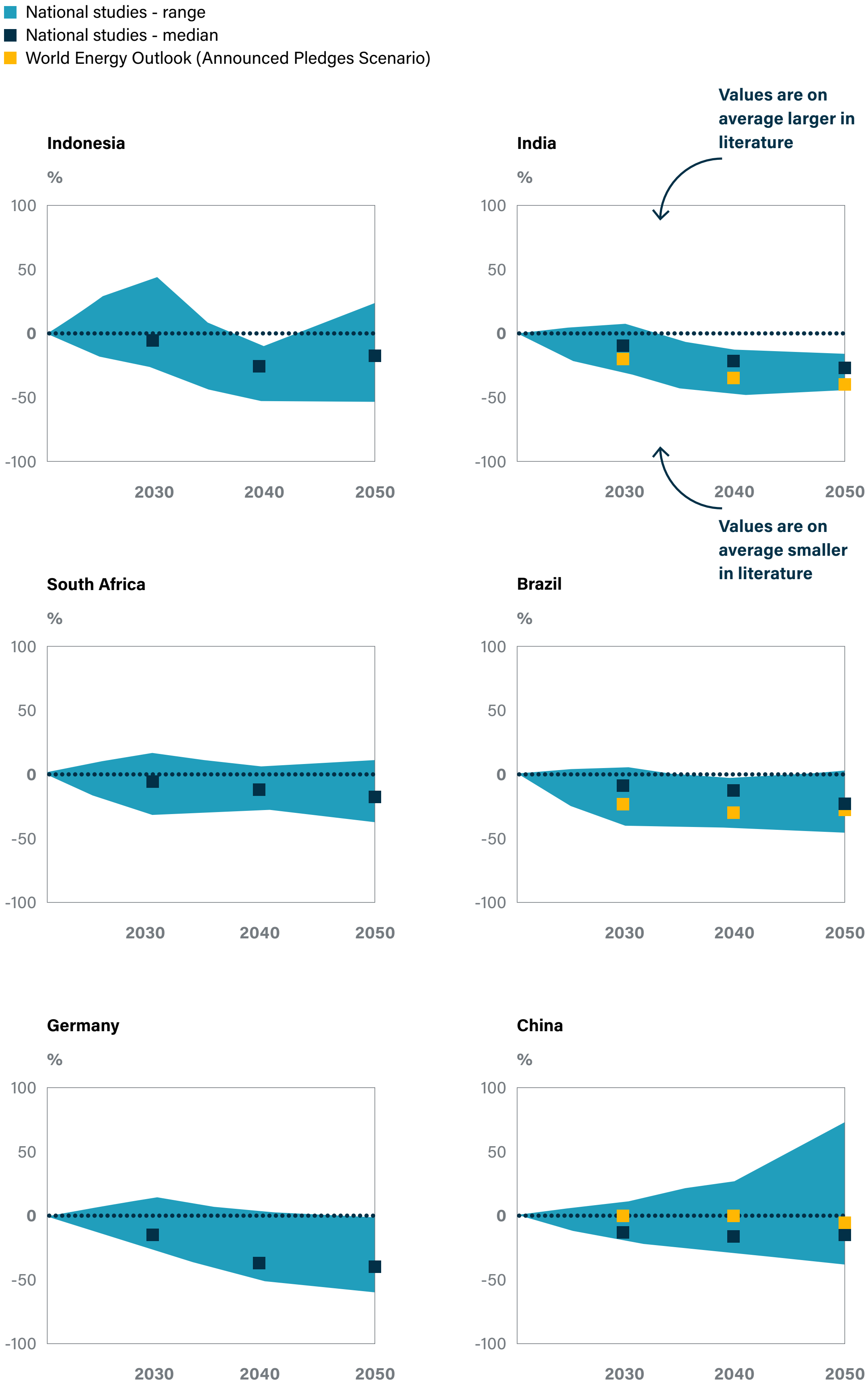
Results of step 1 – Electricity demand growth indexed to base year

As previously described, we made two critical adjustments to the electricity demand from national studies to factor in the higher electrification needs of a decarbonising economy. First, the methodology elevates the demand based on more ambitious electrification rates, aligning with the global average electrification rate necessary to attain net zero emissions by 2050. Secondly, the methodology also ensures that electricity demand is at least equal to the downscaled global pathways.

Our method therefore yields higher electricity demand figures, on average, compared to the initial inputs from national studies. **→ Figure 8** shows how the electricity demand resulting from the proposed methodology compares with the

Figure 8

Comparison of estimated total electricity demand from step 1: Deviation of own results vs. literature



literature, mainly the range of national studies and the IEA's Announced Pledges Scenario (APS) of the World Energy Outlook (WEO), when data is availbale for the corresponding country (IEA, 2022). Nevertheless, it's noteworthy that the resulting electricity demand, while generally greater, consistently falls within the range defined by the national studies for most countries.

The reference line (x-axis) in → **Figure 8** represents the results of our own estimations for electricity demand. Values above this reference line indicate estimates from the literature that are higher than our own estimations, while values below the reference line represent estimates from the literature that are lower than our own estimations. The figures above illustrate the extent to which the total electricity demand results derived from our step-by-step method deviate from both national studies and the IEA's APS, whenever country data is available. It's crucial to emphasize that the APS scenario does not align with a 1.5 °C scenario, and sees lower global electrification rates than the IEA's Net Zero Roadmap.

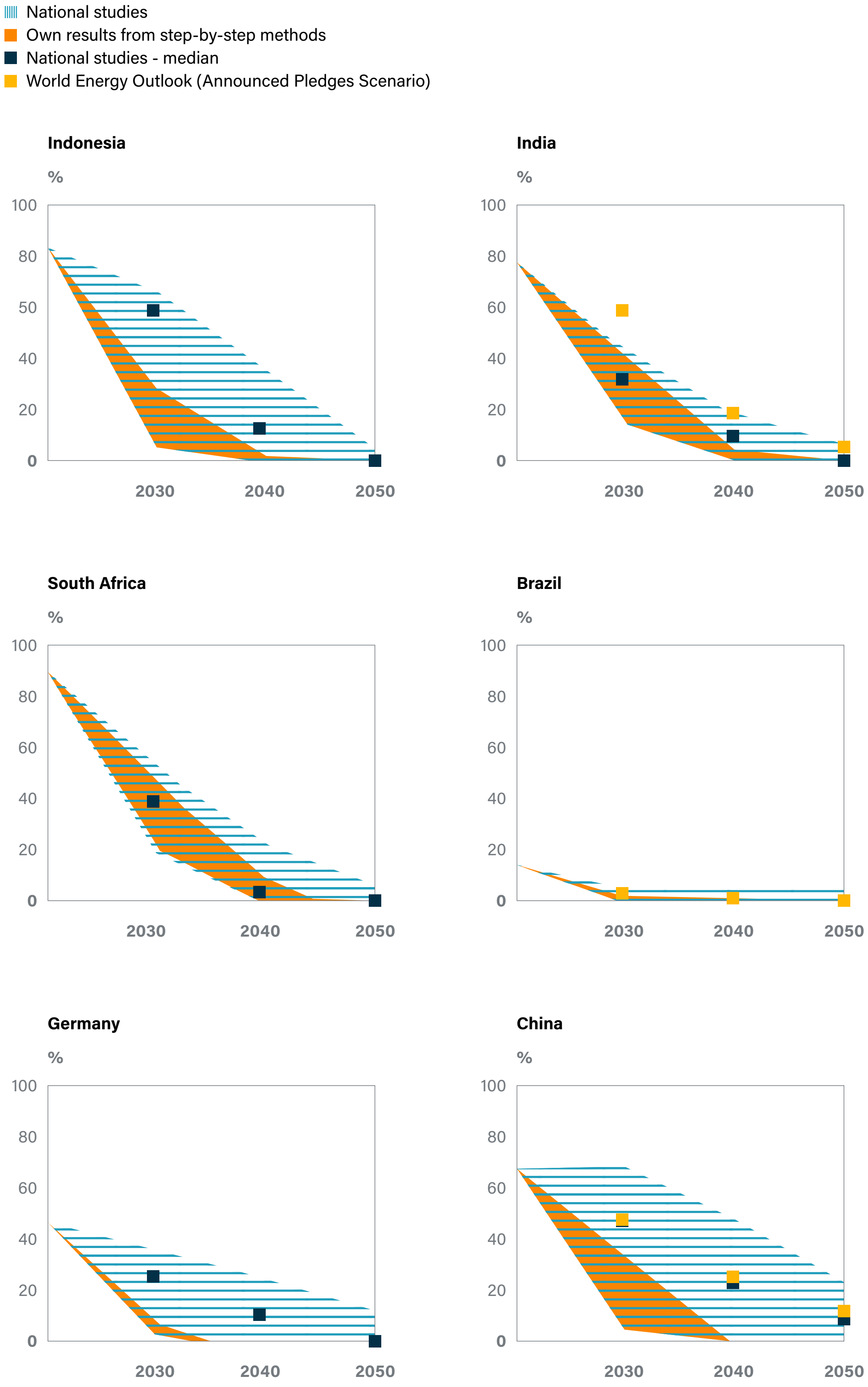
Fossil fuel phaseout pathways

The results of the second step in the step-by-step method show that all countries follow a downward trajectory towards a phase-out of fossil fuel electricity generation by 2035-2040, varying from country to country. → **Figure 9** shows that the most significant reductions in fossil fuel generation occur within the next decade in the pursuit of limiting warming to below 1.5°C. The figure below also shows that our results fall within the range of national studies, slightly outpacing the median of national studies.

When compared to the IEA's WEO APS scenario, our results consistently reflect the declining trend in fossil fuel generation. However, our methodology demonstrates a more ambitious approach in terms of the pace and depth of fossil fuel phase-out. This divergence is largely attributed to the fact that the APS outlined in the IEA's World Energy Outlook is not consistent with the Paris Agreement's 1.5°C temperature limit. Our results, in contrast, embrace the climate ambition necessary to meet these objectives.

Figure 9

Fossil fuel phaseout timelines compared to the literature



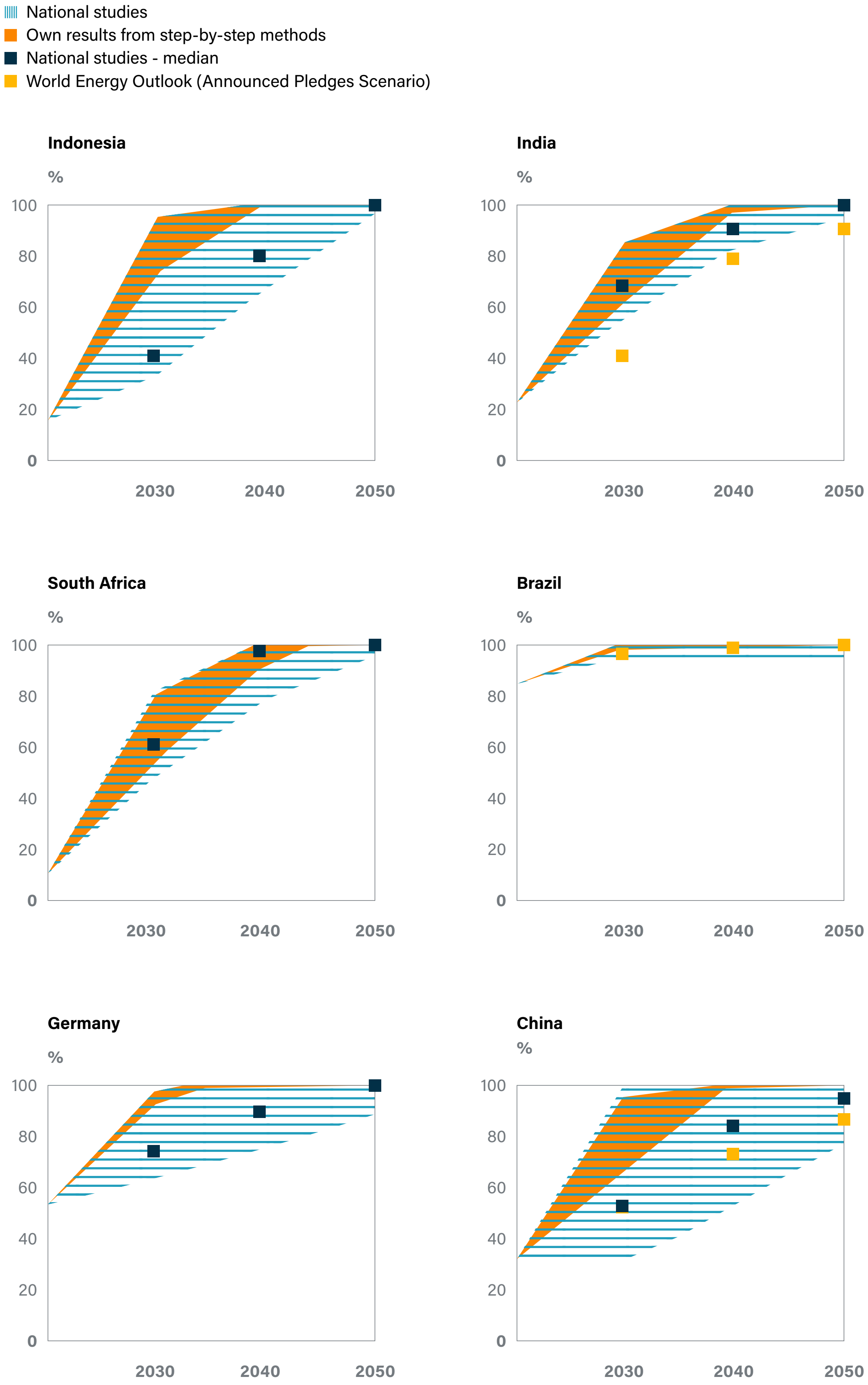
Clean electricity generation

As a direct result of the decreasing reliance on fossil fuels, we observe a substantial increase in the penetration of carbon-free technologies, with the most significant advancements occurring within the next decade. As evidenced in → **Figure 10**, our results indicate that by 2045, at the latest, we anticipate reaching a 100% penetration of carbon-free technologies to meet electricity demand. This category encompasses a spectrum of technologies, including hydropower, biomass, wind, solar, other renewables, and nuclear power.

Our methodology's results align with national studies, tending towards the most ambitious end of the range. Our findings considerably outpace the IEA's APS, reflecting a heightened level of climate ambition.

Figure 10

Share of electricity generation from clean energy compared to literature



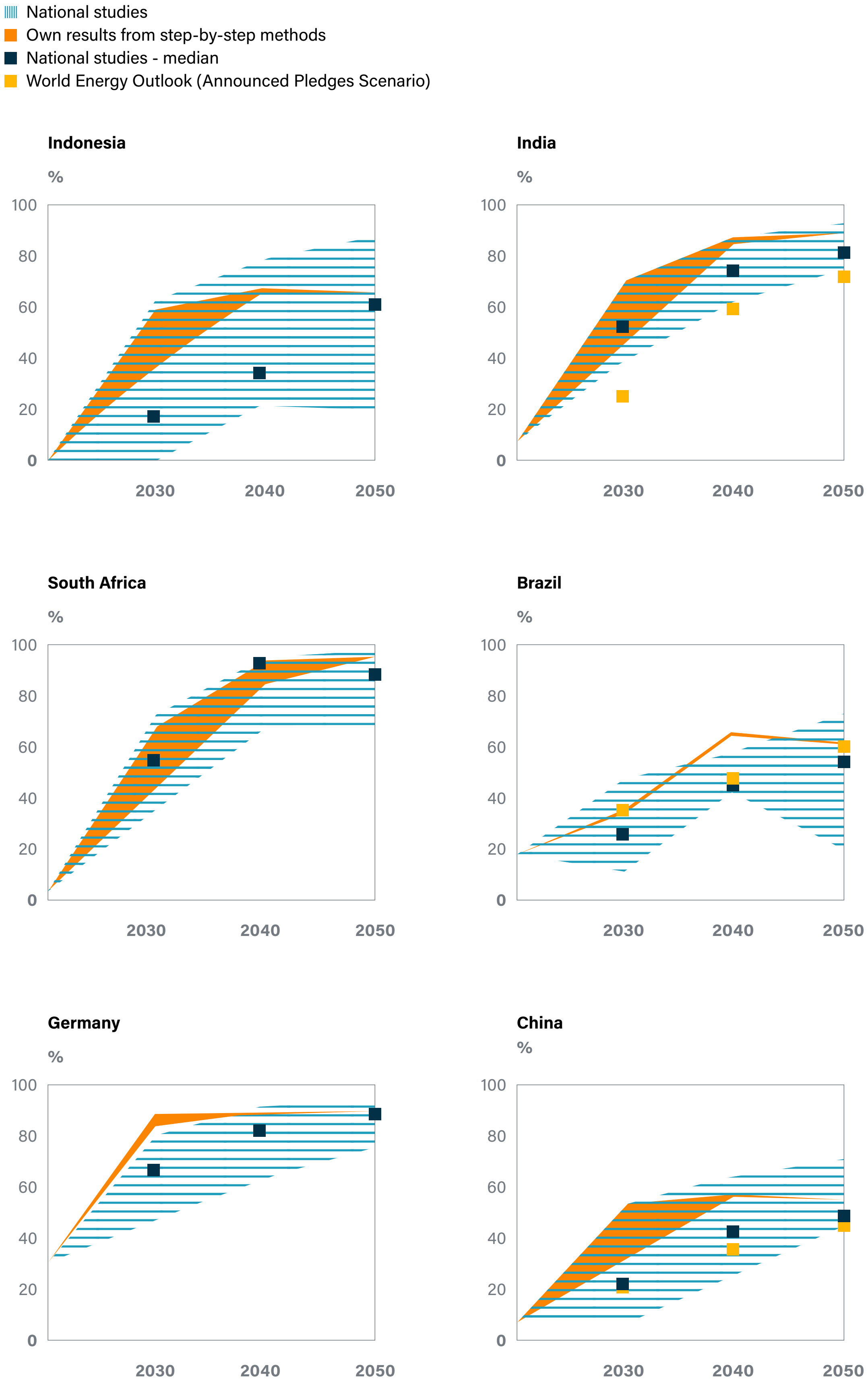
Wind and solar generation

Finally, we observe a substantial upsurge in wind and solar generation, aligned with the results identified in the preceding steps. The increase in wind and solar generation is especially notable in the coming decade, reflecting a concerted push towards clean energy sources.

→ **Figure 11** exhibits considerable variation in the penetration of wind and solar in the generation mix from country to country. This variance is largely influenced by the relevance of other carbon-free technologies within each country. For instance, hydropower continues to play an important role in countries like Brazil and China, which, in turn, results in a comparatively lower penetration of wind and solar. These nuanced variations emphasize the importance of incorporating local circumstances and resource profiles of individual countries.

Figure 11

Generation from wind and solar compared to literature



3.2 1.5°C compatible wind and solar benchmarks

Results summary

We present indicative results for three countries: Brazil, India, and Indonesia. Final benchmarks for both these and further countries will be provided in future work.

Having determined a 1.5°C compatible level of wind and solar generation that will be required to phaseout fossil fuels from the power sector while meeting the demand for clean electrification, we determine the amount of wind and solar that is required to provide this clean power using the detailed renewable potential analysis and a simple PyPSA model.

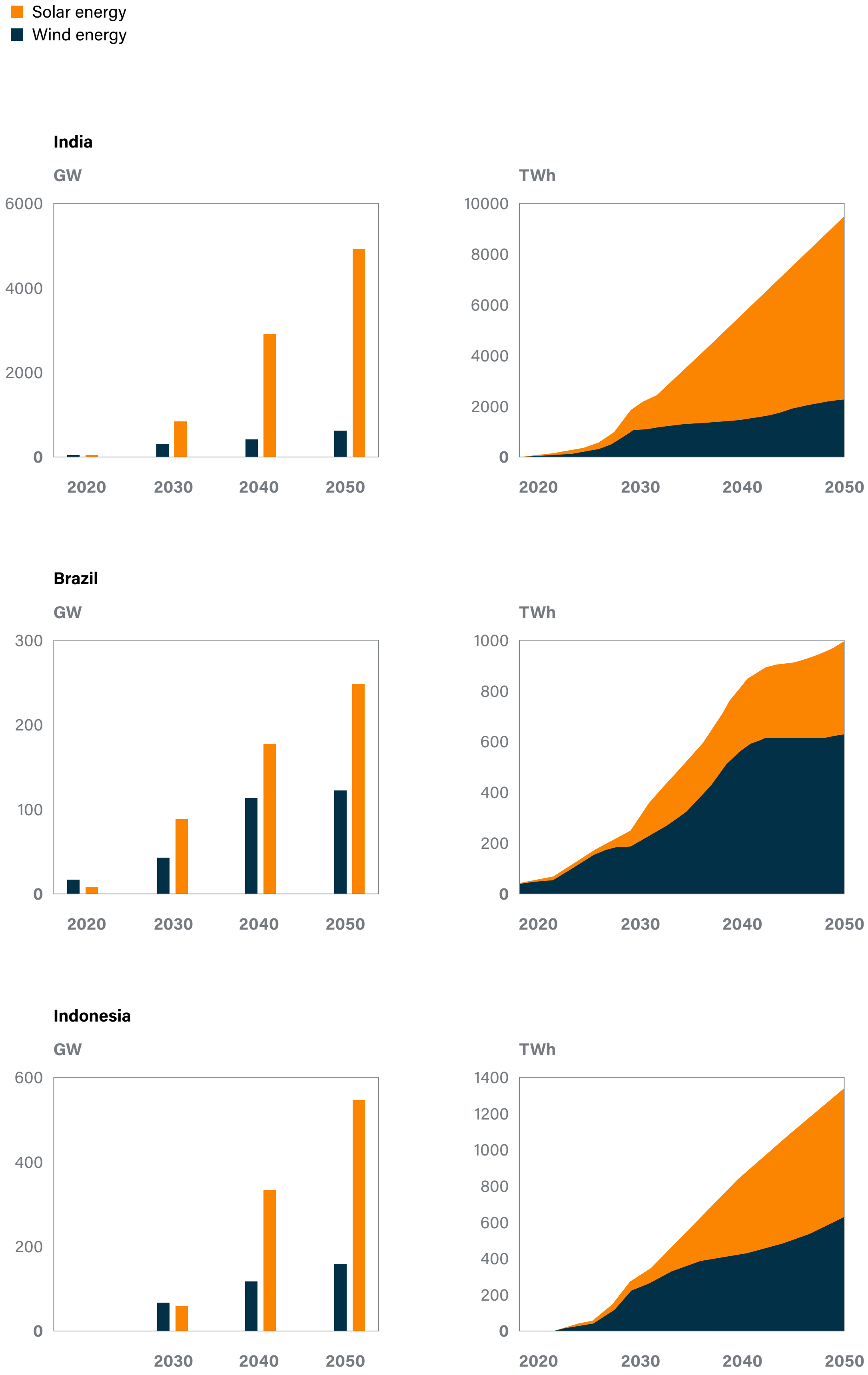
→ **Figure 12** shows the results for the three illustrative countries with medium-cost assumptions for all technologies **(for explanation of medium-cost assumptions, see 'Wind and Solar split' in → Section 2.3)**. The left-hand panels of the figure show capacity deployments, while the right-hand show the resulting generation. These should be seen as preliminary results, which will be finalised next year when the methodology is applied to a broader range of countries.

Wind and solar capacity needs to grow rapidly to align with a global 1.5°C pathway. From 2022 to 2030, wind and solar capacity will grow 4- / 8- / 13- fold in Brazil / India / Indonesia, respectively. This would require annual growth rates in wind and solar capacity of approximately 20% / 30% / 40% per year respectively. These relative increases are particularly large for Indonesia because it is starting from a lower current level of wind and solar capacity. In all countries, a rapid rollout of wind and solar is key for 1.5°C compatible action.

At the same time, wind and solar deployment is guided by national context and circumstances. In India, solar has the greatest techno-economic suitability, and therefore wind and solar deployment is dominated by solar, which represents 89% of capacity in 2050 and provides 76% of generation. In Brazil, on the other hand, over 60% of wind and solar generation in 2050 comes from wind, while in Indonesia there is a fairly equal split between wind and solar generation. When focusing on capacity deployment, solar dominates over wind due to its lower capacity factor.

Figure 12

1.5°C compatible wind and solar deployment for India, Brazil and Indonesia



India

Brazil

Indonesia

Annual capacity deployment

→ **Figure 13** shows ten-year average annual additions of wind and solar in each of the illustrative countries. This again shows that all countries need to increase the pace of wind and solar deployment considerably. Annual additions of wind and solar in the 2020s are around four times larger than in the 2010s for Brazil, while the annual additions in India over the 2020s need to be around 16 times larger than the additions that occurred through the 2010s. At the same time, there are differences in the deployment dynamics between countries. This is driven by differences in the rate of wind and solar deployment required to align with 1.5°C and comply with national targets and the retirement schedule of the existing wind and solar installed capacity in a country.

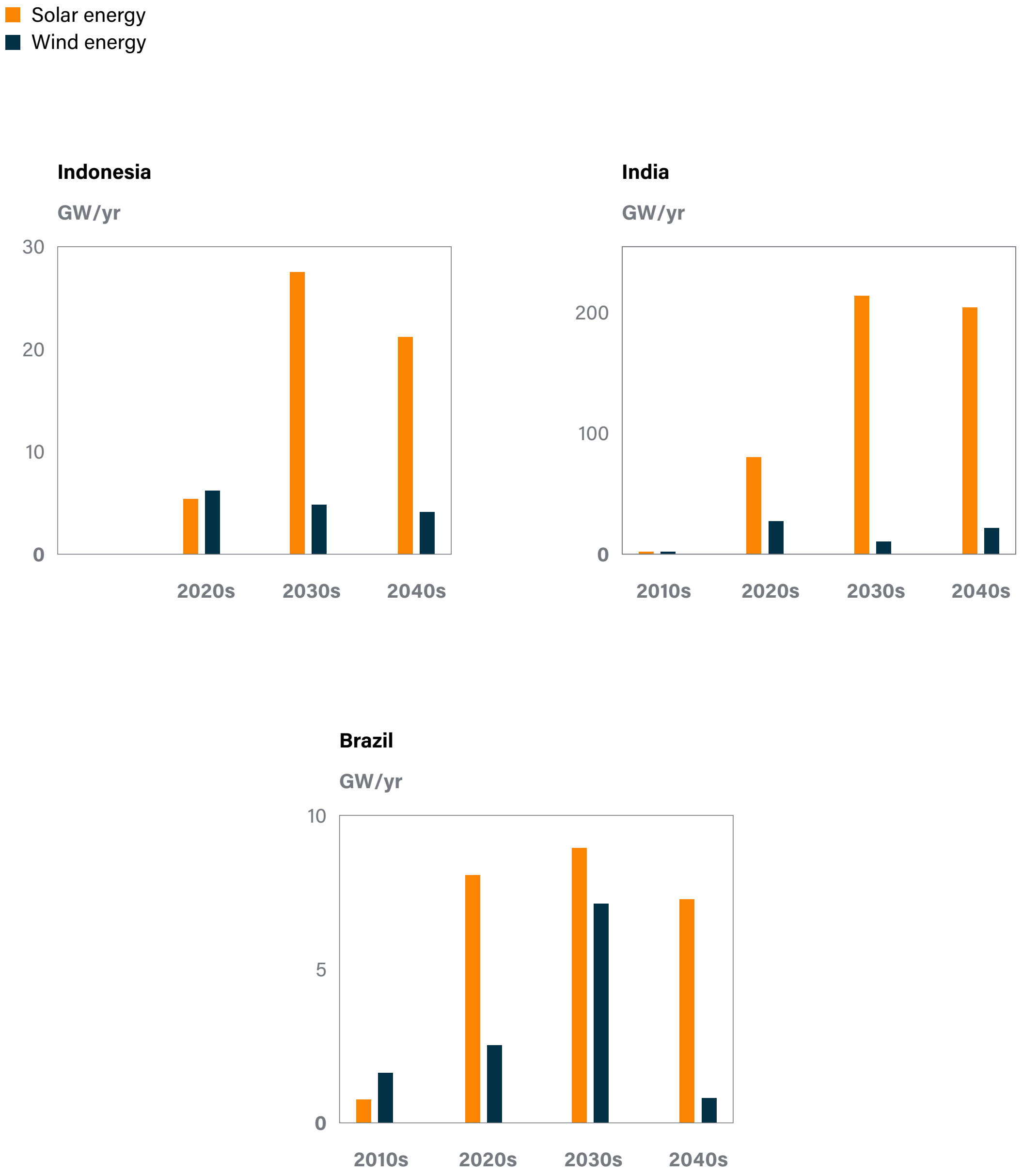
In India, the ten-year average of annual wind additions peaks in the 2020s at around 30 GW/yr, before declining to around 10-20 GW/yr from 2030 onwards, which enables a moderate growth in total wind capacity and generation. Meanwhile, solar PV additions ramp up quickly to reach around 200 GW/yr additions in the 2030s, which is maintained across the time horizon.

In Brazil, solar PV additions are ramped up from the average over the 2010s by around 1 GW/yr to reach 7-9GW/yr across the next three decades. Meanwhile, wind capacity additions grow until the late 2030s, when the pace of wind deployment reaches its maximum. In the 2030s, the average wind capacity installed per year is 7 GW. After this, total wind generation plateaus, and the necessary wind capacity additions fall to around 1 GW/yr in the 2040s.

Indonesia also demonstrates this ‘peak and decline’ behaviour in wind and solar capacity additions, which is discussed in more depth in the following section. Importantly, the date of peak wind and solar deployment in each country is not the same. While this sample of countries is not large enough to make definitive conclusions, if the point of maximum growth (and hence maximum demand on global supply chains) of different countries are not all aligned, it could help avoid bottlenecks in the global race to clean energy that could slow the energy transition.

Figure 13

Decadal annual averages of wind and solar capacity deployment



Note: The bars represent decadal averages. Therefore, annual capacity additions within each decade may vary, having a smooth increasing/decreasing trend over the decade.

There are three dynamics at play that can explain the fluctuations in the decadal annual averages of wind and solar capacity installations in different periods. The first dynamic revolves around the urgent need to rapidly move away from fossil fuels in the energy mix. This requires an accelerated deployment of renewable energy sources, in which wind and solar capacity installations play a key role. This dynamic, which is dominant during the 2020s and 2030s, drives much of the annual installations of solar and wind power capacity in these periods.

Secondly, a sustained annual installation of renewables is needed to meet the growing demand of electricity, derived from both incremental factors (e.g., economic and population growth) and structural changes (e.g., electrification). While relevant at all times, this dynamic is more pronounced in the 2030s and 2040s, when the "S-curve" growth in electrification really takes off.

Finally, the third dynamic involves the installation of additional capacity to replace aging solar panels and wind turbines. However, this aspect is less pronounced because most of the wind and solar capacity has not yet been deployed. The need for replacements may become more apparent and gain significance in the late 2040s as existing installations age and require replacement or renewal.

In general, the trajectory of annual wind and solar capacity installations depicts first a period of rapid exponential growth, as the first two dynamics of fossil phase-out and demand increase require a large amount of new renewable capacity. In India, capacity additions grow strongly out into the 2030s, with around 220GW/yr added on average over the 2030s. This deployment rate is then sustained into the 2040s. Meanwhile Brazil and Indonesia demonstrate a ramp up to maximum capacity additions in the 2030s, followed by a drop in the subsequent decade.

While some stakeholders might anticipate a uniform 'ramp-up and sustain' pattern of capacity deployment, this pattern may not necessarily emerge due to the influence of the three different drivers described above over distinct timeframes. For example, while accelerated deployment is needed in the initial years to both transition away from fossil fuels and meet future demand growth from electrification, in the long-term once fossil fuels have been phased out and widespread electrification has occurred, the growth in wind and solar electricity demand may well slow, and with it capacity installation requirements. In Brazil this slow-down in electricity demand growth post-2040 is particularly noticeable **(see → Figure 12)**, and explains the declining rate of capacity additions in the 2040s.

Regarding the contrast between wind and solar deployment, it is crucial to recognize that the methodology employed in this analysis adopts a cost-minimization approach to splitting wind and solar capacity. The minimum installation of each technology is also determined by policy considerations and targets. However, it is important to mention that certain factors, such as resource complementarity and trade-offs between solar and wind supply chains, are not fully accounted for in this approach. These factors can significantly influence the distribution of wind and solar capacity.

A possible avenue for future research, and improvement in the methodology, could explore smoothening the exponential growth curves of one technology by accelerating deployment in another technology, reducing the strain on supply chains. For example, prioritizing early wind installations with a higher capacity factor could relieve the burden on the required solar installations, and also lead to solar installations achieving semi-stable annual installation rate (rather than peaking and abruptly declining). This approach could also improve the communicability of benchmarks by addressing supply chain issues.

Sensitivity to cost assumptions

Cost reductions in wind and solar represent one of the great success stories of the past decade. From 2010-2020, the cost of solar PV fell by 85%, while the cost of onshore/offshore wind fell by 46/55% (IRENA, 2021). It seems likely that wind and solar will carry on down their cost curves, which will continue to have a transformative impact on energy system transitions. However, future technological progress is inherently uncertain, and the rate at which wind and solar costs will continue to fall may vary.

To explore the sensitivity of our results to the cost assumptions made for wind and solar PV, we perform a sensitivity analysis where the costs of each technology are varied between three levels: high, medium and low. These cost projections are created using IRENA data (see technical annex for more details). The PyPSA model represents four different technologies: residential rooftop solar PV, open-field solar PV, onshore wind, and offshore wind. Varying the cost of each technology independently gives $3^4=81$ different scenarios in which the relative cost of wind and solar vary.

→ **Figure 14** shows how the results for Indonesia vary when the costs of wind and solar are varied across these different assumptions. The median is shown as a solid line, while the 90th percentile range is shown as a shaded envelope. This demonstrates for example, that by 2050 there should be at least

70 GW of offshore wind deployed in Indonesia. However, if offshore wind makes faster cost reductions relative to onshore wind and solar PV, it could be cost-effective to deploy over 100 GW of offshore wind by 2050. This can help identify no-regrets capacity deployment, as well as the potential for acceleration beyond these minimum requirements.

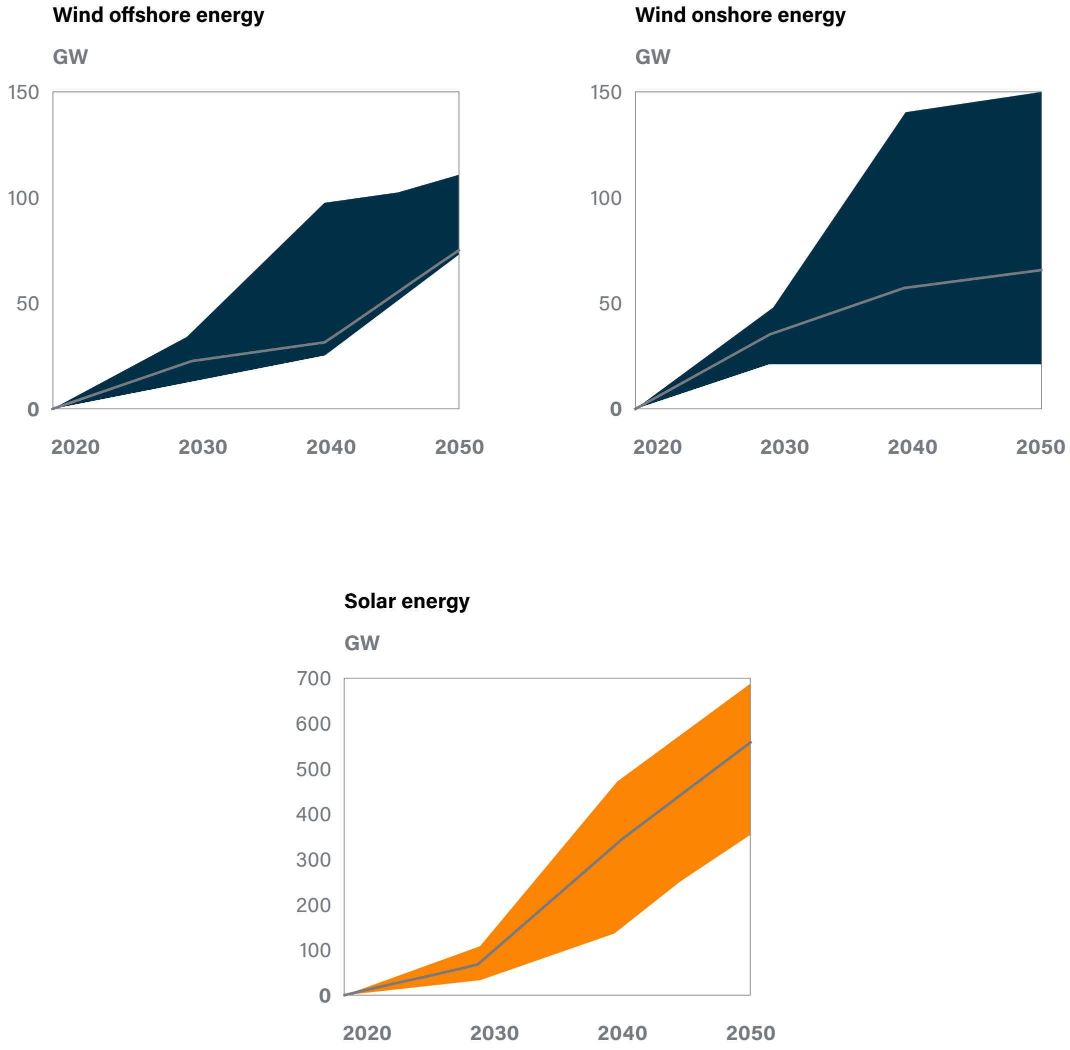


Figure 14

Sensitivity of results to cost assumptions

Note: The figure shows the median and the 90th percentile range of capacity additions over the 81 scenario variations explored.

04 Understanding the benchmarks

Understanding the nature of the benchmarks

Benchmarks for wind and solar capacity can play an important role in showing the way towards achieving the goals of the Paris Agreement. They serve as beacons, guiding the direction, pace, and scale of deployment of these renewable technologies. These benchmarks offer an order of magnitude, help to convey a sense of urgency, and send a policy signal of the level of investment and infrastructure needed in countries to address climate change.

Equally, it is valuable to recognise what these benchmarks are not. They do not serve as detailed deployment plans for the power sector, as such comprehensive plans require a more granular and localised analysis. Additionally, the benchmarks do not directly provide insights into financial needs or investment plans, despite offering estimates of capacity needs in physical terms. The financial aspects of such a transformation entail a more systemic analysis, addressing technological, infrastructure, and investment considerations. The method also does not capture who should shoulder the burden of that finance: while we integrate common but differentiated responsibilities (speed and scale), these equity considerations do not guide the required climate finance transfers from Global North to Global South countries. Moreover, the benchmarks do not give insight into whether the mass deployment of wind and solar technologies to safeguard 1.5°C is equitable, inclusive, or just – this analysis must be accompanied by the requisite just transition planning and community engagement all across the wind and solar value chain.

Moreover, it is essential to clarify that while the methodology incorporates evidence-based safeguards to account for equity concerns across countries, the benchmarks are not intended to prescribe specific actions for each country to develop wind and solar power capacity in alignment with their responsibilities and capabilities. These equitable contributions require a broader analysis that encompasses a range of factors beyond the scope of these benchmarks.

Critically, the use of these benchmarks should be complemented with supporting information to enhance their policy and decision-making relevance. These benchmarks can serve as a foundational reference point, guiding policymakers and stakeholders in the energy transition. However, they should be integrated into a broader framework of information and analysis to facilitate informed, effective, and equitable decision-making.

Limitations

While our methodology provides a simplified but comprehensive framework for estimating wind and solar power generation capacity, it's important to acknowledge certain elements that were not explicitly incorporated into our approach.

First, while the methodology employs a cost-minimization approach to split wind and solar capacity and takes into account renewable targets to determine the minimum capacity for each technology **(see → Section 2.3)**, it is important to note that this method does not comprehensively address other factors relevant to the wind-solar split, such as resource complementarity and potential trade-offs within the wind and solar supply chains. These variables can have a substantial impact on the distribution of wind and solar capacity and may not be fully accounted for in the methodology.

Secondly, while grid representation along with the associated roles of the grid in the energy transition is critical, it was not a direct focus of our methodology. The grid can act as both an enabler and a potential barrier in the scaling up of wind and solar within the energy mix. Similarly, flexibility requirements necessary to accommodate high levels of variable renewables were not directly accounted for in our methodology. Additionally, the methodology does not explicitly factor in hydrogen production for purposes other than electricity generation, such as hydrogen for industrial uses or exports. However, if hydrogen production was explicitly included in national studies, it is therefore 'inherited' within the methodology. These aspects are indeed critical to the integration of renewable sources, and their omission highlights the need for complementary analyses and strategies tailored to grid and flexibility considerations that are aligned with the benchmarks obtained.

Thirdly, our methodology takes an energy-balance approach for calculating capacity benchmarks for wind and solar. This approach focuses on the energy required to meet demand in terawatt-hours (TWh) and does not encompass capacity expansion requirements for meeting peak demand (GW). While addressing peak demand is a crucial consideration for energy planners and system operators, it falls outside the specific scope and purpose of our benchmarks. Nonetheless, this methodological choice has a minimal impact on the estimated capacity requirements for wind and solar technologies, as their unique characteristics (e.g., non-dispatchable and cheapest options to generate once they are installed) make them less dependent on peak demand conditions. Consequently, this methodology should not be used to estimate capacity requirements for other technologies in the energy fleet unless peak demand considerations are included.

Lastly, the resulting energy mix generated through our methodology may not necessarily represent the most cost-optimal mix. Although the methodology relies heavily on national studies, which often employ case optimisation models, the adjustments made during the step-by-step method can alter the optimality of the underlying inputs from these studies.

Despite these elements not being explicitly incorporated, our methodology benefits from the careful selection of national studies that have considered these concerns at the national level, whether through modelling or other detailed analyses. This assumption is made based on the belief that the inputs from national studies indirectly integrate these considerations. Nevertheless, it is essential to recognise that complementary analyses and strategies may be required to address the specific nuances of grid representation, flexibility, hydrogen production, peak demand, and cost optimisation within the broader context of an energy transition strategy.

05 Future work

This section outlines some areas of improvement that were identified as we developed the methodology. These steps will not only expand the methodology's coverage but also refine its accuracy and applicability to a wider array of high-emitting countries.

- → **Expand coverage:** The immediate future work involves implementing the methodology for calculating wind and solar capacity benchmarks across more than 20 high-emitting countries. This expansion will enhance the methodology's global relevance and applicability.
- → **Comparative approaches:** The analysis can be deepened by comparing the resulting benchmarks against alternative methods, such as accelerated S-shaped diffusion curves, historical trends, or best practices. This comparative analysis will provide valuable insights into the methodology's performance and effectiveness.
- → **Methodology refinement:** As country coverage is increased, some elements of the methodology may require revision. For example, how to incorporate ambitious energy efficiency improvements in the methodology (e.g., to meet the imperative requirement to double energy efficiency by 2030 (IEA, 2023b)), or the implications of growing green hydrogen production for exports in total electricity demand. In the refinement of the methodology, alternative simpler methods can also be explored to ensure alignment with other benchmarks in the power sector.
- → **Further explore capacity growth rate dynamics:** The energy system modelling conducted here includes constraints on the growth in total capacity and total capacity additions for wind and solar. We currently observe in some countries a peak in capacity additions followed by a decline (e.g., in Brazil). While this could help stagger peak supply chain requirements in different countries over the next few decades, further work could explore the implications of different constraints to capacity growth rates. This could include a limit on the rate of degrowth in capacity additions, to explore a dynamic where capacity additions are ramped up and then sustained, rather than peaking and declining.
- → **Improve wind and solar split:** A review of the wind and solar capacity split, with a deeper consideration of spatial and temporal resolution, as well as the influence of resource complementarity. The wind and solar split, defined in step 5 of the methodology, can

also benefit from a more careful analysis of how one technology can alleviate supply chain demand peaks in other clean technologies (e.g., how wind deployment can help stagger the deployment of annual solar installations).

→ **Increase yearly resolution in the step-wise approach:** Currently, the 1.5ºC compatible wind and solar generation calculated in the first four steps of the method is done on a 10-year basis, providing values for 2030, 2040 and 2050. We could explore the possibility of improving this resolution to 5-year periods or even annually. Adjusting the temporal resolution could distribute the deployment effort more evenly across the decades, ensuring a balanced transition, and giving more detailed policy guidance on annual installations needed.

→ **Qualitative insights:** Future work should also aim to provide qualitative descriptions of key challenges identified across a broader sample of countries. This will help in understanding the diverse obstacles and opportunities that countries face in their energy transition journeys.

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