Climate Action Tracker

Methodology for 1.5°C compatible sectoral benchmarks

October 2024

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November 2023

[updated in October 2024]

This document was updated in October 2024 to clarify information on the methodology for selecting pathways from the Integrated Assessment Models (IAMs), incorporate additional benchmarks for 2035, and include benchmarks for additional sectors that were derived using the same methods already outlined.

1.5°C compatible sectoral benchmarks

Methods documentation

Summary

While addressing the climate crisis is a collective and global effort, concrete action will happen at the national and sectoral level. To guide the global energy transition towards a zero-carbon future, we therefore need national and sectoral benchmarks to act as a roadmap for what each country needs to do at the sectoral level to limit warming to 1.5°C.

The Climate Action Tracker has defined and analysed a series of Paris Agreement-compatible benchmarks, across four major sectors – Power, Transport, Industry, and Buildings – and for a range of different countries. Within each sector, we define benchmarks for several separate but complementary indicators.

This report provides the underlying technical documentation of the methods used to define these benchmarks. For more information about the benchmark results, please see the specific sectoral reports published by the Climate Action Tracker (CAT, 2023).

Contents

1 Introduction

This report presents benchmarks for key indicators in five sectors: Power, Buildings, Industry, Transport, and Technological Carbon Removal. Currently, only Power, Buildings, and Transport are included; however, this is a living document and additional sectors will be added in the future. For each sector, we develop targets for 2030 and 2050 for a set of sector-specific indicators at the global, and sometimes the national, level. Targets for additional relevant years (e.g., 2035 or 2040) are also defined for some indicators. Further, within the Power chapter, this document contains global-scale benchmarks for Industry and Technological Carbon Removal that are derived from the same methods used for the State of Climate Action report series.

The purpose of developing benchmarks is to set targets for key indicators of necessary progress – in this case related to sectoral transformation – toward meeting Paris Agreement commitments of limiting warming to 1.5°C. Targets can both raise ambition in policymaking by highlighting the scale and pace of change needed and serve as a way to measure progress toward achieving these goals. Benchmarks chart a path toward where we need to be by showing the pace and scale of change needed.

The benchmarks defined in this report explore how fast each sector should be decarbonised within a given nation (or globally) to be compatible with the Paris Agreement, irrespective of who pays for this transition. In other words, these benchmarks show where action needs to happen, but does not provide information on who should pay.

2 Methods applicable to all sectors

CAT uses three key lines of evidence to develop these sectoral benchmarks: a literature review of existing targets, global 1.5°C compatible pathways from the IPCC AR6 scenarios, and bottom-up sectoral modelling. Each of these lines of evidence has strengths and limitations, so combining them allows us to produce more robust benchmarks.

This section details the general methods employed to form each of these lines of evidence. More detail about how these methods were used to set the benchmarks can be found in the sector-specific chapters that follow.

2.1 Global Integrated Assessment Models

Integrated Assessment Models (IAMs) couple detailed models of energy system technologies with simplified economic and climate science models to provide a suite of possible future scenarios allowing an assessment of the feasibility of achieving specific climate goals.

The IPCC has established a criterion for rating these scenarios as being compatible with the long-term temperature goal of the Paris Agreement of limiting warming to 1.5°C. This criterion limits scenarios to those with no - or limited - temperature overshoot. More specifically, those that limit median global warming to 1.5°C throughout the 21st century without exceeding that level ("no overshoot"), or that allow warming to drop below 1.5° at the end of the century (around 1.3°C of warming by 2100) after a brief and limited overshoot of median peak warming below 1.6°C around the 2060s ("low overshoot").

We use the IAM pathways to ensure compatibility of our benchmarks with the global climate goals outlined in the Paris Agreement.

2.1.1 Selecting pathways

Using the IPCC's AR6 Scenario Explorer and Database of IAMs (Byers *et al.*, 2022), we select 33 scenarios which meet five criteria identified by Climate Analytics (2023a).

1. Scenarios limit warming to 1.5°C with no or limited overshoot.
2. Scenarios are published after 2018 (i.e. post- the Special Report on 1.5°C), with the exception of the low energy demand scenario (Grubler *et al.*, 2018). This scenario is retained as it offers a unique perspective on a 1.5°C aligned demand-side transition.
3. Scenarios have good regional resolution (provide data split into the 10 macro regions), which was needed to enable downscaling to the country-level with sufficient confidence.
4. A sustainable amount of carbon dioxide removal is used—specifically, BECCS deployment is restricted to be less than 5 $GtCO_2$/yr over the 2040–60 period, and carbon removal from afforestation and reforestation is limited to be less than 3.6 $GtCO_2$/yr over 2040–2060 and less than 4.4 $GtCO_2$/yr over 2050–2100.
5. Scenarios are consistent with achieving net-zero GHG emissions in the second half of the century, as stated in Article 4.1 of the Paris Agreement.

Importantly, none of these scenarios represent a fair distribution of the effort required to mitigate emissions. Instead, they simulate the most cost-effective routes that limit warming to 1.5°C. Achieving the global targets derived from these modelled scenarios implies that either substantial financial transfers are made among countries, an accelerated decarbonisation pace by wealthier countries compared to the original models, or a blend of both approaches (Bauer *et al.*, 2020).

To better account for regional differences, we employed another set of methods that required additional filtering; due to limitations in the granularity of data from the IAMs, this secondary filtering varied by sector.

- 32 of these 33 scenarios were used for setting targets for the power sector, selecting only those with the regional resolution in data sufficient for downscaling modelled pathways to the country level. By downscaling these scenarios, we were able to make further adjustments to national and global electricity generation benchmarks that more effectively consider equity and feasibility constraints relevant to power sector decarbonization. This process is detailed in Section 0.
- 24 of these 33 scenarios were used for setting targets for the buildings sector. Data limitations in modelled pathways meant that we could not follow a similar approach to that taken for the power sector. Instead, we applied a more simplistic filter to the 33 scenarios and retained only those in which the rate of decline in GHG emissions between 2020 and 2030 is steeper in developed countries than in developing countries. Further scenario selection is detailed in Section 4.4.2.
- Responsibility to mitigate climate change, as well as the capacity to deploy carbon removal technologies, varies enormously by country. All 33 scenarios were used for setting the target for technological carbon removal, given the large uncertainties associated with the magnitude of technological carbon removal required to limit warming to 1.5°C, as well as the feasibility of scaling up these approaches (Grant *et al.*, 2021). This decision reflects the importance of capturing the broadest possible range of perspectives on the role that technological carbon removal could play in achieving the Paris Agreement temperature goal, while remaining within literature-defined sustainability constraints. Future analysis could explore how integrating equity concerns into the analysis could affect the global deployment of technological carbon dioxide removal.

2.2 Sectoral modelling

The Integrated Assessment Models described above provide useful constraints on what is necessary to limit warming to 1.5C at the global level and offer insights into the cost and energy consumption trade-offs between mitigation efforts in different sectors. However, IAMs also have limitations that impact their usefulness for setting sectoral benchmarks. IAMs often do not have sufficient sectoral detail to resolve the indicators and benchmarks that are useful to sectoral policy makers.

An alternative approach is to build a "bottom-up" analysis that examines the key drivers of emissions within a sector and the associated mitigation options. Bottom-up analyses often identify higher mitigation potentials than IAMs within an individual sector (Ch 2.6.2, IPCC, 2018), partly because of a lack of sectoral resolution in the IAMs but also because IAMs are better suited to capturing gradual rather than rapid change (Hare, Brecha and Schaeffer, 2018).

For this report we include existing bottom-up analyses from the literature (see Power) and, where needed, build our own tools for bottom-up analyses (see Buildings and Transport). Each method is tailored to the specific sector and is described in detail in the relevant section.

2.3 Literature review

In addition to the modelling analyses, we integrate existing knowledge from literature into the benchmarks. While the power sector has received considerable research attention in each of the sectors we incorporate our own analysis and compare it with the existing literature. For individual countries with comprehensive national studies we are able to establish meaningful benchmarks that take into account the local conditions and circumstances.

More detailed explanations of how literature is used in setting the benchmarks for each sector can be found in the respective sector chapters.

3 Power sector

The following section provides the underlying technical documentation for the power sector benchmarks produced by the Climate Action Tracker. These benchmarks were published in the report 'Clean electricity within a generation' (CAT, 2023).

Multiple different perspectives will be needed to guide the energy transition at a national level. Country-level roadmaps need to be consistent with the Paris Agreement's global long-term temperature goal, as well as considering national circumstances and local context.

To produce power sector benchmarks, the CAT uses two different lines of evidence: downscaling the latest global pathways as assessed by the IPCC, and an in-depth literature review of the latest power sector modelling at the national level. Our results are therefore based on multiple different lines of evidence, spanning different geographical and temporal scales. Encompassing different perspectives on the energy transition improves the robustness of our method.

3.1 Country selection

The CAT provides power sector benchmarks both at the global level, and for 16 selected countries.

Countries were selected based on their share of global power generation, scale of power sector emissions, geopolitical importance, and diversity (both geographic and economic). We prioritised countries with large power sectors, such as the USA, China, the EU and Brazil.

We also aimed to cover a diverse range of power generation mixes, as this can help show how the pace and nature of power sector decarbonisation may vary across different contexts. Finally, we focused on countries which generally have existing national studies exploring power sector decarbonisation, as this is a key input to the analysis.

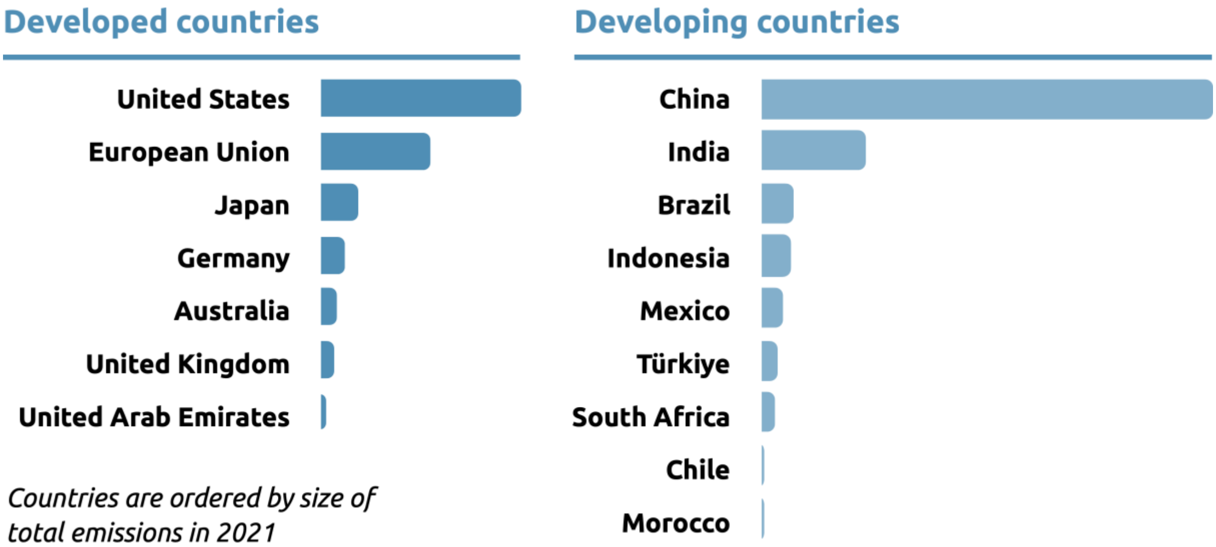

Figure 1: Countries selected for power sector benchmarks

Taking these factors into account, the following countries were selected (shown in Figure 1 and Table 1). Our classification into developed vs. developing countries here is based on a combination of UNFCCC Annex status, and human development index (HDI). We broadly follow Annex I/non-Annex I classifications to define developed vs. developing countries, but classify non-Annex I countries with a very high HDI of > 0.9 as developed. In this classification the UAE is classified as developed, due to its very high HDI of 0.93. The other non-Annex I countries which are classified as developed under this classification are South Korea, Israel and Singapore.

In addition, while Türkiye is an Annex I country, for the purpose of the power sector benchmarks it is treated as a developing country due to its specific socio-economic context. Türkiye only recently achieved a Human Development Index of above 0.8 and has one of the lowest levels of HDI within Annex I countries of 0.838. If Türkiye were treated as a developed country, the top-down perspective would give slightly different benchmarks – with Türkiye achieving 98% renewables by 2030 and 100% by 2035, rather than 96% in 2030, 99% in 2035 and 100% in 2040.

Table 1: Countries selected for power sector benchmarks Countries are ordered in size of total emissions in 2021.

Developed	Developing
United States	China
EU27	India
Japan	Brazil
Germany	Indonesia
Australia	Mexico
United Kingdom	Türkiye
United Arab Emirates	South Africa
	Chile
	Morocco

3.2 The global / top-down perspective: producing national level data from global pathways

The global / top-down perspective uses global pathways assessed by IPCC AR6 as a line of evidence to guide the global energy transition. Figure 2 summarises the steps taken to produce national level power sector transition pathways from these global pathways. The following sections provide further detail on each of these steps, while section 2.1.1 outlines the pathway selection.

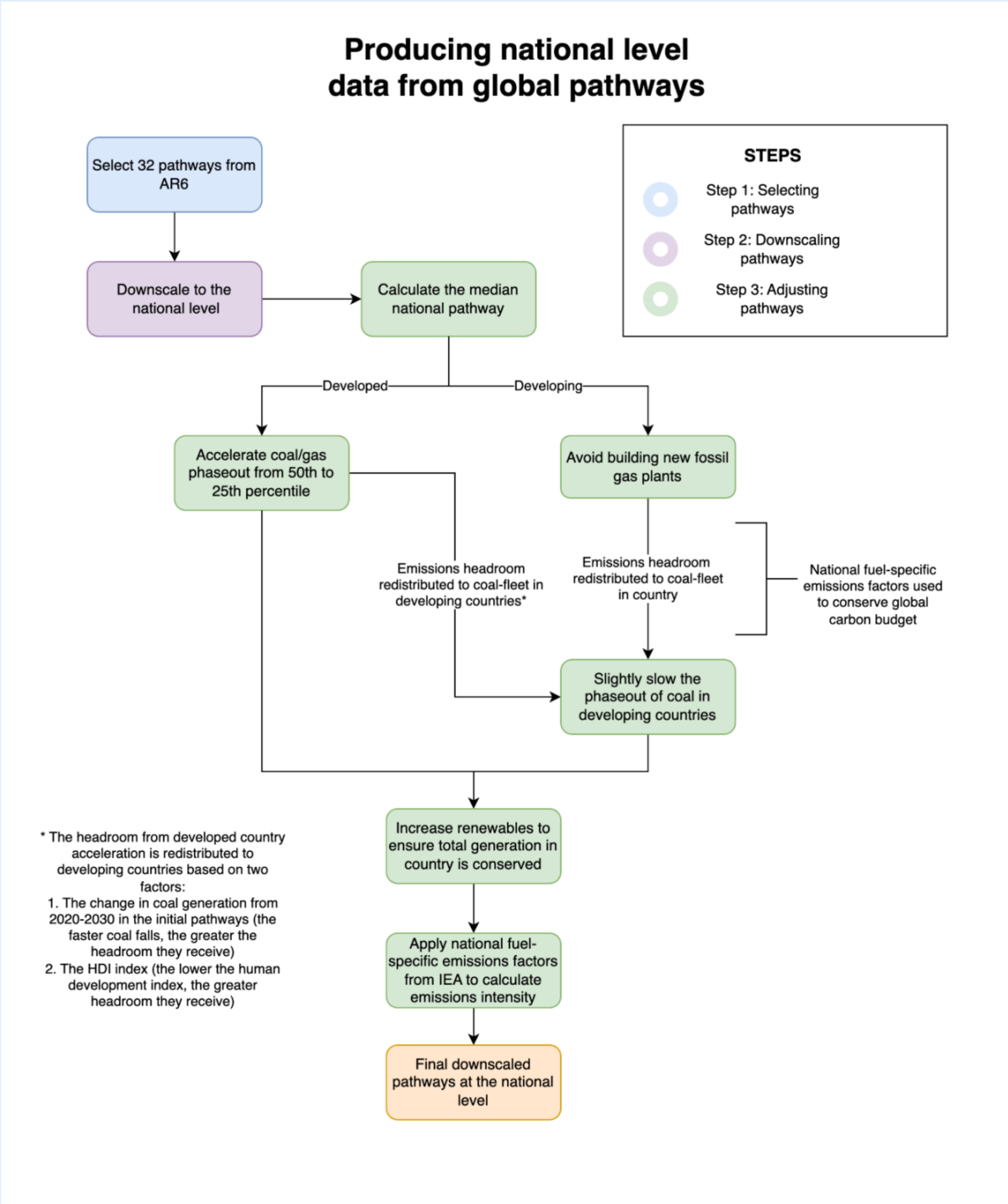

Figure 2: Methods flow chart for producing national level data from the global scenarios assessed by IPCC AR6

3.2.1 Downscaling global pathways

IAMs provide results at the regional, rather than national level. In the IPCC AR6, global pathways are broken up into 10 major world regions, or "macro-regions"[1]. These 'macro-region' results needed to be downscaled to the national level.

To do this, we use the Simplified Integrated Assessment Model with Energy System Emulator (SIAMESE). SIAMESE takes data at a regional level from IAMs and converts it to the national level, providing a perspective on what each country within a given region would need to do to achieve the overarching macro-region pathway. SIAMESE does this by allocating energy consumption to each country in a way that maximises the welfare of the macro-region as a whole – simulating the cost-optimising logic of IAMs. For more details, see Climate Analytics (2021) and Sferra *et al* (2019).

SIAMESE is used here to downscale the electricity mix in the selected 1.5°C compatible pathways to the national level. This results in 32 possible future electricity mixes for each country. Each electricity mix is part of a global pathway which, across all countries and all sectors, limits warming to 1.5°C. This gives us confidence that the combined set of electricity mixes will remain within the 1.5°C limit when summed across all countries.

3.2.2 Adjusting global pathways

The CAT then takes the median of these 32 scenarios and makes three key adjustments on a country-level. These adjustments are made to better represent the call in the Paris Agreement for developed countries to take the lead in reducing emissions, the challenges related to stranded assets in 1.5°C compatible transitions (particularly in the developing world), and the current geopolitical context in the aftermath of the fossil gas price crisis.

These adjustments are as follows:

1. We assume that developed countries can accelerate fossil fuel phase-out, following the 75th percentile (more ambitious than the median) of the set of filtered pathways. We then reallocated the CO_2 emissions saved to developing countries to allow for a slightly slower reduction in coal power generation in the near-term. At all times, country level emissions factors for coal/gas calculated from the IEA (2023b, 2023d) are used to ensure the global carbon budget is conserved. The headroom from an accelerated phase-out in developed countries is redistributed to developing countries weighted by the following two factors:

   a. The rate at which coal generation falls from 2020-2030 in the initial downscaled pathways. The faster the reductions in coal, the more headroom is allocated to this country.

   b. The HDI index of the country. The higher the HDI of the country, the less headroom is allocated here.

   IAMs have been criticised for failing to account for differences in regional circumstances which may limit the pace of power sector decarbonisation in developing countries (Muttitt *et al.*, 2023), and this step responds directly to this critique.

2. To prevent the build-out of fossil gas power plants and minimise the risk of stranded assets across both developed and developing countries, we calculated levels of generation from each country's current gas-fired power fleet (as of 2022) and then limited future generation to this level to prevent any new fossil gas power generation beyond this level for all countries. We then reallocated any emissions savings that would result from limiting the expansion of fossil gas plants to the coal-fired power fleet within each country, again using country-specific emissions factors to conserve emissions.

   Some modelled pathways show an initial growth in fossil gas infrastructure during the 2020s, notably within developing countries. This expansion is then succeeded by a rapid decline in fossil gas-fired power generation throughout the 2030s. However, if this trajectory is pursued, it could result in significant stranded assets and, given the ongoing gas crisis, give rise to heightened concerns about energy security. This step explicitly addresses this issue.

3. We adjusted total renewables generation on the country level for all countries to keep total in-country generation consistent with the median of the filtered pathways for each country.

   This method, then, uses the full range of the filtered IAM scenarios to determine a technically feasible, 1.5°C compatible pathway that simultaneously accounts for feasibility concerns that have yet to be fully incorporated into IAM scenarios. These adjustments lead to a slightly slower coal phase-out, a faster fossil gas phase-out, and a faster scale-up of zero-carbon power sources.

3.3 The bottom-up perspective: an in-depth review of national power systems modelling

Our bottom-up perspective is based on an in-depth review of national-level power systems modelling, which is generally better able to capture national circumstances, but is less good at incorporating larger scale influences such as global trade, international technology spill-overs and global climate policy.

We reviewed the current literature on power system transitions in each of the 16 countries covered in this report, assessing over 300 different pathways from over 250 different individual papers.

We selected literature according to the following criteria:

- **Ambition**: we included only on literature that achieved total power sector decarbonisation by 2050.
- **Methodology**: we included studies that produced power sector pathways using formal energy system models (rather than trend extrapolation, simple econometrics or other approaches), to account for technical feasibility constraints within each country specifically.
- **Narrative**: We looked for literature that included the power sector of a country at the minimum, but preferred studies that coupled power with other sectors such as industry or transport. Additionally, pathways which showed limited increase in electricity demand which was not deemed to be consistent with a high electrification narrative were excluded.
- **Historical accuracy**: Some of the selected pathways model the power sector from 2015 or 2020. This can lead to discrepancies if the model data does not follow historical data over the period up to 2023. To avoid this, we only took pathways where the initial data points prior to 2023 were closely matched with historical data. We excluded pathways in which rapid decarbonisation occurs in the model which was not replicated in the real-world, which could lead to more ambitious benchmarks for 2030 which are not based on the true starting point of 2023.

This led to an eventual pool of almost 120 pathways from around 80 different academic papers which we used to provide a bottom-up national level perspective on the power system transition.

Table 2 lists the studies considered for each country in the report.

Table 2: List of studies used in the production of benchmarks

Country	Studies included
Australia	(AEMO, 2013, 2022; Teske, 2016; Aboumahboub *et al.*, 2020)
Brazil	(de Souza Noel Simas Barbosa *et al.*, 2016; Gils, Simon and Soria, 2017; Breyer *et al.*, 2018; Simon, Naegler and Gils, 2018; da Luz and Moura, 2019; PCE Brasil 2050, 2019; EPE, 2020)
Chile	(Vargas *et al.*, 2018; Nasirov, O'Ryan and Osorio, 2020; Osorio-Aravena *et al.*, 2021; Kinter-Meyer *et al.*, 2022)
China	(Teske *et al.*, 2015; He *et al.*, 2020; Lugovoy *et al.*, 2021; Qiu *et al.*, 2021; ICCSD, 2022; Xue and Liu, 2022; Zhang and Chen, 2022)
European Union	(Child *et al.*, 2019; Auer *et al.*, 2020; Victoria *et al.*, 2020; Anon, 2022)
Germany	(dena, 2018; Bartholdsen *et al.*, 2019; Hansen, Mathiesen and Skov, 2019; Eisemann, 2020; Fraunhofer ISI, 2020; Robinius *et al.*, 2020; Fraunhofer ISI and Consentec GmbH, 2021; Graichen *et al.*, 2021; Nitsch, 2021; Agora Energiewende, 2023)
India	(Teske *et al.*, 2015; Gulagi, Bogdanov and Breyer, 2018; Lawrenz *et al.*, 2018; Teske, 2019; IEA, 2021a)
Indonesia	(IESR, 2021, 2022; Reyseliani and Purwanto, 2021; IEA, 2022b; IRENA, 2022)
Japan (only used for 2050)	(Matsuo *et al.*, 2018; Kato and Kurosawa, 2019; Burandt, 2021; Shiraishi *et al.*, 2023)
Mexico	(Sarmiento *et al.*, 2019; Bataille *et al.*, 2020; Buira *et al.*, 2021)
Morocco	(Ram *et al.*, 2017; Schinko *et al.*, 2019; Zelt *et al.*, 2019)
South Africa	(Teske, 2019; Wright *et al.*, 2019; IRENA, 2020; IEA, 2022a)
Türkiye	(Kilickaplan *et al.*, 2017)
UAE	None
United Kingdom	(CCC, 2020; Patrizio, Pratama and Dowell, 2020; Ember, 2022; Grid, 2022)
United States	(Cole *et al.*, 2021; Larson *et al.*, 2021; Williams *et al.*, 2021; Bistline *et al.*, 2022; Gagnon *et al.*, 2022)

These national studies provide a perspective on power sector transitions that accounts for the specific context in each country. This can help ensure that the benchmarks produced are consistent with the reality on the ground in each country. However, it is important to stress that none of these pathways were explicitly testing the feasibility frontier at the national level — that is, the maximum pace of power sector decarbonisation that is possible. Therefore, they should not be seen as an ambition ceiling that cannot be broken, but simply the current state of knowledge in the academic literature on power sector decarbonisation in each country.

The selected power sector modelling studies all achieve a decarbonised power sector by 2050 but display a wide range of levels of ambition on the path to 2050. As they are produced by national-level energy system models, many of them have no clear link back to 1.5°C compatibility. Therefore, when extracting information from these studies on 1.5°C-aligned power sector transitions, we make two further steps:

We filter the studies to only consider those studies which fall within the 1.5°C compatible range produced by the 32 downscaled pathways. National studies must align with at least one of the downscaled 1.5°C compatible pathways to be considered.

We then take the average of the two most ambitious studies which pass the filter to represent the bottom-up perspective from the literature. If no national studies pass this filter, we take the most ambitious national study as representative of the bottom-up perspective.

We produce a bottom-up perspective for all countries except the UAE. In the case of UAE, there are no existing national studies, so we only use the global top-down perspective.

Additionally, for Japan, we only produce a bottom-up perspective for 2050, not the preceding years. This is because while there are existing national studies for Japan, they do not reduce power sector emissions fast enough in 2030/2040 to align with the 1.5ºC compatible downscaled pathways. The fact that they do not align with the downscaled pathways does not mean the downscaled pathways are infeasible, but simply that a 1.5ºC aligned power sector transition in Japan has yet to be explored at the national level. However, while the studies do not cut emissions fast enough prior to 2050 to align with 1.5ºC, they do demonstrate the feasibility of achieving 100% renewables and 0% fossil generation by 2050 in Japan – and so they are used to help set the 2050 benchmarks.

3.4 Calculating emissions intensity benchmarks

The top-down/global and bottom-up/national perspectives used by the CAT for power sector benchmarking give the electricity mix in a country over time. To calculate emissions intensity benchmarks, we then multiply the coal and fossil gas benchmarks produced in the report by country specific emissions factors calculated from IEA data (2023b, 2023d). To calculate the emissions intensity of fossil fuels w/ CCS (which are deployed at very minimal levels in the scenarios reviewed), we assume a 90% capture rate for CO_2 emissions.

The emissions intensity benchmarks here focus on CO_2 emissions coming at the point of generation, rather than considering life-cycle emissions of generation technologies. Life-cycle emissions can be larger and are influenced by upstream emissions from fossil fuel extraction and emissions released during construction.

The approach also ignores any potential negative emissions that could come from bio-electricity equipped with carbon capture and storage (as it treats bioelectricity as zero-emissions, rather than negative-emissions). This is due to a lack of data on possible emissions factors for BECCS in the power sector at the country level. Large-scale deployment of BECCS in the power sector is a sub-optimal climate strategy, given the limited supply of sustainable biomass (Energy Transitions Committee, 2021) and the better energetic case for BECCS deployment elsewhere (Creutzig *et al.*, 2019). Therefore, the negative emissions that our approach ignores are likely to be small. However, this means that the emissions-intensity benchmarks provided by this analysis should be seen as an ambition floor, and (limited) BECCS deployment would reduce emissions intensity even further, to <0 gCO_2/kWh in some cases.

3.5 Producing global benchmarks

To produce global benchmarks for the power sector transition, the CAT uses a similar approach as for the national level, using two different lines of evidence to inform our work.

First, we use the selected 1.5°C compatible pathways assessed by the IPCC (see Section 2.1.1) Having produced country-level pathways, we then add these country-level pathways back up to provide a global pathway which accounts for the adjustments described in Section 3.2.2.

We then complement this global pathway with a review of the available literature on global power sector transitions. We only considered studies which cut the emissions intensity of power generation as fast as the 1.5°C compatible scenarios assessed by the IPCC. From this, we selected one central study to complement the IAM pathways, produced by the Energy Watch Group (EWG) and Lappeenranta-Lahti University of Technology (LUT) (Ram *et al.*, 2019). This study explores a transition to a 100% renewable electricity system by 2050 in line with 1.5°C. These two data points (IAMs and the EWG LUT study) are used to produce our global benchmarks.

3.6 Comparing different perspectives

The use of both national and global perspectives to produce benchmarks in the power sector is a strength, as it improves the robustness of the benchmarks produced. However, the question then arises – is the national perspective still aligned with 1.5°C, as it is produced by national models which don't have a link back to a single, global, 1.5°C compatible pathway?

Figure 3 shows what would happen at a global level if all countries were to take the bottom-up perspective (blue) compared to them all taking the top-down perspective (green). This is compared to 1.5°C compatible power sector emissions from the selected 32 IAM pathways (pink).

This shows that, even if all countries were to take the literature data, global power sector emissions would remain within the interquartile range of 1.5°C compatible power sector transitions. However, cumulative emissions would be higher by ~16 $GtCO_2$ by 2050. This is approximately 4% of the remaining carbon budget for 1.5°C as of 2020 (IPCC, 2023). This gives us confidence that all the benchmarks produced by both perspectives remain aligned with 1.5°C but highlights the value of countries aligning with the higher end of the benchmarking range wherever possible.

With this in mind, the CAT argues that:

- Developed countries should aim for the more ambitious end of the benchmarking range wherever possible in order to maximise emissions reductions.
- Developing countries should aim for *at least* the less ambitious end of the benchmarking range as an ambition floor. This lower level will still require upscaled climate finance from high-income countries and, conditional on sufficient international support, developing countries should aim to exceed the ambition floor and cut power sector emissions even faster.

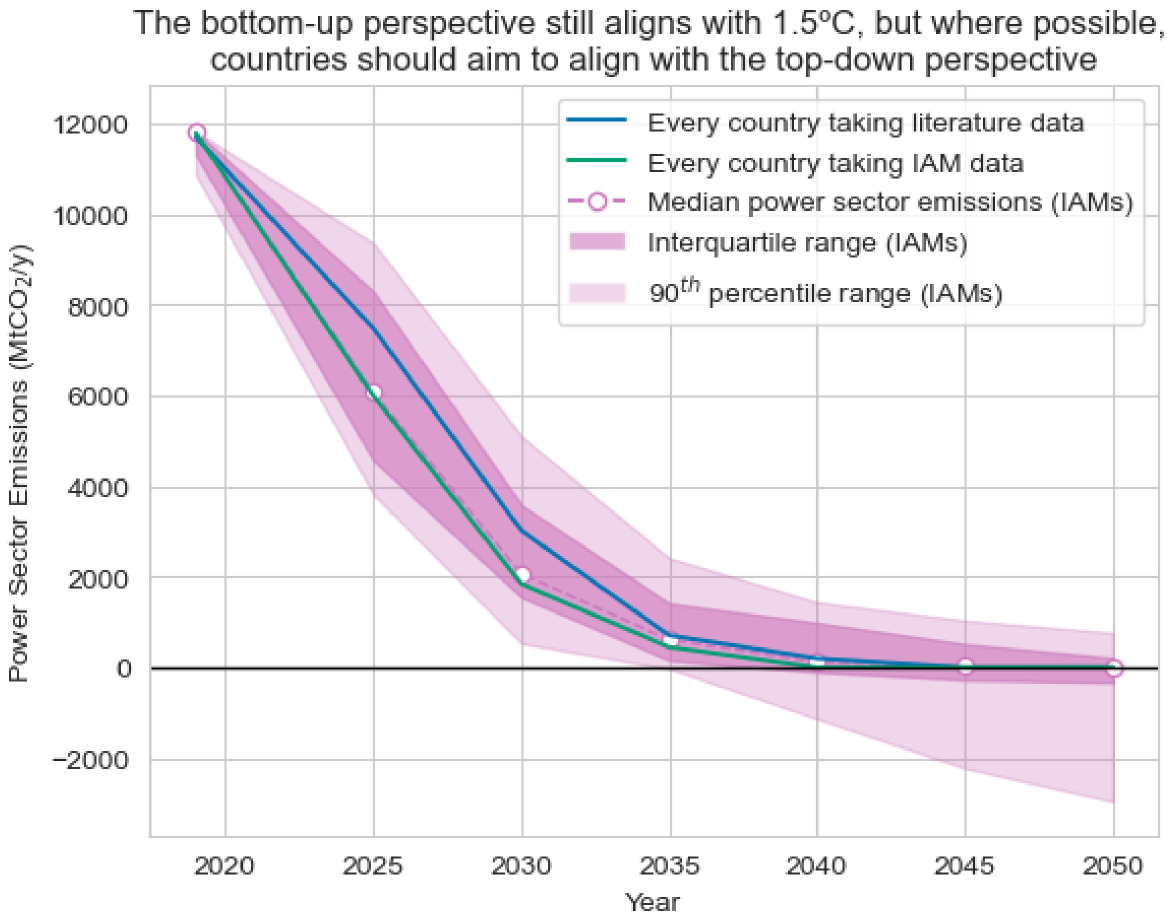

Figure 3: The impact of taking the national perspectives instead of the global perspectives

3.7 Comparison with 2020 report

The latest CAT benchmarks for the power sector represent an update from a previous report published in 2020 (CAT, 2020). This provided benchmarks for the share of coal and renewables in 2030, 2040 and 2050, as well as the emissions intensity of electricity generation, for seven countries/regions: the United States, European Union, Indonesia, India, South Africa and Brazil. This section briefly compares the results of the latest benchmarks produced in 2023 to these previous benchmarks.

The latest coal benchmarks are similar to the previous report, with the exception of India and Indonesia, which have less ambitious benchmarks in 2030. The previous benchmarks for India and Indonesia were for them to achieve a 5-10% share of coal by 2030. The 2023 report finds instead that they should target a 17-19% share (India) or a 7-16% share (Indonesia). This change is due to three factors.

First, little progress has been made in India/Indonesia's coal phase-out since the 2020 report, meaning that achieving a rapid reduction in coal by 2030 is now more challenging. Second, the latest report explicitly addresses the rapid coal phase-out in developing countries seen in many global pathways, attempting to slow it where possible to minimise asset stranding, while still aligning with 1.5°C. This leads to slightly higher shares of coal in 2030 for India and Indonesia in particular. Third, the report conducts a more in-depth review of the existing literature on power sector decarbonisation at the national level, which further informs the benchmarks produced.

The benchmarks for most other countries remain at zero coal in 2030, 2040 and 2050.

The renewables benchmarks are also generally similar to those from the 2020 report. However, the falling cost of renewables and their accelerating deployment means that the potential for rapid growth by 2030 has increased. As a result, the lower end of the renewables benchmark has increased in ambition for all countries in 2030.

Emissions intensity benchmarks show no clear trend between the 2020 and 2023 reports, with the EU, US and China having more ambitious numbers, while India and Indonesia are less ambitious. In the case of the EU and the US, this increase in ambition is likely due to the faster gas phase-out found in the 2023 benchmarking report (although the 2020 report did not explicitly consider fossil gas benchmarks, and so this cannot be confirmed entirely). In the case of India, South Africa and Indonesia, the slightly reduced ambition is due to the slight reductions in the pace of coal phase-out discussed above.

3.8 Additional benchmarks derived using this methodology

There are two additional benchmarks that were derived from the same methodology and process as the Power sector benchmarks and exist only at the global scale in the State of Climate Action report series. These are the Share of electricity in Industry's final energy demand (%) and Technological Carbon Removal (MtCO2/year).

3.8.1 Share of electricity in Industry's final energy demand (%)

The benchmark for the share of electricity in industry's final energy demand was developed using a top-down approach. We identified modelled pathways that limit global temperature rise to 1.5°C with no or limited overshoot and filtered them following the criteria from Climate Analytics (2023a) detailed in Section 3.1.1. In addition, we also added a last criteria to only retained scenarios in which the rate of decline in GHG emissions between 2020 and 2030 is steeper in developed countries than in developing regions. This resulted in a set of 24 scenarios. The 50th percentile from set formed the less ambitious bound, while the 95th percentile served as the more ambitious bound. Insufficient data, as well as limited peer-reviewed literature on bottom-up sectoral modelling of industrial decarbonisation consistent with achieving the Paris Agreement temperature goals, prevented us from integrating additional sources into this benchmarking exercise. Instead, we exclusively relied on the range from these 24 scenarios to establish 1.5°C-compatible benchmarks for industrial electrification.

Table 3: Final benchmark

Indicator	2030	2035	2040	2050
Share of electricity in the industry sector's final energy demand (%)	35-43	43-46	51-54	60-69

3.8.2 Technological Carbon Removal ($MtCO_2$/year)

The technological carbon removal indicator tracks the annual amount of CO2 removed from the atmosphere and sequestered permanently from any carbon removal technology. These technologies currently include DACCS; biomass carbon removal and storage, including BECCS and approaches that include pyrolysis or gasification of biomass; and mineralization, though development of future technologies is expected. The indicator tracks progress across a range of carbon removal technologies, indicating the expected scale of carbon removal that will need to be met by existing and not-yet-developed technologies.

The 2030, 2035, 2040, and 2050 targets for this indicator are based on the range of modelled pathways that limit global temperature rise to 1.5°C with no or limited overshoot, as presented in IPCC (2022). Following the criteria outlined in Section 3.1.1. we filtered these pathways to identify a subset that meets sustainability criteria based on Fuss et al. (2018) for biomass cultivation for carbon removal outlined in IPCC (2018), resulting in a set of 33 pathways. We used a 90th percentile range (i.e., from the 5th to the 95th percentiles) for the 2030 and 2050 levels of technological carbon removal (i.e., from bioenergy with carbon capture and storage, direct air capture, and mineralization, which are the technologies incorporated into integrated assessment models) as 2030 and 2050 targets.

We include a range for each target year to better reflect the uncertainty associated with future need for technological carbon removal, as well as its dependence on the level of mitigation across sectors. The lower end of the range reflects scenarios in which GHG emissions reductions are greater in the near term, and future carbon removal reliance is minimised.

Table 4: Final benchmark

Indicator	2030	2035	2040	2050
Technological carbon removal (MtCO2/year)	30-690	150-1700	290-3100	740-5500

4 Buildings sector

4.1 Introduction

This section details the methodology used to determine the global buildings sector benchmarks.

The benchmarks we define for buildings track progress on energy use and the associated emissions from that energy use. CAT uses three key lines of evidence to develop these sectoral benchmarks: a literature review of existing targets, global 1.5°C compatible pathways from the IPCC AR6 scenarios, and a bottom-up sectoral model. The final results are derived from merging these lines of evidence. It is imperative to radically accelerate the rate of decarbonisation in the buildings sector to meet the 2030 targets and ensure total sector alignment with global climate goals.

4.2 Key mitigation strategies

Emissions from buildings can be classified into two main categories: operational and embodied. Operational emissions are those produced from energy used in the day-to-day functioning of buildings, which includes activities such as heating, cooling, lighting, appliance use, and cooking as well as the electricity and heat used to power these activities. These emissions are driven by the carbon intensity of the energy sources used. Embodied emissions are those that are produced during the construction, retrofitting, and demolition phases throughout a building's lifetime. The indicators detailed in this report address the first category, focusing on energy used and emissions produced from the operation of buildings. Importantly, emissions related to construction are not included in these benchmarks, but they are partly covered by the Industry sector benchmarks for cement and steel (CAT, 2020).

There are several mitigation strategies for the buildings sector which are covered by the benchmarks in this report.

First, it is important to embrace sufficiency principles of reducing energy use and demand, as well as finding ways to reuse and repurpose already existing spaces (IPCC, 2022).

Second, improving the energy efficiency of buildings will play a fundamental role in reducing the intensity of energy used. This can be achieved through energy efficiency upgrades, such as replacing appliances and lighting with more efficient models and improving insulation as well as constructing new buildings to be more energy efficient to avoid the need to retrofit later.

Third, it is necessary to decarbonise the remaining energy used. This can be done by changing the equipment and transitioning to cleaner energy sources for heating and cooking, increasing electrification, and installing on-site renewable power technologies; new buildings should not be constructed with fossil fuel-based systems. Achieving this goal is closely linked to the decarbonisation of the power sector.

Implementing these strategies will involve applying them to both existing and new buildings. For existing buildings, retrofitting is essential to reducing energy demand, repurposing spaces, and improving the efficiency of energy used. New projects should construct buildings to be zero-carbon in operation and minimise embodied carbon throughout their lifecycle.

4.3 Indicator selection

Previously CAT (2020) defined benchmarks for energy intensity and carbon intensity of building operations split by residential and commercial building types. In this update, we set one benchmark for all buildings to better track progress against available data. Additionally, the previous benchmarks were based on an aggregation of targets developed for a set of countries, while the updated benchmarks in this report use global-level data. The buildings sector varies significantly between countries depending on the climate and the age of the building stock, making national benchmarks particularly valuable for understanding the change that is needed within local context. However, global benchmarks are also important for understanding the overall picture. Seeing a need for global benchmarks to track overall progress in the sector, we have adjusted our methods and utilized more recently published data to define benchmarks with global coverage.

4.3.1 Energy intensity of building operations (kWh/m²)

The energy intensity of building operations is measured by the amount of energy used (kWh) per square meter (m^2) of floor space. This indicator covers energy use from building operations, meaning space and water heating, space cooling, lighting, cooking, and appliance use.

4.3.2 Carbon intensity of building operations ($kgCO_2/m^2$)

The carbon intensity of building operations is measured by the amount of carbon emitted ($kgCO_2$) per square meter (m^2) of floor space. This indicator covers emissions produced from building operations, meaning electricity use (including space cooling, lighting, and appliance use), space and water heating, and cooking. Importantly, reducing the carbon intensity of building operations greatly relies on the carbon intensity of electricity generation, therefore a key assumption in setting this target is that we meet the power sector targets for the carbon intensity of electricity generation set by CAT (2023).

4.3.3 Retrofitting rate (%/year)

The retrofitting rate is measured by the share of the building stock that undergoes deep retrofitting every year. Deep retrofitting means upgrading the building envelope and systems to meet zero carbon standards.

4.3.4 Share of new buildings that are zero carbon in operation (%)

The share of new buildings that are zero carbon in operation is measured by the percentage of the new building stock that is built to produce no emissions, through a combination of being powered with on-site renewables and a decarbonised electricity sector. Our definition includes buildings that will be zero carbon following the decarbonisation of the power sector and is comparable to the IEA's "zero carbon ready" terminology.

4.4 Key sources of information

4.4.1 Literature

To incorporate existing knowledge on the buildings sector, we identified global targets for the buildings sector in a review of academic literature and industry sources, looking at reports, declarations, commitments, and other materials from institutions and coalitions, such as the International Energy Agency, C40, the Global Alliance for Buildings and Construction, and the World Green Building Council. In general, there are few quantitative targets in the literature; existing targets for the buildings sector focus on constructing zero carbon buildings, halving total emissions from buildings by 2030, retrofitting, and reducing embodied emissions. These targets set clear and necessary goals for the building sector, but some are not so useful for tracking progress to date due to a lack of data.

However, we do use these targets to define the above intensity indicators that can be used for tracking, to inform the assumptions of the bottom-up sectoral model introduced in Section 4.4.3, and to check the consistency of our own targets. While the benchmarks presented in this report are crucial for tracking progress toward meeting global climate goals and decarbonising the buildings sector, other existing targets are useful for achieving these benchmarks.

The IEA's Net Zero by 2050 Scenario (2021b) and Net Zero Roadmap (2023c) serves as primary references, providing historical data that supports model development and validation as well as targets that we could compare against the benchmarks that we set. The IPCC is also a key source of quantitative targets, providing pathways for buildings sector floor area development, energy demand, and direct emissions.

4.4.2 Global Integrated Assessment Models (IAMs)

To ensure alignment with the goal of keeping global temperature rise under 1.5°C, we used pathways from the IPCC AR6 Scenario Explorer and Database of IAMs (Byers *et al.*, 2022). These global pathways provide projections for floor area, energy use, and emissions, which are used to calculate energy and emissions intensity. Additionally, the floor area projections (in particular, the Mean, Min, Max) serve as crucial inputs to the stock turnover model at the core of our bottom-up sectoral model, providing a range of scenarios for floor area growth.

4.4.2.1 Scenario selection and calculations

To select the scenarios for developing the benchmarks, we filtered these pathways using the criteria established by Climate Analytics (2023a) and detailed in Section 2.1.1. This resulted in a set of 24 scenarios. In addition, we complemented this set with 9 scenarios from buildings-sector models which offer more detail and sectoral granularity. These 9 scenarios were not included in the original filtered set described in Climate Analytics (2023a) because they are not economy-wide; however, they were assessed to ensure they limit warming to 1.5°C in 2100 with no or limited overshoot. The full combined set of 33 scenarios is shown in Table 5. As not all of the scenarios with buildings variables contained floor area data, we used a set of 12 scenarios for floor area (shown in Table 6).

Table 5: Models and scenarios from the IPCC AR6 scenarios database used in the development of the benchmarks

Type	Model	Scenario
Filtered set of scenarios	COFFEE 1.1	EN_NPi2020_400
	MESSAGEix-GLOBIUM 1.0	LowEnergyDemand_1.3_IPCC
	MESSAGEix-GLOBIUM_1.1	NGFS2_Net-Zero 2050
	REMIND 2.1	LeastTotalCost_LTC_brkLR15_SSP1_P50 R2p1_SSP1-PkBudg900
	REMIND-MAgPIE 2.1-4.2	EN_NPi2020_400 NGFS2_Net-Zero 2050 CEMICS_SSP1-1p5C-fullCDR CEMICS_SSP1-1p5C-minCDR EN_NPi2020_200f EN_NPi2020_300f EN_NPi2020_400f EN_NPi2020_500 NGFS2_Divergent Net Zero Policies NGFS2_Net-Zero 2050 - IPD-95th NGFS2_Net-Zero 2050 - IPD-median SusDev_SDP-PkBudg1000 SusDev_SSP1-PkBudg900
	REMIND-MAgPIE 2.1-4.3	DeepElec_SSP2_ HighRE_Budg900
	WITCH 5.0	EN_NPi2020_400f EN_NPi2020_500 EN_NPi2020_450 EN_NPi2020_450f EN_NPi2020_500f

Buildings specific scenarios	EDGE-Buildings 2.0	Practices-low Practices-verylow
	EDGE-Buildings 3.0	SSP2_2020_0.3_All SSP2_2020_0.3_NC SSP2_2020_1.0_All SSP2_2020_1.0_NC SSP2_Ctax
	REMIND-Buildings 2.0	BEG-Budg600 BEG-Budg600-EG

Table 6: Models and scenarios from the IPCC AR6 scenarios database for which floor area data was available and used in the development of the benchmarks

Model	Scenario
MESSAGEix-GLOBIUM 1.0	LowEnergyDemand_1.3_IPCC
REMIND-MAgPIE 2.1-4.2	SSP1 SSP2 Average
EDGE-Buildings 1.0	SSP1 SSP2
EDGE-Buildings 2.0	Practices-reference Practices-low Practices-verylow
EDGE-Buildings 3.0	SSP1 SSP2
REMIND-Buildings 2.0	BEG-Budg600

Figure 4 shows the range of floor area projections from the set of scenarios. Not all of the scenarios from the filtered set and buildings sector models included floor area data, so we expanded the set for this variable to include all scenarios of C1 and C2 categorization (with an exception for EDGE Buildings 2.0, described below) from the models selected in the initial filtering process. There are several ways in which we use the available floor area data to calculate energy and emissions intensity:

- Where floor area is available for a given model/scenario, we use that floor area data for calculating energy and carbon intensity.
- For models with multiple scenarios that used the same floor area data for all types of scenarios (SSP1, SSP2), we took one sample from each unique set of floor area data. In cases where a scenario does not have floor area data but the same model/scenario type (SSP1, SSP2) does, we use the floor area from that model/scenario type. In one case

where there was not a corresponding scenario type, we used the average of the floor area projections from the same model.

- One model/scenario did not have any floor area data, so we used the Mean of all the floor area projections to calculate intensities.

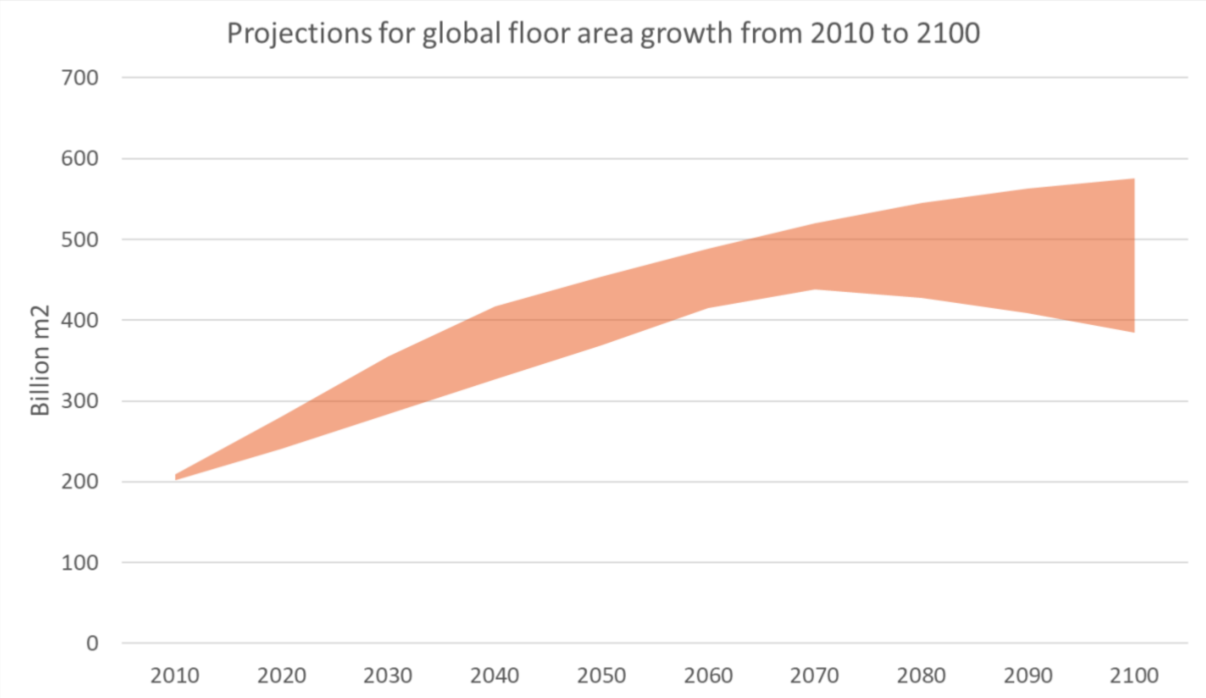

Figure 4: The range of projections for total global floor area from 2010 to 2100 from the IPCC AR6 scenarios used

4.4.2.2 Results from the IAMs

The scenarios from the EDGE Buildings 2.0 model do not have a climate assessment category, but we decided to include them after reviewing the documentation and comparing its results with other C1 category scenarios. Because these scenarios exist to demonstrate the feasibility of drastically reducing emissions, we only retain scenarios that include emissions reductions because they reflect a world with higher ambition and that are more likely to maintain the 1.5°C warming limit. We note that one scenario (from COFFEE 1.1) has strongly decreasing emissions until mid-century that then increase again toward 2100.

Figure 6 and Figure 7 show the total range, 10^{th}, 33^{rd}, 66^{th}, and 90^{th} percentiles, and the median from the final set of scenarios for emissions and energy intensities. Among the projections for total direct emissions from buildings, one set of scenarios keep emissions stable through 2050, while the other show a reduction in emissions to 2050 (Figure 5). How we use or exclude scenarios in defining the benchmarks is explained below.

The IAM scenarios provide a range of 1.5°C compatible energy and emissions intensities throughout the century. The statistics of the distribution are summarised in Table 7 and Table 8. We note from both the table and the figures above that scenarios for emissions intensity, in particular, are distributed toward the lower end of the full range.

To define the benchmarks, we therefore take the more ambitious end of the range to ensure that meeting the targets will be 1.5°C compatible without relying on additional effort from other sectors. From Figure 5, we observe that some scenarios retain significant direct emissions in the building sector throughout the century while others identify substantial or complete reduction of emissions. We therefore take the part of the range that ensures a reduction in emissions both in the near term and sustained throughout the century.

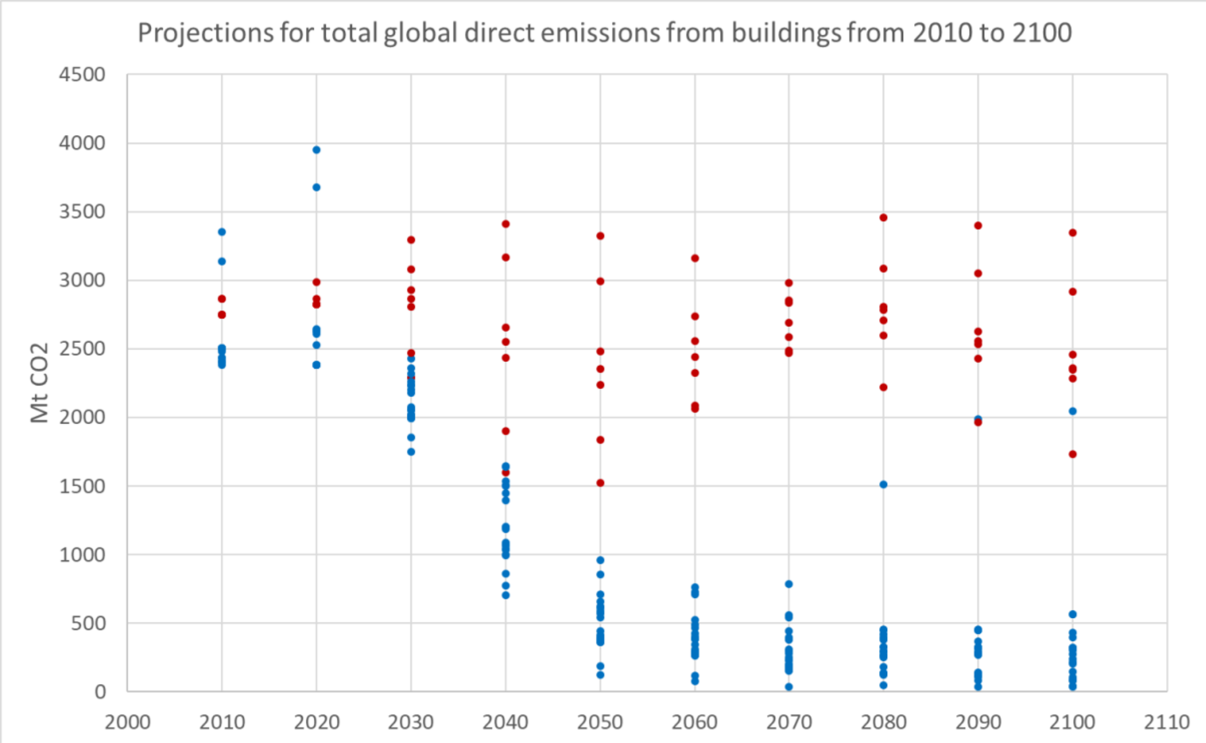

Figure 5: The range of total direct emissions projections from the IPCC AR6 scenarios used. The figure highlights two subsets of pathways. In the first set (red), emissions remain relatively stable to 2050, while in the second set (blue), emissions decrease to 2050.

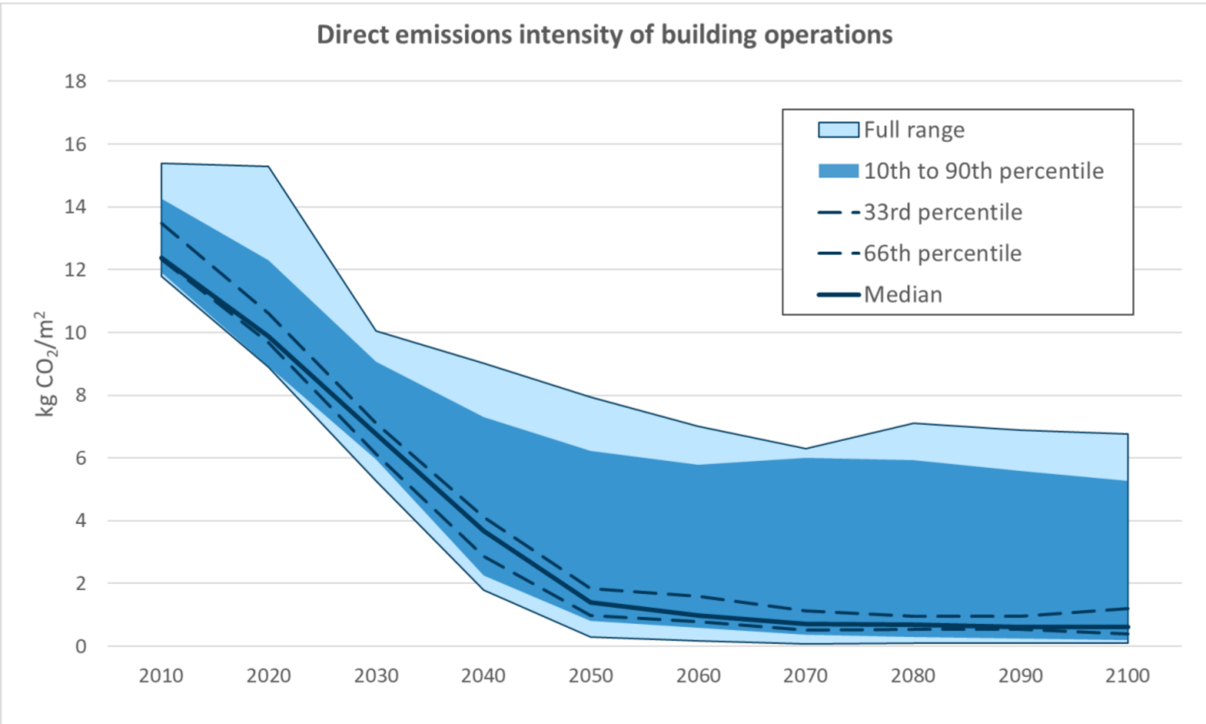

Figure 6: The range of buildings emissions intensities calculated using direct emissions and floor area projections from 1.5C compatible IPCC AR6 scenarios

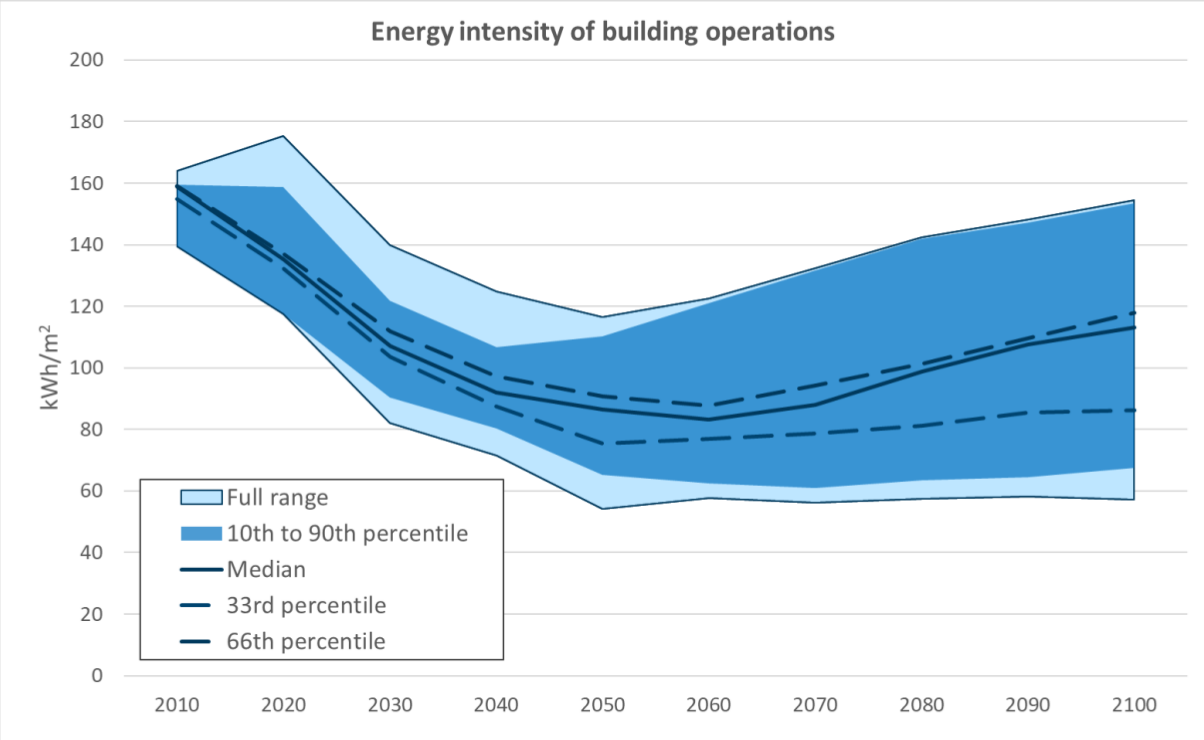

Figure 7: The range of energy intensity calculations using energy demand and floor area projections from the IPCC AR6 scenarios

Table 7: Distribution statistics of energy intensities in 1.5°C compatible IPCC AR6 scenarios

Energy intensity (kWh/m^2)	**2010**	**2020**	**2030**	**2040**	**2050**
Minimum	139	118	82	71	54
10th percentile	139	118	90	80	65
33rd percentile	155	132	103	87	75
Median	159	135	107	92	87
66th percentile	159	137	112	97	91
90th percentile	160	159	122	107	110
Maximum	164	175	140	125	116

Table 8: Distribution statistics of direct emissions intensity in 1.5C compatible IPCC AR6 scenarios

Direct emissions intensity ($kgCO_2$ /m^2)	**2010**	**2020**	**2030**	**2040**	**2050**
Minimum	12	9	5	2	0
10th percentile	12	9	6	2	1
33rd percentile	12	10	6	3	1
Median	12	10	7	4	1
66th percentile	13	11	7	4	2
90th percentile	14	12	9	7	6
maximum	15	15	10	9	8

We also recognise that minimizing energy demand will make it easier to decarbonise the remaining energy use. It's important to stress that minimising energy demand cannot be achieved through a slowing of improvements to energy access and development where it is needed, but rather through sufficiency measures, and improvements to energy efficiency in places where needs are already well met.

For both emissions and energy intensity, we therefore take the minimum and 66th percentile across scenarios to define the target range, in combination with the other lines of evidence.

The emissions intensity from the IAMs is for direct emissions only whereas our indicator also encompasses indirect emissions. We therefore combine the direct emissions with an indirect emissions target from the IEA for 2030 (9 $kgCO_2/m^2$) (IEA, 2023a). This addition of indirect emissions is not needed for 2050 benchmarks because the power sector should be fully decarbonized by that time.

4.4.3 Sectoral modelling

While the IAMs provide valuable insights into 1.5°C compatibility, they are limited in their sector-specific detail and therefore usefulness for directly deriving sectoral benchmarks. As such, we complement the IAMs with a bottom-up analysis to understand what drives emissions in the sector and explore the impact of different mitigation strategies. This approach offers a more granular and sector-specific perspective that can complement the top-down perspective of the IAMs.

4.4.3.1 Description of the model

We developed an Excel-based tool that uses a stock-turnover model and component analysis to provide a bottom-up perspective on buildings decarbonisation. To do this, we break down GHG emissions from energy use in buildings and categorize them by component, calculating the energy demand and emissions for each component. The components we consider are heating (space and water), cooling, lighting, cooking, and appliance use. We used literature to set reasonable and ambitious use/m^2 or use/capita intensities and investigated the impact of each of these components on overall energy use and emissions from buildings. We combine this information with the data from the stock-turnover model to derive energy use and associated emissions targets for each component for 2030, 2035, and 2050.

4.4.3.2 Modelling principles

At the core of the tool is a stock turnover model that uses the floor area projections from the IPCC AR6 scenarios (described in Section 4.4.2), with alternative data options from the IEA. In our calculations, we apply selected demolition and retrofit rates to the total floor area to account for the demolition of old building stock, deep retrofits of the existing stock, and the transition of new buildings from standard designs (meaning those built to a better standard than existing buildings, but not yet zero carbon) to zero carbon.

The tool is built using global level data. The energy use and emissions components of buildings are separated and calculated at the component level, factoring in floor area or population (depending on whether the intensity is per m^2 or per capita) and the emissions factors of the energy sources. The resulting absolute and intensity values are then used to form an overall picture of buildings energy use and emissions.

4.4.3.3 Input needs and assumptions

To calculate energy use, we determine parameters for use/m^2 or use/capita for each component and building type (existing, new standard, new zero carbon, and retrofit buildings) and apply these to the corresponding floor area outputs for each building type. To calculate emissions for energy-consuming components that use electricity, we apply the carbon intensity of electricity generation targets from the power sector (CAT, 2023) as the emissions factor; for energy-consuming components that are not fully electrified, we derive an emissions factor from other sources.

Floor area is expected to grow with global population and economic development, including increased access to housing. The stock-turnover model assumes that improvements will be made to building envelopes to increase efficiency through retrofitting and the construction of new buildings that are zero carbon in operation.

Heating and cooling are major drivers of energy use and emissions in buildings, with heating being the largest energy end-use in buildings. Energy demand from space heating can be reduced by upgrading equipment and optimizing efficiency through improvements to the building envelope. Emissions can be curtailed through equipment upgrades, electrification, and the integration of on-site renewables. Energy use for heating is calculated using the floor area output from the stock-turnover model, the share of floor area that requires heating, and the energy intensity of heating parameter that we set. Emissions factors for heating, which depend on the fuel and technology mix, are applied to calculate the total emissions from this component. We assume that fossil fuel-based heating infrastructure will be phased out and replaced with alternatives such as heat pumps, solar thermal heating, and district heating.

Cooling is a rapidly growing energy end-use demand in buildings. To mitigate this demand, it is crucial to improve the efficiency of cooling equipment and optimize the building envelope to increase efficiency. Emissions reduction strategies include decarbonizing the electricity supply in the power sector and installing on-site renewables. Energy use for cooling is calculated using the floor area output from the stock-turnover model, the share of floor area cooled, and the energy intensity of cooling parameter that we set. The carbon intensity of electricity generation (CAT, 2023) is used to calculate emissions.

For water heating, we make the same assumptions as in (CAT, 2020), namely that water heating demand reaches 700 kWh/capita in 2040. This target means an evening-out of demand across contexts, whereby some countries with high demand per capita reduce demand and increase efficiency, while demand in other areas can increase while also improving efficiency. Strategies to reduce energy demand from water heating include behaviour change, while emissions can be lowered through electrification and the decarbonisation of electricity generation in the power sector. The installation of on-site renewables is also key in this context.

For lighting and appliance use, energy demand reductions can be achieved by upgrading lighting to LED technology and improving the efficiency of appliances. Emission mitigation strategies include electrification and decarbonisation of electricity production in the power sector, as well as installing on-site renewables.

For cooking, we consider population shares using different types of cookstoves and their respective emissions intensities. Emissions can be lowered by transitioning from traditional biomass and gas to modern biomass and electricity. While gas is often used as a bridge fuel, there is a pressing need to shift toward renewable-powered cooking.

4.4.3.4 Model parameterisation

The historical energy use and emissions data is taken from the IEA and complemented with information from Ürge-Vorsatz et al. (2015), Levesque et al. (2019), and Grubler (2018).

The parameters for the stock turnover model are the demolition rate, pre-2023 retrofit rate, and post-2023 retrofit rate, which are applied to the floor area projections data. An example output is shown in Figure 8. The minimum, maximum, and mean floor area projections from the IPCC AR6 scenarios can be selected, as well as projections from the IEA (2022c). From 2010 to 2020, we assume that new floor area is constructed to a standard level, based on the knowledge that only 5% of new buildings were zero carbon ready in 2020 (IEA, 2021b). From 2020 to 2030, we assume that the floor area of standard new buildings decreases, while that of zero carbon new buildings increases. After 2030, we assume that 100% of new buildings are zero carbon from 2030. A low retrofit rate is assumed until 2022, based on the fact that the retrofitting rate was below 1% in 2019 (IEA, 2020). After 2023, we assume a pickup in the retrofitting rate.

In terms of the components, we set space heating and cooling energy intensities for the different floor area types, and an energy intensity per capita for water heating. Literature, targets like the Passive House standard (15 kWh/m^2) (Passive House Institute, 2015) and current energy intensities all inform these parameter decisions.

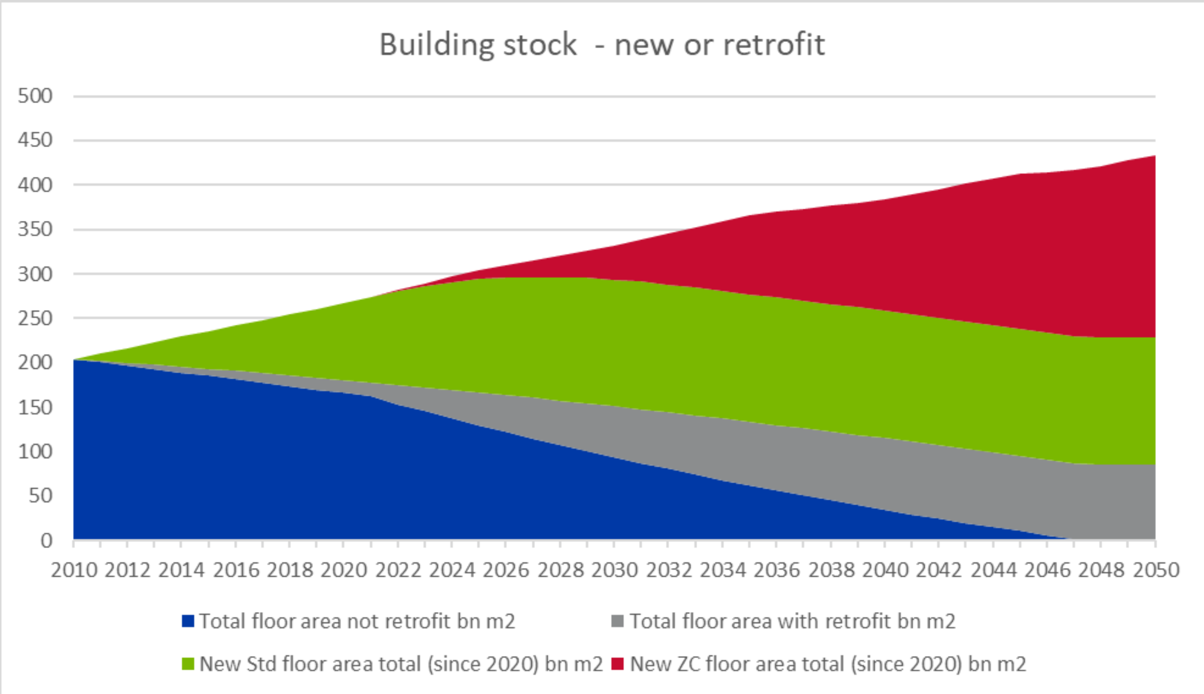

Figure 8: An example output from the stock-turnover model using the IPCC mean floor area projections, a demolition rate of 1%/ year, pre-2023 annual retrofit rate of 0.8%, and annual retrofit rate of 3%.

4.4.3.5 Results from the bottom-up modelling

Figure 9 shows an example output from the buildings sector model. The scenarios constructed in this model give a range of energy use and emissions, and their related intensities per floor area to 2050. As electrification of buildings energy end-uses increases, emissions from buildings will decrease along with the decarbonisation of the power sector. As such, remaining emissions from buildings are driven by the carbon intensity of space and water heating, meaning that the rate of phase out of fossil fuel systems for heating will greatly impact emissions and emissions intensity. The impact of different parameters can be seen starkly in the emissions results, but for energy the changes are more incremental at the component level.

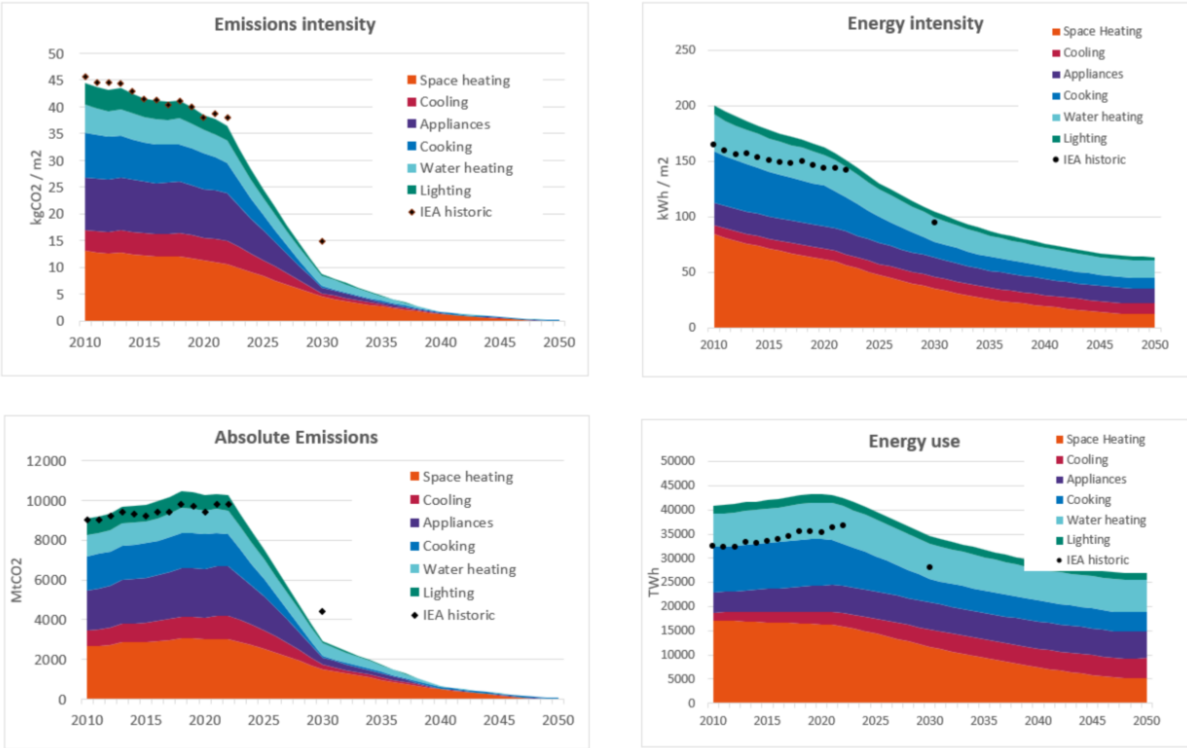

Figure 9: An example output from the buildings sector model showing energy and emissions from each element of energy use. Total energy and emissions from the IEA are shown for comparison (IEA, 2023c)

The emissions and emissions intensity results from the sectoral modelling are generally lower than those from the IEA, while energy and energy intensity are higher. This is mainly due to the carbon intensity of electricity generation variable, for which we use the targets set in CAT (2023). These targets are more ambitious than the IEA's data for the carbon intensity of electricity generation, which translates to more rapid decarbonisation in buildings and more ambitious targets for 2030. The results from a selection of scenarios are presented in

Table 9 for energy and Table 10 for emissions.

The three scenarios were chosen to demonstrate possible pathways reaching or falling short of what is needed. The first combines low energy use (meaning low parameter settings for the intensity of heating and cooling) with a high retrofitting rate (3.5%). This scenario represents a pathway that meets the targets for energy use and retrofitting that are necessary for sector decarbonisation. The second scenario does the opposite of the first, combining high energy use (meaning high parameter settings for the intensity of heating and cooling) with a low retrofitting rate (2%). This scenario represents a pathway that does not meet the targets for energy use and retrofitting. The third scenario combines a high energy use for heating (meaning high parameter settings for the intensity of heating) with a low stock turnover (meaning low demolition and retrofit rates). This scenario represents a locking-in and slow phase-out of high energy-intensive and emissions-intensive heating sources. These scenarios show that a high retrofit rate is crucial for reaching our targets.

Table 9: Energy use and energy intensity results from 3 scenarios generated with the sectoral model

Scenario	Variable	2030	2050
Low energy use combined with a high retrofit rate (reaching target)	Energy use (TWh)	35000	27000
	Energy intensity (kWh/m2)	100	64
High energy use combined with a low retrofit rate (not reaching target)	Energy use (TWh)	39000	33000
	Energy intensity (kWh/m2)	120	78
High energy use for heating combined with a low stock turnover (not reaching target)	Energy use (TWh)	42000	37000
	Energy intensity (kWh/m2)	130	87

Table 10: Emissions and emissions intensity results from 3 scenarios generated with the sectoral model

Scenario	Variable	2030	2050
Low energy use combined with a high retrofit rate (reaching target)	Emissions (MtCO2)	2900	70
	Emissions intensity (kgCO2/m2)	9	0
High energy use combined with a low retrofit rate (not reaching target)	Emissions (MtCO2)	3300	130
	Emissions intensity (kgCO2/m2)	10	0
High energy for heating combined with a low stock turnover (not reaching target)	Emissions (MtCO2)	3600	600
	Emissions intensity (kgCO2/m2)	11	1

4.5 Results

4.5.1 Combining the lines of evidence

The final benchmarks for energy intensity and carbon intensity of building operations were determined by combining the inputs from literature, the IAMs, and the bottom-up sectoral analysis model.

There is no single pathway to 1.5°C because there are trade-offs between and within sectors in terms of technology options and choices around energy consumption. Uncertainties in the rate of development of technologies and their costs also lead to variations across pathways from different models and analyses. However, some aspects of a 1.5°C pathway are very clear in the buildings sector; the key technologies are well-known and already available, new buildings should not rely on fossil fuels for heating, and substantial retrofitting of existing stock will be necessary to improve energy efficiency. As electrification of water and space heating will play a large role in eliminating direct fossil fuel emissions in buildings, decarbonisation of the power sector is also essential. As with all sectors, these changes are needed urgently and must evolve rapidly.

However, there remains some uncertainty and flexibility in the exact pathway, particularly as it pertains to our indicators. The energy intensity indicator covers a wide range of energy uses, from space heating to appliance use. While it's clear that a shift to more energy efficient technologies is necessary, the various sources we've identified reveal a range in estimates of what is feasible or likely. Some of these uncertainties depend on behaviour, others on scenarios of population growth and per capita floor area demand.

In defining benchmarks for the buildings sector, we take into account these different possible scenarios by defining the benchmarks as a range that encompass a set of scenarios with slightly different underlying assumptions but that are all compatible with 1.5°C.

It's worth noting that one recommendation to reduce total energy consumption, and thereby emissions, is to minimize the amount of floor area used per person. This approach to sufficiency means that total space heating or cooling requirements are lowered. However, as our indicator encompasses additional energy uses that are likely to scale with population rather than floor area (such as appliance use), a lower floor area actually leads to a higher intensity/m^2 for these activities. Our selected indicators provide a useful overview of total progress but additional information on specific activities would provide a more nuanced picture and is a potential area of future research.

The IAM scenarios described above provide bounds for energy intensity directly, but only provide emissions intensity for direct emissions (i.e., excluding emissions from electricity generation). To use the carbon intensity information from these IAMs, we therefore combined the direct emissions intensity from the IAM scenarios with the indirect emissions intensity from the IEA for 2030. For 2050, the power sector should be fully decarbonised and therefore not contribute to the overall buildings emissions intensity.

The final benchmarks for the buildings intensity indicators are outlined in Table 11 below. The ranges are primarily taken from the IPCC AR6 IAM scenario ranges (minimum to 66th percentile), with additional supporting information provided by the IEA Net Zero by 2050 scenario (IEA, 2021b, 2023c) and the sectoral bottom-up modelling. Both the IEA scenario and the bottom-up modelling fall within the range of the IPCC scenarios for energy intensity. Table 12 and Table 14 show a comparison of the final benchmarks with the results from the different methods.

For emissions, the bottom-up model uses carbon intensity of electricity based on the CAT benchmarks. The CAT benchmarks have a lower power sector emissions intensity by 2030 than in the IEA Net Zero by 2050, so emissions intensity in the bottom-up modelling results are accordingly lower. Therefore, we use the IAMs and the IEA targets to set the upper end of the range and extend the lower bound based on the bottom-up model; however, we do not extend it as low as the most ambitious bottom-up results. There are several uncertainties in the bottom-up modelling and, importantly, it doesn't account for any economic or institutional feasibility that may slow progress as compared to an idealised model. The final targets therefore are broadened to a more ambitious range but are not based on a technical transition alone.

We additionally checked the energy and emissions intensity targets for consistency with the CAT (2020) targets and that the % reduction from historical values is consistent across scenarios, given the difference in historical estimates across information sources.

The retrofitting rate is derived from the sectoral modelling exercise and IEA analysis (2021b, 2023c). With the sectoral modelling we see that a retrofit rate of 2.5% is only sufficient under certain circumstances and that depending on demolition rates and the status of stock built in the next few years, retrofit rates may need to be as high as 3.5% to ensure that the building stock is fully retrofitted in time to decarbonise the sector by 2050.

Finally, there is consensus across the literature that all new buildings should be designed and constructed so that they will be zero carbon in operation, at the latest when the power grid is fully decarbonised. Different sources have set different target years by when this should be achieved with the CAT calling for reaching this target already by 2020 (CAT, 2020) and the IEA (2021b, 2023c) setting a 2030 target (see Table 12 for a comparison of the 2030 targets with the IEA's). The earlier this goal is achieved, the less need for retrofits and technology exchanges will be needed in the future. We therefore set the target for all new buildings being zero carbon for as soon as possible, but latest by 2030.

Table 11: Final benchmarks

Indicator	2030	2035	2050
Energy intensity of building operations (kWh/m^2)	85-115	Forthcoming	55-80
Carbon intensity of building operations (kgCO_2/m^2)	13-16	Forthcoming	0-2
Retrofitting rate (%/year)	2.5-3.5	2.5-3.5	3.5 (2040)[1]
Share of new buildings that are zero carbon in operation (%)	100	100	100

1. All buildings should already have been retrofit to the highest standards by 2050; retrofitting rates must remain high until all the building stock is energy efficient and fossil free.

Table 12: Comparison of final benchmarks for 2030 with IEA net zero scenario (IEA, 2023c) *and the results from the IAMs and bottom-up modelling*

Indicator	**This report** (CAT 2023)	**IEA** (2023)	**IAMs** (0-66th percentile range)	**Bottom-up scenarios**
Energy intensity of building operations (kWh/m^2)	85-115	94	82-112	100-130
Carbon intensity of building operations (kgCO_2/m^2)	13-16	15	14-16	9-11
Retrofitting rate (%/year)	2.5-3.5	2.5	N/A	1-3.5
Share of new buildings that are zero carbon in operation (%)	100	100	N/A	100

Table 13: Comparison of final benchmarks for 2035 with the results from the IAMs and bottom-up modelling

Indicator	**This report** (CAT 2023)	**IEA** (2023)	**IAMs** (0-66th percentile range)	**Bottom-up scenarios**
Energy intensity of building operations (kWh/m^2)	Forthcoming	N/A	Forthcoming	Forthcoming
Carbon intensity of building operations (kgCO_2/m^2)	Forthcoming	N/A	Forthcoming	Forthcoming
Retrofitting rate (%/year)	2.5-3.5	2.5	N/A	1-3.5
Share of new buildings that are zero carbon in operation (%)	100	100	N/A	100

Table 14: Comparison of final benchmarks for 2050 with the results from the IAMs and bottom-up modelling

Indicator	**This report** (CAT 2023)	**IEA** (2023)	**IAMs** (0-66th percentile range)	**Bottom-up scenarios**
Energy intensity of building operations (kWh/m^2)	55-80	N/A	54-91	64-87
Carbon intensity of building operations (kgCO_2/m^2)	0-2	N/A	0-2	0-1
Retrofitting rate (%/year)	3.5	2.5	N/A	1-3.5
Share of new buildings that are zero carbon in operation (%)	100	100	N/A	100

These benchmarks signal the scale and pace of change needed to achieve the full decarbonisation of buildings by 2050, while leaving some room for residual emissions in 2050, primarily for cooking and heating. It is technically feasible to fully decarbonise heating and cooking by 2050 but some specific cases, such as back-up fossil generation for healthcare services and heating in rural areas, or clean cooking with biomass may form part of a net zero world.

The buildings sector is incredibly diverse, and global benchmarks cannot be easily applied in the same way across countries. Advanced economies with more existing building stock and higher energy use and emissions should aim for the more ambitious end of the range.

There are limitations in the method described in this report. First, we incorporated data from the IEA and other sources where it existed, but the availability of data for buildings at the global level is thin. Second, the bottom-up model is a simplification of the buildings system, and it does not account for geographical, climate, and building stock differences at a national or regional level. Additionally, the distribution of floor area among building stock types and the emissions intensity of different components are estimations. As such, the chosen input assumptions for the global level inevitably have an impact on the results. Finally, and importantly, our analysis does not cover construction or embodied emissions, mainly due to a lack of related data at the global level. However, incorporating embodied emissions through materials or building stock changes is a potential avenue for future research.

5 Light-duty road transport

5.1 Introduction

The Decarbonising light-duty road transport report analyses benchmarks for four different indicators at global and national level:

- Share of light-duty EVs in total vehicle sales
- Share of light-duty EVs in total vehicle stock
- Emission reductions from light-duty vehicles
- Share of zero emission fuels in domestic transport (excluding international aviation and shipping)

The first two indicators are produced from two different models; the hybrid FLEX model and the bottom-up EV model, which represent the different ranges. The emission reductions benchmarks could only be produced by the hybrid FLEX model. The share of zero emission fuels are direct outputs taken from the Integrated Assessment Models.

5.2 Bottom-up approach: EV Model

The upper range of our EV sales share and EV stock share benchmarks were taken from the EV Model (see New Climate Institute (2018) for more details). The EV model is a bottom up model which uses the PROSPECT scenario evaluation tool to forward project the emissions reduction trajectories and derived the resulting share of EVs as explained in Climate Action Tracker (2020).

The use of this approach also stems from the Climate Action Tracker's Scaling Up Climate Action series (see from more details on methodology). In brief, the PROSPECTS model also assumes that EV rollout will occur along an S-curve (in a manner similar to the FLEX model). The scenario produced by PROSPECTS assumes that EV sales must reach 100% by 2035, in order for the fleet as a whole to reach 100% EVs by 2050 (assuming a fifteen year lifetime for cars). The PROSPECTS model then fits an S-curve to historical data on EV sales which reaches 100% by 2035.

5.3 Hybrid approach: FLEX model

The lower range of our EV sales share and EV stock share, as well as the emission reductions benchmarks were derived from the hybrid FLEX model in Microsoft Excel as described in Climate Action Tracker (2020).

The FLEX model is considered hybrid because it combines two perspectives; a bottom-up vehicle stock turnover model coupled with constraints from the top-down IAM emission pathways.

This model was used to calculate the share of EV sales and EV stocks through variable[1] optimisation to fit calculated emissions to 1.5°C compatible top down emission, energy consumption and passenger kilometre (pkm) pathways. Two 1.5°C aligned pathways were selected from the IPCC Integrated Assessment Models (IAMs) provided at regional level. This data is downscaled to national level using the SIAMESE model. For more details, see Climate Analytics (2023b) and Sferra et al. (2019).

[1] Optimised parameters: (1) annual EV sales growth rate, (2) annual ICE vehicle retirement rate (2030, 2040, 2050), (3) annual rate of change in distance travelled (2030, 2040, 2050), (4) fleet growth rate (2030, 204, 2050). In the case of some developing countries, the annual rate of decrease in ICE vehicle carbon intensity and energy intensity is also optimised for 2030, 2040 and 2050 checkpoints, otherwise constant rate of improvement is assumed.

As part of the hybrid FLEX model, we develop a bottom up stock-turnover model which brings together historical data on total vehicles sales, EV sales and EV fleet with assumption literature reviewed input data on stock dynamics, as shown in Figure A1. The model utilises historical data on EV sales, EV fleet and total fleet of each country from 2010 to 2022, taken from national sources and the IEA's EV Data Explorer (IEA, 2022d). The model combines with assumptions on the driving level, retirement rate, fuel efficiency, fleet growth and grid carbon intensity to give the total energy demand, emissions and passenger kilometres through to 2050. Assumptions on these variables are optimised and adjusted to fit to top-down constraints for energy demand, emissions and passenger kilometres from the selected IAM pathways. For more details see Climate Action Tracker (2020). We use the model developed in 2020 and refined to make adjustable variables decade specific to allow for more dynamic future scenarios. We also add fleet growth rate and annual ICE vehicle retirement rate as adjustable variables, to reflect plausible policy changes, while keeping load factor constant. Additionally, grid carbon intensity was inserted directly into the bottom-up model from the Climate Action Tracker benchmarks (Climate Action Tracker, 2023) for the calculation of the well to wheel emission from EVs.

From a bottom up perspective, we consider several driving forces that influence the uptake of EVs in the market and fleet; annual EV growth rate, annual ICE retirement rate, and the rate of change in annual distance travelled by a vehicle are the primary drivers. Other drivers include the trend in total LDV fleet growth rate and in general assume a constant rate of decrease in the carbon and energy intensity of the remaining fleet.

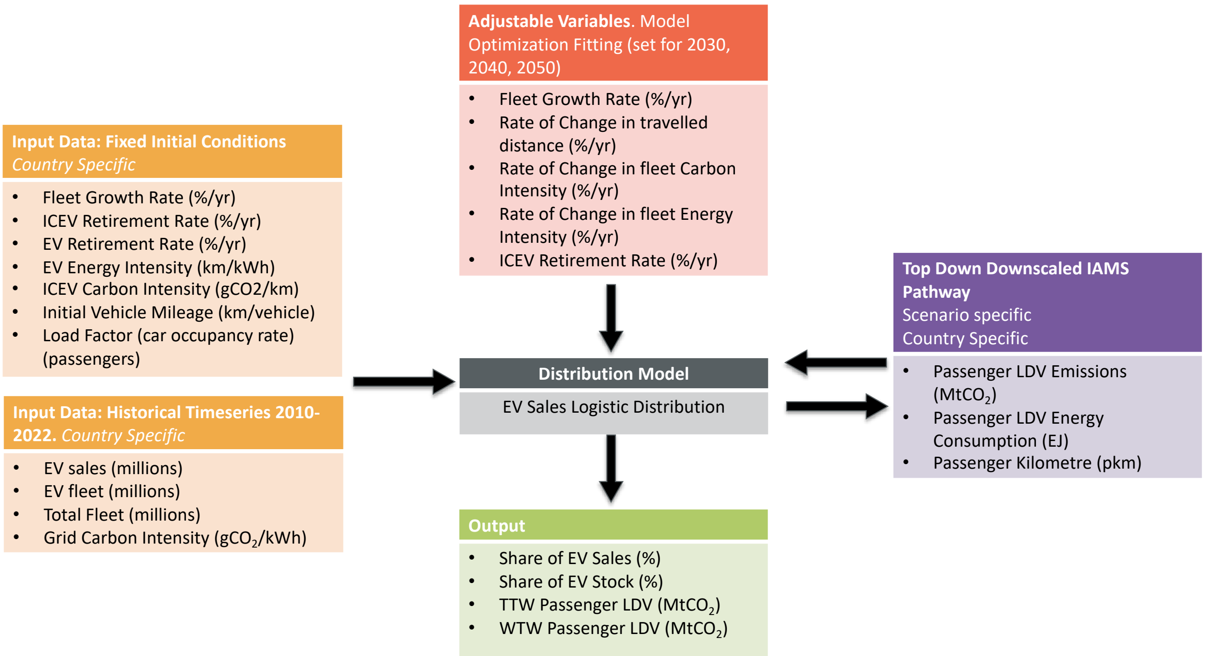

Figure 100: Illustrative depiction of hybrid top down and bottom up model process in FLEX model

In our bottom up scenarios, we envisage nationals total fleets to grow faster in next decade before slowing down after 2040, following a similar trajectory to GDP per capita trends (OECD, 2021).

The FLEX model, operated in Microsoft Excel, requires input of historical EV sales and EV stock data from 2010 to 2022 taken from the IEA's EV Data Explorer (IEA, 2022d), for each country and the world. The FLEX model's S-curve calculations into the future use these historical data as the starting point

The FLEX model then takes as constraints limits on LDV emissions, LDV energy demand and total passenger kilometres. These are provided by downscaling 1.5°C compatible pathways from global integrated assessment models. Here two pathways were taken. The Sustainable Development pathway (SDP) (Soergel et al., 2021) and Minimal CDR – SSP1 pathway (Strefler et al., 2021) produced by the REMIND modelling framework (Baumstark et al., 2021) were selected following a filtering procedure to ensure1.5°C compatibility, as described by the 1.5°C National Pathway Explorer (Climate Analytics, 2023b). These pathways met the required data specifications required to fit the bottom up FLEX model, which other pathways did not. The final benchmark output from these pathways were taken as an average of the two pathway results. These pathways do not explicitly include equity considerations, but instead present a globally cost-effective pathway to limiting warming to 1.5°C.

It is important to acknowledge that to fully account emission reductions the full life cycle of a vehicles emissions need to be accounted for, this includes the material needs for electric vehicle production and the well-to-wheel fuel needs (Hou et al., 2021). While our analysis only calculates benchmarks to fit the tailpipe tank-to-wheel emissions, any emissions to do with energy usage and materials are accounted for, indirectly, elsewhere in the REMIND 2.1 model (Baumstark et al., 2021). The well-to-wheel emissions from electric vehicles are also 1.5°C compatible if the power sector is decarbonised in line with the CAT 1.5°C aligned power sector benchmarks (Climate Action Tracker, 2023a).

Recent national level literature exclusively developing 1.5°C compatible or Paris Agreement-aligned benchmarks for EV sales and stock in the selected countries is relatively narrow. Many current benchmarking exercises do not explicitly set 1.5°C compatibility as a key parameter, rather focusing on pathways that are still ambitious, but which lack a clear link to the Paris Agreement's 1.5°C temperature goal. As a result, we do not integrate national studies into the benchmark production at this stage. If national studies emerge which have clear consistency with the Paris Agreement, future work could consider incorporating them into benchmark production.

5.4 Top-down perspective: Zero and low emission fuels

For three other indicators bottom up modelling was required to translate the emissions pathways from the IAMs to tangible outputs for EV sales and stocks values. However, the IAMs provided the share of zero and low emission fuels directly at global and regional level. We use a subset of the pathways from several models (shown in Table 15) that have been filtered for 1.5°C compatibility – for details on the filtering process see Section 3.2. From the resulting 24 IAM pathways, the shares of electricity, hydrogen and biofuels allocated at regional level, which include; global, China, USA, India, EU, Latin America, Sub-Saharan Africa and Other Asia. The latter three regions represent Brazil, South Africa and Indonesia, respectively. Given downscaled data was not available for these three countries, it is assumed that the share of zero and low emission fuels at regional level is the same at country level.

We take the 50th percentile (median) and the 95th percentile of all 24 pathways to represent the lower and upper range of our 1.5°C compatible benchmarks, to capsulate the upper levels of ambition needed to deliver the fuel transition globally and nationally.

Table 15: The 24 IAM pathways filtered for 1.5°C compatibility.

Model	Filtered 1.5°C compatible pathways
REMIND-MAgPIE 2.1-4.3	DeepElec_SSP2_ HighRE_Budg900
REMIND-MAgPIE 2.1-4.2	SusDev_SDP-PkBudg1000
	CEMICS_SSP1-1p5C-fullCDR
	R2p1_SSP1-PkBudg900
	NGFS2_Divergent Net Zero Policies
	SusDev_SSP1-PkBudg900
	NGFS2_Net-Zero 2050
	CEMICS_SSP1-1p5C-minCDR
	NGFS2_Net-Zero 2050 - IPD-median
	NGFS2_Net-Zero 2050 - IPD-95th
	LeastTotalCost_LTC_brkLR15_SSP1_P50
	EN_NPi2020_400
	EN_NPi2020_400f
	EN_NPi2020_300f
	EN_NPi2020_200f
	EN_NPi2020_500
WITCH 5.0	EN_NPi2020_400f
	EN_NPi2020_450f
	EN_NPi2020_500f
	EN_NPi2020_500
	EN_NPi2020_450
MESSAGEix-GLOBIOM_1.1	NGFS2_Net-Zero 2050
	EN_NPi2020_600_DR2p
	EN_NPi2020_600_DR4p

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The Consortium

The Climate Action Tracker (CAT) is an independent scientific analysis produced by three research organisations tracking climate action since 2009. We track progress towards the globally agreed aim of holding warming well below 2°C, and pursuing efforts to limit warming to 1.5°C.

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Climate Analytics is a non-profit institute leading research on climate science and policy in relation to the 1.5°C limit in the Paris Agreement. It has offices in Germany, the United States, Togo, Australia, Nepal and Trinidad and Tobago.

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