

# Methods Report Elaborating the decarbonisation roadmap

# Climate Action Tracker Paris Agreement Compatible Sectoral Benchmarks August 2020





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While national emissions trends are a useful tool for measuring government progress towards meeting the Paris Agreement 1.5°C temperature limit at a global level, each government will have to



We have also drilled down to present the benchmarks in these sectors for seven individual countries: Brazil, China, EU, India, Indonesia, South Africa, and the US, taking into account the current technical and infrastructure circumstances in each country. We have developed the benchmarks for both 2030 and 2050, with additional temporal resolution depending on the approach and indicator.

The data from this work has been added to the Climate Action Tracker interactive data portal https://climateactiontracker.org/data-portal, in addition to the visuals in the Summary Report.

We have identified the following key lessons:

- Decarbonisation by 2050: the Paris Agreement requires the world to decarbonise by 2050: on average, all sectors need to decarbonise in this timeframe, albeit at slightly different rates. In this report, we have identified the potential for such rapid decarbonisation across all sectors.
- Differences shrink: in terms of timing, benchmarks differ between countries and sectors, because they all start from a different base. But ultimately, governments must pursue all options in all sectors, and sometimes this will require support between countries
- Benchmarks useful to assess progress: policymakers can use the benchmarks to assess the adequacy of interventions with respect to the Paris Agreement. Our benchmarks provide a guide as to the scale of change that needs to happen, and where and when, leaving governments the freedom to meet them through different decarbonisation strategies.
- Progress by 2030 is important: decarbonisation by 2050 alone is not sufficient; to keep carbon budgets within reach, progress must ramp up well before 2030.
- Power sector is relatively advanced: the power sector is already making quite some progress in decarbonising, and it should continue to be a government priority, especially in avoiding new infrastructure incompatible with the Paris Agreement, such as coal-fired power plants.
- Industry, transport, buildings need to advance significantly: these sectors are not yet moving as quickly as is necessary, and efforts to meet 2030 benchmarks must significantly ramp up.

# Contents

Ex	Executive summary1							
Сс	ontents		2					
1	Introduction							
2	Ger	neral Methods for Defining Paris Agreement-compatible Benchmarks	3					
	2.1	Global Integrated Assessment Models	3					
	2.2	Sectoral modelling	5					
	2.3	Literature review and national/regional studies	5					
3	Pov	ver						
	3.1	Key mitigation options in the power sector	8					
	3.2	Sector-specific methods to define Paris Agreement-compatible benchmarks	8					
4 Transport								
	4.1	Key mitigation options in the transport sector						
	4.2	Deriving benchmarks						
5	Ind	ustry	32					
	5.1	Cement						
	5.2	Iron and steel						
	5.3	Electrification of Industry	51					
6	Buil	ldings	54					
	6.1	General approach and scope	54					
	6.2	Analysis	54					
	6.3	Benchmarks						
	6.4	Key lessons and priorities for the buildings sector						
Aı	uthors.		67					
Bi	bliogra	phy	68					

# 1 Introduction

In this document, we present the analysis and results for benchmark definition across four major sectors: **Power, Transport, Industry, and Buildings**. Within each sector, benchmarks for several separate but complementary indicators are defined. Please also see our Summary Report that shows similar information in a more condensed form.

The benchmarks are defined at the **global level** and for seven individual countries: **Brazil, China, EU, India, Indonesia, South Africa, and the US**. National level benchmarks take account for current technical and infrastructure circumstances in each country. Benchmarks are developed for **2030 and 2050** in all cases, with additional temporal resolution depending on the approach and indicator.

Because all sectors need to decarbonise by 2050, the 2050 benchmarks for 2050 are similar across all countries whereas the 2030 benchmarks provide an interim step on the pathway towards 2050.

# 2 General Methods for Defining Paris Agreement-compatible Benchmarks

The methods used in this study to define the Paris Agreement-compatible benchmarks include three main strands: extraction of results from global integrated assessment models, own analysis using bottom-up models, and information from existing literature. Here we explain the broad methods under each of these three strands and further explain the sector-specific details in each of the sector chapters below.

# 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 21<sup>st</sup> 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").

Among these scenarios, only 19 simultaneously honour the sustainability criteria of the IPCC (IPCC, 2018) related to the two main carbon dioxide removal (CDR) options: namely biomass with carbon capture and storage (BECCS), as well as reforestation and afforestation. The primary goal of the top down approach is to encapsulate the global perspective embodied in IAMs and their associated enforced global CO2 limitations, and to delineate the regionally modelled pathways to country-specific pathways for the chosen countries under investigation.

Contingent on data availability, we implement a two-stage approach to complete our analysis for national benchmarks that are compatible to the Paris Agreement:

- 1. Assess existing scenarios for a country from independent source towards the compatibility to a 1.5°C
- 2. Downscale a global IAM based 1.5°C compatible scenarios to the country level (SIAMESE (Sferra et al., 2018a)) harmonising results with country-specific historical data

The IAM pathways used here limit warming to below 1.5°C in 2100 with "limited overshoot". Because IAMs are based on the underlying concept of least-cost pathways for regions on a global scale, the provided top-down benchmarks reflect the technological and economical perspective of possible system changes. However, downscaled pathways do not cover equitable distribution of investment, cost and mitigation burden. Instead, these pathways reflect a 'maximum plausible ambition' transition which may require international financing to achieve.

## **Downscaling IAM results**

SIAMESE (Simplified Integrated Assessment Model with Energy System Emulator) is a reduced complexity IAM that provides cost-optimal emissions pathways at the country or state level, taking into account the complex interactions between economic growth, energy consumption (Sferra et al., 2018b). While downscaling the energy-sector results from a given model (e.g. the IEA/ETP 2017), SIAMESE takes into account a coherent set of assumptions in line with a "middle of the road" socio-economic storyline, e.g. (Dellink, Chateau, Lanzi, & Magné, 2017; Fricko, Havlik, Rogelj, Klimont, & Gusti, 2017). This storyline relies on a continuation of historical trends regarding technological developments and GDP growth at the country (or state) level. At the same time, SIAMESE has a cost optimisation perspective when allocating how much a country or a region would need to contribute to global emissions reductions in line with the Paris Agreement long term goal.

Using IAM benchmarks at the country level faces the challenge of splitting regional results (reported as R5ASIA, R5OECD+EU, R5MAF, R5LAM and R5REF in the IPCC 1.5 data base) to the national level. SIAMESE incorporates various sources of national data for this task. It uses the reported national projections of the individual scenarios for the population and GDP development in the projected time frame and the current energy use, in the base year of the analysis. The current available IAM pathways use 2010 as a base year, SIAMESE is using more recent data from 2015 and therefore incorporates the national developments of countries not in the original IAM model pathway.

The SIAMESE approach can be applied to the overall economy (e.g. scaling down the overall primary energy consumption and emissions), or adapted to individual sectors (e.g. transport, power and others). SIAMESE takes as input the original IAM pathways (e.g. of the OECD region, which start in 2010 in this scenario) and the observed energy consumption and emissions data of the specific country. Based on the SIAMESE simulation, we calculate the Paris Agreement-compatible energy projection for the specific county. Limitations of the downscaling are embedded in the driving scenario, which in this case is weak in several areas including decarbonisation in industry, electrification of transport, and costs of renewable hydrogen as an energy carrier. We therefore use the SIAMESE simulation for multiple scenarios and IAM models to incorporate the full range of possible compatible pathways.

The resulting fuel mix in each scenario can be processed using the emissions factors to derive Paris Agreement-compatible budgets, emissions intensities and other related indicators.

#### Uncertainty assessment

Providing benchmarks for a changing system faces various challenges including data gaps, model limitation and limited scenarios for socio-economical changes. Therefore, estimates for economic, technological and political feasibility are constantly in discussion and development. However, using multiple different approaches and models, robust benchmarks can be evaluated using statistical analysis methods. We assess statistical measures (e.g., median or 75<sup>th</sup> percentile) of 11 pathways as a robust synthesis of pathways, unless otherwise specified for specific benchmarks. In addition, the range (between minimum and maximum values) provides insight about the agreement and disagreement among all studies.

# 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, 2018a), 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, & Schaeffer, 2018).

For this report we include existing bottom-up analyses from the literature (see below) and, where needed, build our own tools for bottom-up analyses in the transport, industry and building sectors. Each method is tailored to the specific sector and is described in detail in the relevant section. However, some elements are consistent across all sectors:

- We identify the mitigation options that would bring us as close to full decarbonisation of the sector as quickly as possible.
- The current statuses of the individual countries assessed are taken into account when setting benchmarks, recognising current practices and that some changes can occur more readily in some countries than others. For example, we account for the changes in the building stock through time.
- We do not perform a full economic analysis and rather focus on the changes necessary to meet the Paris Agreement goals within the bounds of technical feasibility.

A challenge of setting benchmarks for individual sectors is in evaluating whether those benchmarks are compatible with a global 1.5°C emissions trajectory. While the IAMs discussed above model economy-wide emissions and can therefore assess Paris compatibility with global emissions and their associated warming, that is not the case for bottom-up models. However, we can take some steps to ensure that the benchmarks are Paris Agreement-compatible:

- Within a global model, it is possible to trade-off the pace and magnitude of emissions reductions between sectors and to utilise carbon dioxide removal (CDR) to reduce cumulative net emissions. In setting benchmarks, we ensure that no sector relies on action in another sector and minimise the reliance on CDR by setting sectoral benchmarks at as ambitious level as possible given technical constraints.
- We compare sectoral benchmarks with the overall emissions of the sector in 1.5°C compatible IAM scenarios. These total sectoral emissions give an upper envelope in which our benchmarks should sit to be 1.5°C compatible.
- ▶ In many cases, the bottom up models include additional mitigation options and recent trends that are not yet incorporated within the IAM scenarios and the bottom-up approaches therefore achieve emissions reductions more quickly. Where that is the case, we assume that the bottom-up scenarios and benchmarks are 1.5°C compatible.

# 2.3 Literature review and national/regional studies

To complement the above modelling analyses, we also incorporate existing knowledge into our benchmark definitions. The power sector is particularly well-researched but we incorporate and compare our own analysis to the existing literature in all sectors. National studies in particular allow us to define meaningful benchmarks for individual countries that are informed by local circumstances and current conditions, while studies at the regional scale are used in the absence of such nationally focused studies.

For the benchmarks that utilise a top-down approach of down-scaling regional IAM pathways, in some instances we use existing key literature to supplement the resulting downscaled pathway in deriving the final benchmark. Relevant literature is used in this way to ensure the benchmarks reflect the "highest plausible ambition level", given the numerous factors that have led IAMs to underestimate the potential for high levels of ambition in climate mitigation actions including the tendency to underestimate the gradient of learning curves of key technologies.

Where possible, additional, pre-existing modelling is provided as context to situate a number of the derived benchmarks across some sectors, namely the power, transport, and industry sectors. These are outlined below:

#### IEA Energy Technology Perspectives: Beyond 2 Degrees Scenario

The Energy Technology Perspectives is an IEA report that models how far clean energy technologies could move the energy sector towards higher climate change ambitions if technological innovations were pushed to their "maximum practical limits". It includes both a '2 Degrees Scenario' and a 'Beyond 2 Degrees Scenario' (B2DS), with the latter being consistent with "a 50% chance of limiting average future temperature increases to  $1.75^{\circ}$ C". With this stated aim of the B2DS and its high degree of scenario granularity, it becomes an ideal point of comparison for benchmarks derived herein. However, it is important to highlight that given the B2DS stated aim of limiting warming to  $1.75^{\circ}$ C, it is questionable whether this scenario is truly Paris Agreement-compatible as we interpret the Paris Agreement to mean limiting warming to  $1.5^{\circ}$ C. It can thus provide only an upper bound, at best, for Paris-compatible benchmarks.

#### **Deep Decarbonisation Pathways Project**

The Deep Decarbonisation Pathways Project is a global collaboration of energy research teams from leading research institutions in 16 of the world's largest greenhouse gas emitting countries. These research teams form a consortium led by The Institute for Sustainable Development and International Relations (IDDRI) and The Sustainable Development Solutions Network (SDSN). This consortium has produced country-specific scenarios that include energy sector pathways compatible with limiting global warming to below 2°C. Each partner country in 2015 produced a country-specific report, with some containing one modelled energy sector pathway and others containing multiple. Due to the fact that the framework of these reports is embedded within is the need to limit warming to 2°C as opposed to 1.5°C, we have chosen to provide the most ambitious pathway modelled for each country for comparison<sup>1</sup>.

Where there is more than one modelled pathway in the countries covered, the most ambitious pathways chosen for comparison in this analysis are outlined below:

India:	'Sustainable' Scenario
Indonesia:	'Renewable' Scenario
South Africa:	'Economic Structure' Scenario
USA:	'High Renewables' Scenario

#### Energy Watch Group/LUT University (2017)

This study was chosen for inclusion in our analysis as it provides evidence of the feasibility of a high degree of renewable energy penetration across every region on the planet. This joint modelling initiative between the Energy Watch Group and LUT University simulates a total global energy transition across multiple sectors including electricity and transport, and shows that a transition to 100% renewable energy is economically competitive with the current fossil-fuel and nuclear-based system (Ram et al., 2017a). This study is utilised in the following sectors:

<sup>&</sup>lt;sup>1</sup> As the DPPP involves only a core number of individual member countries from the EU, it is not possible to provide comparable EU level benchmarks from this project.

#### Power

- The finding that every region as defined by the study can feasibly reach either very close to, or a 100%, renewable energy electricity system by 2050 is utilised to provide an upper bound to the share of renewables benchmark. Where possible, this is substantiated by additional literature with a national focus.
- The related finding that asserts every region can achieve an electricity system with an emissions intensity of 0g CO2/kWh by 2050 is used to substantiate the downscaled IAM findings that emissions intensities need to be, and can feasibly be, negative by 2050 in each country.

#### Transport

- The implication of a fully decarbonised electricity system in each region of this study is used to substantiate the finding that emissions per km of passenger vehicles can and should reach zero by 2050.
- ▶ A fully decarbonised electricity system also implies a very high degree of zero-carbon fuels in the transport sector. The findings on this indicator for each region are utilised to formulate the upper bound of this benchmark between 2030 and 2050.

#### Teske et al (2019)

This comprehensive study provides global and regional energy modelling scenarios compatible with limiting warming to 1.5°C. It was chosen as it provides sectoral analysis in the transport and industry sectors that overlaps with our chosen benchmarks.

#### Transport

For our benchmark "EV share in stock" the regional modelling results from this study are used as a point of comparison against our bottom-up stocktake models. As the Teske results are less ambitious than our modelled results, they do not form part of our final benchmarks for this indicator.

#### Industry

▶ The electrification of industry benchmark is a range for each country derived through a combination of the Teske et al. regional results and the results from down-scaled IAM pathways. Where the downscaled pathway represents the highest level of ambition between the two, it forms the upper bound of the range, and where the Teske et al. regional result represents the highest level of result, this forms the upper bound of the range. Both represent 1.5°C compatible shares of electricity in industry sector.

Sector-specific literature is also included in each sector and described in more detail in the sector-specific sections of this report.

#### Data availability

All energy and emissions-related data at a national level is provided by the IEA World Energy Balance and IEA  $CO_2$  Fuel Combustion Emissions database (IEA, 2019c). For transport-related indicators, various other sources are used and indicated within the report. In line with IPCC guidelines, we harmonise the model data in the base year 2015 to the historical data provided by the International Energy Agency (IEA). The difference is linearly reduced until the year 2050.

# 3.1 Key mitigation options in the power sector

In 2015, the base year used for our analysis of the power sector, fuel input to the global power sector was roughly 38% of global total primary energy demand. This makes the power sector the sector with the largest energy demand, and the highest share of global  $CO_2$  emissions of any sector (IEA, 2019a). It is therefore imperative to speed up the widespread implementation of strategies to decarbonise the world's power systems, to achieve the rapid and deep emissions cuts required to limit warming to 1.5°C as agreed under the Paris Climate Agreement.

In all 1.5°C compatible pathways analysed for the power sector, there is a high degree of uptake in renewable energy technology, with its share of total demand increasing over time, from 2015 to beyond 2050. This indicates the critical role they will play in achieving the outcomes of the Paris Agreement.

In later years (primarily beyond 2030), carbon capture and storage (CCS) plays an increasingly important role in achieving decarbonisation under most 1.5°C compatible pathways. This later uptake, rather than early, reflects the fact that it is currently not a commercially viable option, and requires further development before it can be rolled out on the scale necessary for deep decarbonisation of the power sector. There are, however, large variations in the extent of eventual CCS utilisation across pathways of the same region, which underscores the uncertainty associated with this technology that is embodied in these pathways. Most "low CCS" pathways compensate for this by substituting a higher share of renewable energy, and this is a main reason behind the considerable range that exists between pathways in the "share of renewables" indicator for the countries analysed.

Many pathways across all regions exhibit low overall energy demand growth until 2025 or even 2030. This demonstrates an expectation of widespread energy efficiency gains, with many such measures being cost-effective and simple to implement. Energy efficiency measures implemented in the industry and building sectors both have the potential to significantly reduce electricity demand.

# 3.2 Sector-specific methods to define Paris Agreement-compatible benchmarks

The three indicators chosen in order to reflect critical elements of the necessary transition in the power sector over time are: **electric emissions intensity, share of renewables, and share of unabated coal** in the electricity mix of the countries chosen for analysis. These indicators were chosen in order to provide both a general overview (electric emissions intensity) of where the electricity sector needs to be in the milestone years of 2030, 2040, and 2050, as well as a more granular description of how much the build-up (renewables share) and phase-out (coal share) of specific critical energy sources needs to have progressed in each country.

The Paris Agreement-compatible benchmarks for these indicators reflect a synthesis of the values in the chosen interval years (2030, 2040, 2050) of the 75<sup>th</sup> percentile across the Paris Agreement-compatible pathways analysed and the highest level of ambition found to be viable in the relevant literature. Eleven scenarios provide the necessary data at the required level of

granularity to derive country-level pathways<sup>2</sup>. The median and 75<sup>th</sup> percentile pathways for each country are illustrated by the dotted and solid blue lines respectively in

Figure 3-1, Figure 3-2 and Figure 3-3 below, and are selected rather than the average in order to safeguard the value of the resultant benchmark from potential outlier pathways. This is illustrated by the range of pathways for South Africa's electric emissions intensity in

Figure 3-1 compared to the median and 75<sup>th</sup> percentile.

The 75<sup>th</sup> percentile is chosen as the lower end of the benchmark ranges, rather than the median, to account for a number of factors that have led to IAMs underestimating the potential for high levels of ambition in climate mitigation actions. For example, the IEA has consistently underestimated the penetration of renewable energy generation in the global energy mix, and IAMs have underestimated the declining trends in capital costs of renewable energy systems, especially photovoltaics and storage technologies. Additionally, many IAMs tend to depend to a large extent on Carbon Dioxide Removal (CDR) technologies (e.g., BECCS) in order to meet temperature targets, which does not capture the near-term action needed should those technologies not be available at the massive scale needed.

While an IAM-based assessment provides a consistent estimation of the minimum necessary ambition for Paris compatibility of each benchmark, additional lines of evidence are assessed to further explore the landscape of pathways to meet the Paris Agreement. These sources are employed in a synthesis of the IAM results, including the available literature using bottom-up, hybrid, and sectoral models to estimate the top-end range of plausible ambition.

Because these studies are based on detailed technological assessments, including on the feasibility of certain technical futures, and are often combined with energy system cost estimation, they complement IAM-based estimates, and they can provide an upper bounding term of "highest plausible ambition level" in line with a 1.5C outcome. For this reason, they form the upper bound of the Paris Agreement-compatible benchmarks for the power sector. The literature utilised in this way is outlined in section 2.3.

One study in particular is employed in our analysis, as it provides evidence of the feasibility of a high degree of renewable energy penetration across every region on Earth. This joint modelling initiative between the Energy Watch Group and LUT University simulates a total global energy transition across multiple sectors including electricity and transport, and shows that a transition to 100% renewable energy is economically competitive with the current fossil-fuel and nuclear-based system (Ram et al., 2017b). This study forms the lower end of the benchmark range for the power sector.

In order to further place results for the power sector into context, we have provided benchmarks for the same countries and indicators from two alternative sources that provide an adequate level of granularity in their analyses to enable comparison. These sources are the **Deep Decarbonisation Pathways Project**, and the **Beyond 2 Degrees Scenario (B2DS)** from the **International Energy Agency's Energy Technology Perspectives Report**, outlined in section 2.3.

IMAGE-SSP1-19 WITCH\_CD-LINKS\_NPi2020\_1000 MESSAGE\_SSP1-19 AIM\_TERL\_15D\_LowCarbonTransportPolicy AIM\_SSP2-RCP1.9

<sup>&</sup>lt;sup>2</sup> IMAGE\_IMA15-LiStCh WITCH\_CD-LINKS\_NPi2020\_400 MESSAGE\_ADVANCE\_2020\_1.5C-2100 AIM\_TERL\_15D\_NoTransportPolicy AIM SSP1-RCP1.9

#### **3.2.1 Electricity Emissions Intensity** g CO<sub>2</sub> / kWh

A clear measure of the decarbonisation of the energy system is CO<sub>2</sub> intensity in the power sector, measured in grams of CO<sub>2</sub> emitted per kWh of electricity generated (gCO<sub>2</sub>/kWh) equivalent units. As a very rough indication, coal-fired power results in 1000 g/kWh and natural gas power about half that. The CO<sub>2</sub> intensity of the power sector is a complementary indicator to that of renewable energy share in the power sector and is clearly connected to the rate of coal phase-out.

The CO<sub>2</sub> emitted through the three fossil fuel electricity sources coal, oil and gas is considered in IAMs, and for each fuel and country, specific electric emissions intensities ( $gCO_2/kWh$ ) are calculated according to IEA fuel demand in electricity data in 2015 (World Energy Balances (IEA, 2019c)). For bioenergy with CCS (BECCS), we assume a capture rate of 90% and an electricity emissions intensity of -300 gCO<sub>2</sub>/kWh, a negative of the weighted average of the default direct emissions factors for the various forms of bioenergy provided in the IPCC 2006 guidelines (IPCC, 2006).

The incorporation of negative emissions intensity for electricity produced using BECCS is chosen in order to express the relative degree to which particular countries are projected to rely on BECCS in the analysed pathways, a technology that is currently not viable and has limitations on the extent to which it can be utilised. This also provides a more detailed picture of country-specific fuel-mix trajectories than simply treating electricity resulting from bioenergy with and without CCS as resulting in zero emissions. However, by including BECCS in overall emissions intensity allows for different solutions providing negative emissions and still, overall, as a sum over countries and sectors, achieve a global 1.5°C compatible pathway.

Emissions factors derived from for all fossil fuels are used to compute the overall emissions in the power sector and divided by the electric power generated to compute the electric emissions intensify.



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Figure 3-1. Emissions intensity of electricity incl. BECCS, also including uncertainty ranges using 11 different IAM model/scenario runs

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Table 3-1.	Emissions	Intensity o	r electricity inc	I. BECCS

<b>Emissions intensity</b> g CO <sub>2</sub> / kWh									
Country	Year	IAM pathways median	IAM pathways p75	ETP B2DS	EWG & LUT	DDPP 2°C	PA Final Benchmark		
	2030	175	125	229	48		50-125		
Global	2040	31	24	72	6		5-25		
	2050	5	-5	-8	0		<0		
	2030	186	132	323	29*		30-130		
USA	2040	55	32	70	0*		0-32		
	2050	13	-4	-31	0*	35	<0		
	2030	113	77	78	82*		75-80		
EU	2040	14	0	27	6*		0-5		
	2050	-25	-31	-30	0*		<0		
	2030	42	20	10	2*	32	0-20		
Brazil	2040	-6	-11	11	0*		<0		
	2050	-17	-46	6	0*	0	<0		
	2030	241	156	256	114*		115-155		
India	2040	18	3	97	0*		5		
	2050	-6	-22	32	0*	36	<0		
	2030	197	109	277	95*	450	100-110		
China	2040	24	7	44	0*		0-5		
	2050	3	-1	-22	0*	68	<0		
	2030	447	377	304	47*		45-377		
South Africa	2040	38	12	34	5*		5-10		
	2050	-3	-21	12	0*	35	<0		
	2030	303	256		50*	400	50-255		
Indonesia	2040	45	32		5*		5-30		
	2050	7	-11		0*	68	<0		

Figure 3-1 shows the range, median and 75<sup>th</sup> percentile of the eleven pathways downscaled from regional IAM scenarios. The solid line (75<sup>th</sup> percentile) represents the pathway chosen to derive the lower bound of the 2030, 2040 and 2050 Paris Agreement-compatible benchmarks for each country. The range shown for each country in one sense provides an indication of the degree of uncertainty at any one interval year, but also demonstrates the fact that there is no definitive trajectory that a country must follow to achieve Paris Agreement compatibility. It is generally true, however, that the slower a country decarbonises over the short term, the more drastic the emissions reductions are required over subsequent years.

Table 3-1 shows the 2030, 2040 and 2050 Paris Agreement-compatible benchmarks for emissions intensity of the electricity sector for the chosen countries, which are a synthesis of the "high" ambition 75<sup>th</sup> percentile IAM pathway and the top end range of plausible ambition found in the literature.



For each scenario and country, the **share of renewable power sources (including bioenergy) of the total generated power** are derived from the country-specific pathways reflecting the fuel mix over time, downscaled from the regional-level electricity sector pathways.

Our definition of 'renewable energy' in this context is broad and encompasses not only variable generators like solar and wind, but also dispatchable sources like hydro and power plants fuelled with sustainable, net-zero emissions biomass. Grid stability and reliability in these scenarios is maintained in a cost-effective manner through multiple technologies, including storage. Storage on week-to-month timescales is enabled by pumped storage and on hourly-daily time scales by battery technologies and compressed air storage. Models can still find the need for spinning up gas-based reserves to help balance electrical load; in 100% RE scenarios, such turbines are fuelled with synthetic gas derived from renewable sources (e.g., methanation, electrolysis).

As with the variation in the overall fuel mix in the country-specific downscaled pathways, the variation across countries in the share of renewables and unabated coal indicators across time can be explained by the same interconnected factors. These factors are the country-specific relative magnitude of demand for specific fuels in the base year, and the trajectories of demand for the various fuels at the regional level over time. A high degree of intra-country variation across pathways exhibited by, for example, the USA, South Africa and Indonesia is primarily explained by a large variation between pathways of the relative proportions of renewable energy, and nuclear and fossil fuel-based power generation with CCS.

#### **Results:**

Figure 3-2 shows the range, median, and 75<sup>th</sup> percentile of the eleven pathways downscaled from regional IAM scenarios. The solid line (75<sup>th</sup> percentile) represents the pathway chosen to derive the lower bound of the 2030, 2040 and 2050 benchmarks for each country. Table 3-2 then shows the range of 2030, 2040, and 2050 Paris Agreement-compatible benchmarks reflecting a synthesis of the "high" ambition 75<sup>th</sup> percentile IAM pathway and the top end range of plausible ambition found in the literature.



Figure 3-2. Share of renewable energy sources in the electricity sector

#### Selection of Paris Agreement-compatible benchmarks

We develop Paris-compatible benchmarks for the share of renewable energy in the power sector from different sources of evidence in the scenario literature. We rely on IAMs and existing literature to provide an envelope of possible transitions in the 2030s and 2040s. However, we are noting criticisms with the IAM long-term assumptions of costs and peculiarities in technical constraints placed within the models. Therefore, for the 2050 benchmark, we derive the 2050 benchmarks based on recent literature studies only.

In order to meet the Paris Agreement, it is clear that the power system must be carbon-neutral or negative by mid-century – as is reflected in our energy intensity benchmarks. The technology mix which achieves this target can be varied, including fossil-based CCS and nuclear. Literature is available describing cost-effective (i.e., at or below today's energy costs) 100% RE systems for most of the countries under consideration in our benchmarks as well as global scenarios which do not include these technologies. The CAT therefore makes some normative assessments as to the viability of these possible futures.

Dependence on fossil-based CCS will further increase the mitigation burden (only ~90% of emissions are captured in an idealised system) and pressure land-use sectors to extract ever more emissions from the atmosphere. Given the difficulty in mitigating other sectors mentioned in this report, the CAT therefore does not assess fossil-based CCS in the power sector as a viable option for countries to target in Paris-Agreement compatible scenarios.

Nuclear power has other well-discussed complications. not least of which concern intergenerational-equity issues. While nuclear power is a near-zero carbon emissions power source, it suffers from political acceptability, safety issues, concerns in relation to the nuclear fuel cycle including proliferation as well as disposal of high level nuclear waste which is nowhere resolved, high economic cost, slow build times, and inflexibility in relation to its technical integration in large-scale RE systems, which is an ongoing matter of scientific discussion.



Country pathways medianIAM pathways p75ETP B2DS pathways p75EWG & LUT bodsDDP 2'C Final Benchmark Benchmark Benchmark Benchmark Benchmark203052%56%47%89%55-90%Clobal204073%76%63%99%55-90%205071%82%74%100%98-100% <sup>34 se</sup> 205071%82%74%100%98-100% <sup>34 se</sup> 205071%82%73%99%70-100%205072%85%66%100%84%98-100% <sup>7</sup> 205072%85%66%100%84%98-100% <sup>7</sup> 205068%70%59%88%70-90%205086%92%75%100%9899-100%205086%92%75%100%9899-100%205095%96%93%98%92%90-100%205095%96%44%99%97%98-100% <sup>9</sup> 205095%96%42%81%40%65-80%205086%88%62%98%31%75-90%205084%88%75%98%31%75-90%205084%88%75%98%31%75-90%205084%88%75%98%31%75-90%205084%88%75%98%31%75-90%205090%91%61%96%9	Share of renewables (including biomass) % of total generation								
Sigmed baseSigmed baseSigmed baseSigmed base10010010098-100% 3 <sup>1</sup> /3 <sup>1</sup> 20011%82%74%100%98-100% 3 <sup>1/3</sup> /3 <sup>1</sup> 10020071%82%74%100%98-100% 3 <sup>1/3</sup> /3 <sup>1</sup> 10020070%72%33%94%50-95%20070%72%51%99%70-100%10020072%66%100%84%98-100% 7410020072%65%66%100%84%98-100% 7410020066%66%100%84%98-100% 8410083%65%66%97%88%70-90%10084%92%90-100%84%98%92%90-100%10184%92%9093%98%92%90-100%10120086%97%98%92%90-100%9610195%95%93%98%92%90-100%9610195%95%94%99%96969610195%95%96%97%98-100% 94969610195%95%98%75%98%75%9875%9875%9875%9816%45100%959598100%100%100%100%100%100%100%100%100%100%100%100%100%100%100% </th <th>Country</th> <th>Year</th> <th>IAM pathways median</th> <th>IAM pathways p75</th> <th>ETP B2DS</th> <th>EWG &amp; LUT</th> <th>DDPP 2°C</th> <th>PA Final Benchmark</th>	Country	Year	IAM pathways median	IAM pathways p75	ETP B2DS	EWG & LUT	DDPP 2°C	PA Final Benchmark	
Global         2040         73%         76%         63%         98%         75-100%           2050         71%         82%         74%         100%         98-100% <sup>3/4/5/6</sup> 2030         48%         52%         33%         94%         50-95%           2040         70%         72%         51%         99%         70-100%           2050         72%         85%         66%         100%         84%         98-100% <sup>7/4</sup> 2050         72%         85%         66%         100%         84%         98-100% <sup>7/4</sup> 2040         83%         85%         69%         97%         85-95%           2050         86%         92%         97%         98-100% <sup>8/4</sup> 2050         86%         92%         90-100%         84           2040         95%         96%         94%         99%         95-100%           2050         95%         97%         96%         99%         97%         98-100% <sup>41</sup> 2050         95%         97%         96%         99%         97%         98-100% <sup>41</sup> 2040         86%         88%         75%         98%         31% <t< th=""><th></th><th>2030</th><th>52%</th><th>56%</th><th>47%</th><th>89%</th><th></th><th>55-90%</th></t<>		2030	52%	56%	47%	89%		55-90%	
1000000000000000000000000000000000000	Global	2040	73%	76%	63%	98%		75-100%	
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India         2030         65%         66%         42%         81%         40%         65-80%           India         2040         86%         88%         62%         98%         90-100%           2050         84%         88%         75%         98%         74%         98-100% <sup>9</sup> 4           India         2050         84%         88%         75%         98%         31%         75-90%           India         2040         89%         91%         61%         96%         90-95%           2050         90%         94%         70%         99%         52%         98-100% <sup>41011</sup> India         2030         40%         44%         39%         98%         16%         45-100%           India         2040         81%         85%         55%         99%         85-100%           Indonesia         2050         65%         70%         62%         100%         94%         98-100% <sup>12</sup> 4           Indonesia         2040         68%         79%         84%         50-85%         99%         80-100%           Indonesia         2050         74%         79%         99%         98-100% <sup>13</sup> 4         98-100% <sup>13</sup> 4		2050	95%	97%	96%	99%	97%	<b>98-</b> 100% <sup>4</sup>	
India         2040         86%         88%         62%         98%         90-100%           2050         84%         88%         75%         98%         74%         98-100% <sup>9</sup> 4           Logon         70%         76%         49%         89%         31%         75-90%           Logon         89%         91%         61%         96%         90-905%           2040         89%         91%         61%         96%         90-905%           2050         90%         94%         70%         99%         52%         98-100% <sup>410</sup> 11           Logon         40%         44%         39%         98%         16%         45-100%           South Africa         2040         81%         85%         55%         99%         88-100% <sup>12</sup> 4           Logon         65%         70%         62%         100%         94%         98-100% <sup>12</sup> 4           Logon         65%         50%         84%         50-85%         80-100%         80-100%           Logon         74%         79%         99%         98-100% <sup>13</sup> 4         98-100% <sup>13</sup> 4		2030	65%	66%	42%	81%	40%	65-80%	
2050         84%         88%         75%         98%         74%         98-100%         94           A         2030         70%         76%         49%         89%         31%         75-90%           2040         89%         91%         61%         96%         90-95%         90-95%           2050         90%         94%         70%         99%         52%         98-100% <sup>410</sup> 11           2050         90%         94%         39%         98%         16%         45-100%           South Africa         2040         81%         85%         55%         99%         85-100%           2050         65%         70%         62%         100%         94%         98-100% <sup>12</sup> 4           Indonesia         2040         68%         79%         84%         50-85%           2040         68%         79%         99%         80-100%         124           2050         74%         79%         99%         98-100% <sup>13</sup> 4	India	2040	86%	88%	62%	98%		90-100%	
China         2030         70%         76%         49%         89%         31%         75-90%           2040         89%         91%         61%         96%         90-95%           2050         90%         94%         70%         99%         52%         98-100% <sup>41011</sup> Appendix         2030         40%         44%         39%         98%         16%         45-100%           South Africa         2040         81%         85%         55%         99%         88-100% <sup>12</sup> 4           2050         65%         70%         62%         100%         94%         98-100% <sup>12</sup> 4           Indonesia         2040         68%         79%         84%         50-85%           2040         68%         79%         99%         80-100%           2050         74%         79%         99%         80-100% <sup>13</sup> 4		2050	84%	88%	75%	98%	74%	<b>98-</b> 100% <sup>9</sup> <sup>4</sup>	
China         2040         89%         91%         61%         96%         90-95%           2050         90%         94%         70%         99%         52%         98-100% <sup>41011</sup> Apple		2030	70%	76%	49%	89%	31%	75-90%	
2050         90%         94%         70%         99%         52%         98-100% <sup>41011</sup> Apple App	China	2040	89%	91%	61%	96%		90-95%	
South Africa         2030         40%         44%         39%         98%         16%         45-100%           2040         81%         85%         55%         99%         85-100%           2050         65%         70%         62%         100%         94%         98-100%         124           Indonesia         2040         68%         70%         62%         99%         50-85%           2040         68%         79%         99%         80-100%         80-100%           2050         74%         79%         99%         98-100% <sup>13</sup> 4		2050	90%	94%	70%	99%	52%	<b>98-100%</b> <sup>4 10 11</sup>	
South Africa         2040         81%         85%         55%         99%         85-100%           2050         65%         70%         62%         100%         94%         98-100% <sup>12</sup> 4           Apple Africa         2030         45%         50%         84%         50-85%           2040         68%         79%         99%         80-100%           2050         74%         79%         99%         98-100% <sup>13</sup> 4		2030	40%	44%	39%	98%	16%	45-100%	
2050         65%         70%         62%         100%         94%         98-100%         12 4           100         45%         50%         84%         50-85%           2040         68%         79%         99%         80-100%           2050         74%         79%         99%         98-100% <sup>13</sup> 4	South Africa	2040	81%	85%	55%	99%		85-100%	
2030         45%         50%         84%         50-85%           2040         68%         79%         99%         80-100%           2050         74%         79%         99%         98-100% <sup>13</sup> 4		2050	65%	70%	62%	100%	94%	<b>98-100%</b> <sup>12</sup> 4	
Indonesia         2040         68%         79%         99%         80-100%           2050         74%         79%         99%         98-100% <sup>13</sup> 4		2030	45%	50%		84%		50-85%	
2050 74% 79% 99% <b>98-100%</b> <sup>13</sup> 4	Indonesia	2040	68%	79%		99%		80-100%	
		2050	74%	79%		99%		<b>98-100%</b> <sup>13</sup> 4	

Table 3-2. Share of renewables (including biomass) % of total generation

<sup>3</sup> Greenpeace. (2015). Energy [R] Evolution. Energy [R]Evolution.

<sup>4</sup> Teske, S. et al., 2019. Chapter 8 Energy Scenario Results. In Achieving the Paris Agreement Goals, Springer, pp. 175-402.

<sup>5</sup> Bogdanov, D., Farfan, J., Sadovskaia, K., Aghahosseini, A., Child, M., Gulagi, A., ... Breyer, C. (2019). Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nature Communications*, *10*(1), 1–16. https://doi.org/10.1038/s41467-019-08855-1

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- <sup>7</sup> Aghahosseini, A. et al. (2019) 'Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030', Renewable and Sustainable Energy Reviews, 105, pp. 187–205. doi: https://doi.org/10.1016/j.rser.2019.01.046.

 Löffler, et al. (2017), Designing a Model for the Global Energy System—GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS), doi: 10.3390/en10101468

<sup>11</sup> Burandt, T et al. (2019), Decarbonizing China's energy system – Modeling the transformation of the electricity, transportation, heat, and industrial sectors, https://doi.org/10.1016/j.apenergy.2019.113820

<sup>&</sup>lt;sup>8</sup> Zappa, W., Junginger, M. and van den Broek, M. (2019) 'Is a 100% renewable European power system feasible by 2050?', Applied Energy, 233–234(January 2018), pp. 1027–1050. doi: 10.1016/j.apenergy.2018.08.109. Ram, M. et al. (2018) Energy Transition in Europe Across Power, Heat, Transport and Desalination Sectors. LUT University and Energy Watch Group. http://energywatchgroup.org/wp-content/uploads/2018/12/EWG-LUT\_Full-Study\_Energy-Transition-Europe.pdf

<sup>&</sup>lt;sup>9</sup> Das, S. et al. (2013) 'The Energy Report - India 100% Renewable Energy by 2050', p. 110. Available at: http://awsassets.wwfindia.org/downloads/the\_energy\_report\_india.pdf.

<sup>&</sup>lt;sup>12</sup> Oyewo, A. S. et al. (2019) 'Pathway towards achieving 100% renewable electricity by 2050 for South Africa', Solar Energy, 191(September), pp. 549–565. doi: 10.1016/j.solener.2019.09.039.

<sup>&</sup>lt;sup>13</sup> Wang, C., Dargaville, R., and Jeppesen, M. (2018). Power system decarbonisation with Global Energy Interconnection - a case study on the economic viability of international transmission network in Australasia. Matthias Günther, Irina Ganalb, and Stefan Bofinger (2018). A 100% Renewable Electricity Scenario for the Java-Bali Grid. Available at: https://ejournal.undip.ac.id/index.php/ijred/article/view/13910/pdf [Accessed April 18, 2019].

Our analysis suggests that to be Paris Agreement-compatible and reach complete decarbonisation by 2050, the most promising option is to fully transition the electricity sector to 100% renewable sources using variable and dispatchable sources, firm biomass capacity, all storage options and flexible electricity demand. Other alternative low-carbon technologies are not expected to compete economically with renewable energy and storage where costs are falling and are expected to continue to fall. A combination of biomass, mass battery storage, hydropower and power-to-gas technologies will provide enough storage potential to compensate for the variation in wind and solar power supply (Bogdanov et al., 2019; Brown et al., 2018; Cheng, Blakers, Stocks, & Lu, 2019). However, there are uncertainties of future development, and different national preferences may take hold to keep non-renewable, low-carbon technologies in the marketplace.

While we assess an upper bound in 2050 for this benchmark at 100%, consistent with available global study of (Teske et al., 2019). We omit using IAM based results for the lower bound in 2050, since recent decrease in the costs of renewables suggest a much faster market penetration rate and will significantly change projections in 2050. Therefore, we provide a lower bound of 98% across the board. This lower bound is derived from the lowest country-specific renewables penetration rate from global study of EWG/LUT (Zappa, Junginger, & van den Broek, 2019) which most closely aligned with recently observed developments in the renewable energy space, and reflects the abovementioned uncertainties. However, the CAT assesses that 100% renewable electricity is a technically and economically feasible means of reaching zero emissions in the power sector by 2050 and involves the lowest sustainability trade-offs.

Ram, M., Bogdanov, D., Aghahosseini, A., and Oyewo, A. S. (2017). Global 100% RE System: Southeast Asia - Indonesia, Papua New Guinea. Available at: https://www.researchgate.net/publication/320756200\_Global\_100\_RE\_System\_Southeast\_Asia\_-\_\_\_\_Indonesia\_Papua\_New\_Guinea [Accessed March 19, 2019]

#### **3.2.3 Share of unabated coal in the power sector** Percentage coal in total generation

The share of unabated coal represented in the country-specific benchmarks reflects only coalfired power without CCS. As coal-fired power with CCS is an almost emissions neutral power source and therefore does not contribute significantly to the exhaustion of a country's Paris Agreement-compatible carbon budget, the share of this technology represented in the down scaled pathways is not captured by this indicator. CCS technologies also represent a more expensive version of the original fossil technology. Since IAMs do not consider social and political implications, CCS technologies could be interpreted as unused potential for renewables or biomass. Coal plays a large role in the world energy system and is the most  $CO_2$ intensive fossil fuel. Although the coal share in power generation has decreased in many countries in recent years, it is still growing in others, e.g. India or Indonesia.

#### **Results:**

Figure 3-3 shows the range, median and 75<sup>th</sup> percentile of the eleven pathways downscaled from regional IAM scenarios. The solid line (75<sup>th</sup> percentile) represents the pathway chosen to derive the lower bound of the 2030, 2040 and 2050 benchmarks for each country.





Figure 3-3. Share of unabated coal-fired power in the electricity sector and uncertainty ranges

Share of coal % of total generation									
Country	Year	IAM pathways median	IAM pathways p75	ETP B2DS	EWG & LUT	DDPP 2°C	PA Final Benchmark		
	2030	7%	2%	14%	1%		0-2.5%		
Global	2040	1%	0%	3%	0%		0%		
	2050	0%	0%	1%	0%		0%		
	2030	5%	1%	6%	0%	0%	0%		
USA	2040	1%	0%	2%	0%		0%		
	2050	0%	0%	1%	0%	0%	0%		
	2030	3%	1%	7%	1%	0%	0%		
EU	2040	0%	0%	1%	0%		0%		
	2050	0%	0%	0%	0%	0%	0%		
	2030	0%	0%	2%	0%	26%	0%		
Brazil	2040	0%	0%	1%	0%		0%		
	2050	0%	0%	1%	0%	2%	0%		
	2030	19%	11%	15%	7%	17%	5-10%		
India	2040	1%	1%	1%	0%		0%		
	2050	0%	0%	1%	0%	1%	0%		
	2030	17%	8%	29%	7%	52%	5-10%		
China	2040	1%	0%	7%	0%		0%		
	2050	0%	0%	0%	0%	5%	0%		
	2030	43%	36%	35%	1%	79%	0-35%		
South Africa	2040	6%	2%	6%	0%		0%		
	2050	2%	0%	2%	0%	0%	0%		
	2030	13%	8%	11%	6%	26%	5-10%		
Indonesia	2040	1%	0%		0%		0%		
	2050	0%	0%	0%	0%	2%	0%		

Tuble 5 5. Shale of anabalea coal filea power in the electricity secto	Table 3-3. Share o	f unabated o	coal-fired p	power in the	electricity secto
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Table 3-3 provides 2030, 2040, and 2050 Paris Agreement-compatible benchmarks for the share of coal in the electricity sector reflecting a synthesis of the "high" ambition 75<sup>th</sup> percentile IAM pathway and the top end range of plausible ambition found in the literature.

# 4 Transport

# 4.1 Key mitigation options in the transport sector

Transport emissions represent close to 20% of global CO<sub>2</sub> emissions, with the transport sector having the second highest level of total final consumption behind the power sector, accounting for at least 20% of energy consumed (IEA, 2019).

Although reducing transport emissions will require a reduction in demand for transportation and enabling a modal shift to non-motorised mobility, a key sectoral strategy for the decarbonisation of both passenger and freight transport by 2050 is electrification. This is contingent on a simultaneous decarbonisation of the power sector (see section on power sector). Catalysing a rapid penetration of electric vehicles (EVs) to reduce the share of internal combustion engine vehicle (ICEVs) will be key in reaching this target and will be facilitated through the widespread deployment of charging infrastructure together with incentives for passengers to shift to EVs. This acceleration could be driven by the implementation of ICEV sales-ban targets, which has already been the case in several countries.

While the penetration of EVs within different markets needs to be scaled up, it also needs to be accompanied by an improvement in fuel efficiency of ICEVs through the introduction or the improvement of fuel efficiency standards. Passenger car fuel efficiency standards exist for a wide range of countries but with different levels of stringency. If standards were broadly applied at the level of the 2025 EU car standards, this could achieve a potential global emissions reduction of 1.9  $GtCO_2$  (Fekete et al., 2015).

Investments in public transport and urbanisation policies ensuring accessible routes for alternative transports will be key in supporting modal shift for passengers from vehicles to public transport or alternative modes, such as bicycles, as urban population grows.

# 4.2 Deriving benchmarks

Four indicators are chosen in order to reflect critical elements of the necessary transition in the transport sector over time:

- share of electric vehicles in stock (%) defined as the number of EV cars, two and three wheelers (only in the case of China, Indonesia and India), expressed as the % of overall Light duty vehicle (LDV) fleet. Our definition of EVs includes only battery electric vehicles (BEVs).
- share of electric vehicles sales (%) defined as the % of EV sales of the overall LDV sales, including cars, two and three wheelers (only in the case of China, Indonesia and India).
- land-based emissions per passenger kilometres (gCO<sub>2</sub>/pkm) travelled by cars, two and three wheelers (only in the case of China, Indonesia and India), buses and rail transport.
- share of low-emissions fuels (biofuels, electricity and hydrogen) of the total (domestic) transport sector demand (%) of final energy, including passenger and freight.

As with other sectors, our benchmarks are determined from a range of inputs; literature review, a bottom-up model of the transport sector focusing on passenger vehicles (cars, two and three-wheelers depending on the context of the country), and an analysis of 1.5°C compatible scenarios.

The first three indicators require the use of a detailed bottom-up model while the last indicator can be derived using IAM pathways as was done for the power sector.

# 4.2.1 1.5°C compatible scenarios

EV shares in stock, sales, and land-based emissions per passenger kilometres require a very detailed technology perspective. Thus, we rely on the IEA Energy Technology Perspectives (ETP) 2017 (International Energy Agency (IEA)., 2017) and the IEA Mobility Model 2017 (as used for World EV Outlook 2017). The "Beyond 2 degrees scenario" (B2DS) applies a combination of back-casting and forecasting over three scenarios from now to 2060. The analytical approach used in the ETP model is described as aiming at identifying a "cost-effective way for society to reach the desired outcome".

The Energy-related CO<sub>2</sub> emissions in the B2DS scenario up to 2060, together with its peak warming at 1.6°C around 2060, are comparable with low-overshoot 1.5°C scenarios and is likely to be a compatible pathway with the Paris Agreement. However, scenario data from 2060 to 2100 is missing, thus a final statement is not possible. It will, however, require further negative emissions after 2060 to reach 1.5°C (Climate Action Tracker, 2018a, 2018b). Therefore, we further analyse the transport component of the B2DS and the compatibility with the Paris Agreement goal.

For using the B2DS in these benchmarks we investigated how transport sector emissions compare to the CAT-defined set of 1.5°C compatible pathways<sup>14</sup>. Figure 4-1 shows the full range of sectoral CO<sub>2</sub> emissions in the transport sector, as well as the median. The green diamonds, representing the B2DS, place well within the range of 1.5°C pathways, thus can be categorised as within the set the Paris Agreement-compatible scenario pathways. However, we note that the B2DS is above the median during the transition from 2030-2050, providing a more conservative estimation in this period than most compatible pathways.

14 'SSP1-19 SSP1-19', 'SSP2-19 SSP2-19', 'TERL 15D LowCarbonTransportPolicy TERL 15D LowCarbonTransportPolicy', 'TERL\_15D\_NoTransportPolicy TERL\_15D\_NoTransportPolicy', 'IMA15-LiStCh IMA15-LiStCh', 'SSP1-19 SSP1-19'. 'ADVANCE\_2020\_1.5C-2100 ADVANCE\_2020\_1.5C-2100', 'SSP1-19 SSP1-19', 'SSP2-19 SSP2-19', 'EMF33\_1.5C\_cost100 EMF33\_1.5C\_cost100', 'EMF33\_1.5C\_limbio EMF33\_1.5C\_limbio', 'EMF33\_1.5C\_nofuel EMF33\_1.5C\_nofuel', 'EMF33\_WB2C\_limbio EMF33\_WB2C\_limbio', 'EMF33\_WB2C\_nobeccs EMF33\_WB2C\_nobeccs', 'EMF33\_WB2C\_nofuel EMF33\_WB2C\_nofuel', 'EMF33\_WB2C\_none EMF33\_WB2C\_none', 'CD-LINKS\_NPi2020\_1000 CD-LINKS\_NPi2020\_1000', 'CD-LINKS NPi2020 400 CD-LINKS NPi2020 400',



Figure 4-1: Comparison of the ETP-B2DS pathways within the transport sector compared to 1.5°C compatible pathways

The 1.5°C compatible pathways from Integrated Assessment Models (IAMs) do not provide the granularity of data on EVs and road transport sector needed for this study (LDVs emissions, passengers-km, energy consumption per transport mode, etc.). Therefore, we rely mostly on the IEA ETP 2017 – Beyond 2 Degrees Scenario (B2DS) (International Energy Agency (IEA)., 2017) and the Mobility Model Data (2017) together with projections based on current developments and market research.

We also use results from the (Teske (ed.), 2019) study on global and regional 1.5°C compatible energy scenarios as a point of comparison for the EV share in stock benchmark as described in section 2.3.

# 4.2.2 Bottom-Up Flex Model

Electric vehicle share and emissions per passenger km (see section below) have been derived from a distribution model developed within the framework of this project and representing the distribution of EVs within the car fleet across time. The underlying assumption is that the uptake of electric vehicles is represented by a logistic function, assuming that EVs will be replacing conventional vehicles across time and thus their relative market share will be increasing, independently of the general fleet growth (Grubler, Wilson, & Nemet, 2016). In cases of China, India and Indonesia, EVs two or three wheelers are also included in the model, both electric and combustion-based versions.

While two and three wheelers account for more than 80% of the total fleet in Asian countries and in India, and more than 70% in China, they account for less than 10% in OECD countries. They are projected to reach close to 50% in ASEAN, India and China and 10% in OECD countries by 2050 (IEA ETP Mobility Model, 2017). Two and three wheelers are thus included in the model for Indonesia, India and China together with passenger cars whereas we decided to consider only passenger cars for the other countries considered in this study. The share of two and three wheelers across time has been extracted from the ETP Mobility Model 2017.

EV penetration across time is modelled with a sigmoid curve distribution which is optimised to fit three basic indicators that were extracted from the B2DS scenario:

- CO2 emissions of the fleet;
- total energy consumption;
- **passenger kilometres** (pkm).

The parameters allowing the fitting are based on technological advances such as the reduction of energy intensity of ICEVs, mobility behaviour such as EV growth rates, fleet growth, a growth rate of kilometres travelled across time, and decarbonisation of the grid (decreasing rate of grid carbon intensity). The model fitting has been operationalised iteratively in three steps to match the passenger kilometres, the emissions, and energy consumption in order to find reasonable benchmarks for the EV market share. For each iterative step, the fitting has been performed by using the least square error optimisation method parametrised on kilometre per auto and varying growth rate of travelled kilometres for the first step, the grid carbon intensity rate for the second step (bounded by results from the B2DS scenario to account for feedbacks from the power sector) and for the third step, the EV initial growth and the ICEV carbon intensity growth rates. Model inputs are historical data (EV fleet, EV Sales, Car fleet, Retirement Rates, Grid carbon intensity, ICEVs Carbon Intensity, km per vehicle per year).

Benchmarks derived by this bottom-up approach do not necessarily provide a unique solution but rather a guiding landing zone. This is because the emissions reduction needed can be accomplished using various measures. A given emissions reduction can, for example, be accomplished by a reduction in pkm per year or the emissions per km. The emissions per pkm can be achieved through reducing the weight of the car fleet, higher passengers per vehicle km, or more efficient engine technologies or a switch in engine type (e.g. combustion-based vs electric).

Source		Year	BRA	EU	IND	CHN	IDN	ZAF	USA
IEA	Mobility Model	2017			х	х	х	х	х
IEA	Global EV Outlook	2018	Х	Х	Х	Х	Х	Х	Х
IEA	ETP - B2DS	2017	Х	Х	Х	Х	Х	Х	Х
ICCT	Roadmap	2017	Х	Х	Х	Х	Х	Х	Х
BTS - Bureau of Transportation Statistics	U.S. Automobile and Truck Fleets by Use	2019							х
EPA - Environmental Protection Agency	Emissions & Generation Resource Integrated Database (eGRID)	2018							Х
ICCT	A Next Phase Passenger Car Efficiency Program in Brazil	2017	х	Х	х	х	х	х	х
EEA	Electric vehicles as a proportion of the total fleet	2019		Х					
EEA	Pocketbook	2019		Х					
EEA	CO2 Emissions Intensity Grid	2019		Х					
Sindipecas Abripecas	Relatorio da Frota Circulante	2019	Х						
CCFA	Commité des constructeurs francais d'Automobiles	2014			Х	х	Х		
DATA.GOV.IN	Open Government Data India - Total Number of Registered Motor Vehicles in India during 1951-2013	2014			х				
ADB - Asian Development Bank	Indonesia's Summary Transport Assessment	2016					х		

#### Table 4-1: Main Data Sources used within Bottom-Up Mode

The detailed process is presented in following figure:



Figure 4-2: Methodology for EV shares benchmark and LDV passenger carbon intensity.

National sources have been prioritised for historical data selection. However, data availability differs widely from one country to another and whenever national data is unavailable, historical data has instead been extracted from third party studies (IEA, 2018).

In the case of Indonesia, the Light Duty Vehicle Emissions as well as the passenger kilometres used to optimise the model have been derived by using the results of ASEAN region from the B2DS transport summary as a proxy. The input values of energy consumption are derived by downscaling the transport sector from the ETP - B2DS 2017 for Indonesia using SIAMESE, described above. Results of this model approach are provided in the "Flex model benchmark" column (see Table 4-2. EV share in stock (% of total LDV fleet).

# 4.2.3 Bottom-up EV-model

Alternatively, the benchmarks for the transport sector take into account modelling from this study as well as previous CAT evaluations. The Scaling-Up Climate Action series uses the PROSPECTS scenario evaluation tool for the quantification of sectoral and total emissions trajectories until 2050. The analysis of accelerated climate action in, among others, the transport sector for each country identifies value ranges of relevant indicators in different scenario categories '1.5°C Paris Agreement-compatible benchmarks', 'Applying best-in-class level(s)', and 'National scenarios'. These indicators serve as direct input into the PROSPECTS scenario evaluation tools in the respective sectors from which was derived emissions trajectories for the respective scenario. For the purpose of this study, we use the benchmarks defined within the scenario '1.5°C Paris Agreement-compatible benchmarks' (Climate Action Tracker, 2018c). Benchmarks based on this approach are provide in the column "EV model share".

The Paris Agreement-compatible benchmarks for these indicators reflect the range of values for these two approaches in the chosen interval years (2030, 2040, 2050).

## 4.2.4 Electric vehicle stock share Percentage of electric vehicles in total fleet

To reach decarbonisation by 2050, sales of new passenger vehicles must be globally zeroemissions by 2035 (Kuramochi et al., 2018). The benchmark assessed here is the share of Electric Vehicle (EV) and is defined as the number of EV light duty vehicles (LDVs) such as passenger cars expressed as the % of overall LDV fleet. For India. Indonesia and China, we also included twowheelers and three-wheelers since those have a significant share in the LDV numbers, while for other countries shares of two or three-wheelers are insignificant. Two and three-wheelers follow the definition of the IEA mobility model (MoMo) powered two-wheeled vehicles including motorcycles, shooters and rickshaws. For the whole analysis, we assume that the share of electric vehicles is evenly spread among all different types of LDVs. Our definition of EVs includes only battery electric vehicles (BEVs), since for plugin-hybrids the emissions mostly depends on the usage and a clear contribution to decarbonisation is unclear.

Our results show that the European Union should have more than half of its light duty vehicle fleet composed of electric vehicles by 2030, when China and USA will have more than 65% of their fleet composed of EVs by 2040. The EV penetration of India and China is tightly linked to the carbon intensity of the grid: ICEVs become less carbon intensive in both countries in the 2030s, which means the sooner the power sector is decarbonised, the quicker EV penetration will have an impact on the decarbonisation of the transport sector in both countries. On the contrary, as Brazil is highly reliant on hydropower, the carbon intensity of its grid is much lower relative to other countries, thus a rapid uptake of EVs could significantly accelerate the decarbonisation of the transport sector. However, the use of biofuels in its fleet is expanding considerably over time, reducing the carbon intensity of its ICEVs, which slows down the need for EV uptake.



#### Table 4-2. EV share in stock (% of total LDV fleet)

	EV share in stock % of total LDV fleet									
Country	Үеаг	Flex model benchmark	EV model benchmark	DDPP 2°C	Teske 2919	PA Final Benchmark	Comments			
	2030	21%	41%			20-40%				
Global	2040	66%	90%			65-90%				
	2050	86%	100%			85-100%				
	2030	32%	40%	-	30%*	30-40%				
USA	2040	67%	90%	-	-	70-90%				
	2050	84%	100%	60-90%	80%*	85-100%				
	2030	53%	40%	-	26%*	40-55%				
EU	2040	85%	89%	-	-	85-90%				
	2050	95%	100%	-	85%*	95-100%				
	2030	21%	40%	-	-	20-40%				
Brazil	2040	52%	90%	-	-	50-90%				
	2050	76%	100%	46%	-	75-100%				
	2030	15%	53%	-	22%	15-55%	- 1-1			
India	2040	69%	96%	-	-	70-95%	I wo and I hree-			
	2050	86%	100%	-	82%	85-100%	wheeler included			
	2030	33%	52%	-	45%	35-50%	The second The second			
China	2040	62%	96%	-	-	65-95%	I wo and I hree-			
	2050	79%	100%	60%	85%	80-100%	wheeler meludeu			
	2030	28%	49%	-	5%*	30-50%				
South Africa	2040	61%	95%	-	-	60-95%				
	2050	83%	100%	15%	50%*	85-100%				
	2030	13%	47%	-	-	10-45%	Two and Three-			
Indonesia	2040	47%	95%	-	-	45-95%	wheeler included			
	2050	69%	100%	30%	-	70-100%				

\* Regional benchmark



#### **4.2.5** Electric vehicle sales share Percentage of electric vehicles in annual sales

The benchmark assessed here is the share of Electric Vehicle (EV) sales and is defined as the sales of EV light duty vehicles (LDVs) such as passenger cars expressed as the % of overall LDV sales. This benchmark is derived using the same model approaches as EV stock share in the previous section.



<b>EV share in sales</b> % of annual vehicle sales										
Country	Year	Flex Model benchmark	EV-model benchmark	IEA B2DS	GEVO 2019 EV30@30 Scenario	GEVO 2019 NPS Scenario	PA Final Benchmark	Comments		
Global	2030	75%	95%				75-95%			
	2040	100%	100%				100%			
	2050	100%	100%				100%			
USA	2030	98%	95%	-	50%	26%	95-100%			
	2040	100%	100%	-	-	-	100%			
	2050	100%	100%	97%	-	-	100%			
EU	2030	100%	95%	-	50%	26%	95-100%			
	2040	100%	100%	-	-	-	100%			
	2050	100%	100%	96%	-	-	100%			
Brazil	2030	47%	95%	-	-	-	45-95%			
	2040	87%	100%	-	-	-	85-100%			
	2050	97%	100%	-	-	-	95-100%			
India	2030	77%	95%	-	29%	-	80-95%	Two and Three-		
	2040	100%	100%	-	-	-	100%	wheeler		
	2050	100%	100%	93%	-	-	100%	included		
China	2030	100%	95%	-	70%	57%	95-100%	Two and Three-		
	2040	100%	100%	-	-	-	100%	wheeler		
	2050	100%	100%	95%	-	-	100%	included		
South Africa	2030	51%	95%	-	-	-	50-95%			
	2040	89%	100%	-	-	-	90-100%			
	2050	98%	100%	-	-	-	100%			
Indonesia	2030	97%	95%	-	-	-	95%	Two and Three-		
	2040	100%	100%	-	-	-	100%	wheeler		
	2050	100%	100%	-	-	-	100%	included		

#### Table 4-3. EV share in sales (% of annual vehicle sales)

\* Regional benchmark

#### Some considerations:

- The proposed benchmarks presented in the table above have been rounded to the nearest five. The limited data availability and limited country-specific projections based on current developments requires several historical datasets to be combined and thus raises the uncertainty of the results. The benchmarks indicated propose thresholds allowing to decarbonise the transport as aligned with the B2DS scenario and given decarbonisation of the grid and given assumption transportation indicators (km per car, km per passenger, fleet growth etc.).
- In the case of Indonesia, the benchmarks are proposed in ranges as the uncertainty is greater due to the use of the ASEAN region as proxy to downscale the energy consumption for the transport sectors for Indonesia.

#### **4.2.6 Emissions intensity of land-based transport** g CO<sub>2</sub> / passenger kilometre

In 2015, the majority of global total passenger-km (pkm) in passenger transport (around 85% of total pkm) is attributed to road transport modes. By contrast, freight transport is largely operated by rail (Teske et al., 2019). The benchmark proposed here is the carbon intensity per pkm and is defined as emissions (in gCO<sub>2</sub>) per pkm travelled by cars, two and three wheelers (only in the case of China, Indonesia and India), buses, and rail transport.

The emissions per pkm for light duty vehicles are derived from the previously defined benchmarks (EV shares) and the emissions per pkm for buses and rails are derived from the IEA ETP – B2DS (IEA, 2017).

#### passenger transport g CO<sub>2</sub> / pkm Brazil China **EU-28** • India Indonesia South Africa 🔰 USA World 🕀

**Emission intensity of land-based** 

2040 2045 2050

Emissions intensity of land-based transport g CO <sub>2</sub> / pkm								
Country	Үеаг	EV model	SU model	EWG & LUT	PA Final Benchmark			
	2030	60	45	34	35-60			
Global	2040	30	15	0	0-30			
	2050	10	0	0	0-10			
	2030	100	95	48*	50-100			
USA	2040	40	20	8*	10-40			
	2050	5	0	0	0**			
	2030	50	50	48*	50			
EU	2040	15	10	7*	5-15			
	2050	0	0	0	0			
	2030	40	30	29*	30-40			
Brazil	2040	20	5	5*	5-20			
	2050	5	0	0	0**			
	2030	35	20	18*	20-35			
India	2040	20	5	4*	5-20			
	2050	10	0	0	0-10			
	2030	40	35	26*	25-40			
China	2040	15	5	4*	5-15			
	2050	5	0	0	0-5**			
	2030	70	60	28*	30-70			
South Africa	2040	30	10	4*	5-30			
	2050	10	0	0	0**			
	2030	32	39	25*	25-30			
Indonesia	2040	20	10	4*	5-20			
	2050	10	0	0	0-10			

#### Table 4-4. Emissions of land-based passenger transport per km (LDVs, Buses, Rails)

\* Regional Benchmark

\*\* Benchmark set to zero due to high share of zero emission fuels (see zero-emission fuel share benchmark)

#### **4.2.7** Share of zero emissions fuels in the transport sector Percentage of final energy demand in transport sector

For each scenario and country, the **share of zero** emissions fuels (biofuels, electricity and hydrogen) of the total (domestic) transport sector demand of final energy. This excludes international aviation and shipping, but includes domestic rail, road, shipping, and aviation. The benchmarks are derived from scenarios that provide the required level of data granularity (transport sector fuel share). This includes four 1.5C compatible IAM pathways<sup>15</sup> and the B2DS from the IEA. Each scenario is downscaled from the regional-level sector pathway, as described in previous sections. In the benchmark synthesis of land-based emissions per pkm in the year 2050, we considered additional benchmarks from the EWG&LUT study of zero-emissions fuel shares in the transport sector.

We account for the fact that aviation and shipping are included in domestic transport emissions in IAMs by assessing benchmark ranges differently for high-values of low-carbon transport fuel use (>85%). As an example, in the B2DS, 35% of total transport energy use in 2050 is consumed by land-based transport, with the remaining consumption in aviation and heavy freight. We therefore assume that at such a high value of low-carbon fuel use in transport as whole, any *non-low-carbon* fuels will be consumed by the freight and aviation subsectors. In other words, once results derived by IAMs reach this threshold, we assume the road transport uses entirely low-carbon fuels.

The final Paris Agreement-compatible benchmarks are defined as the range between the IAM- based benchmarks and the benchmarks from the EWG&LUT study benchmarks.



<sup>15</sup> MESSAGE-GLOBIOM\_1.0 - SSP1-19 MESSAGE-GLOBIOM\_1.0 - SSP1-19 MESSAGE-GLOBIOM\_1.0 - SSP2-19 IMAGE 3.0.1 - IMA15-LIStCh

IMAGE\_3.0.1- SSP1-19

#### **Results:**



Figure 4-3. Share of zero-emissions fuels in the transport sector - Benchmarks ranges and historical data

Share of low carbon fuels in the transport sector (Electricity-hydrogen+biofuels) % of final energy demand								
Country	Үеаг	IAM results	IEA B2DS	EWG LUT	PA Final Benchmark			
	2030	15%	15%	15%	15%			
Global	2040	40%	35%	60%	40-60%			
	2050	70%	60%	96%	70-95%			
	2030	20%	-	16%*	15-20%			
USA	2040	45%	-	59%*	45-60%			
	2050	75%	70%	96%*	75-95%			
	2030	20%	20%	16%*	15-20%			
EU	2040	55%	40%	59%*	55-60%			
	2050	88%	64%	96%*	80-100%			
	2030	30%	-	28%*	30%			
Brazil	2040	60%	-	63%*	60-65%			
	2050	85%	90%	93%*	85-95%			
	2030	15%	-	20%	15-20%			
India	2040	45%	-	61%	45-60%			
	2050	75%	55%	93%	75-95%			
	2030	15%	-	21%	15-20%			
China	2040	35%	-	63%	35-65%			
	2050	70%	60%	95%	70-95%			
	2030	20%	-	22%	20%			
South Africa	2040	50%	-	59%	50-60%			
	2050	80%	50%	87%	80-90%			
	2030	20%	-	23%	20-25%			
Indonesia	2040	55%	-	60%	55-60%			
	2050	80%	-	92%	80-90%			

Table 4-5 Share of zero-emissions fuels in the transport sector (Electricity-hydrogen+biofuels)

\* Regional Benchmarks

# 5 Industry

As for other sectors, we used a combination of global models and sectoral tools to derive the benchmarks for the industry sector. Only limited analysis from global models is available for industry as most of those models do not model industry sub-sectors explicitly, but rather industry as a whole. Rather than look at all industry sub-sectors we focus on just two: **cement and steel**. For these two sectors we define **emissions intensity** benchmarks mainly using a bottom-up approach using inhouse analysis and calculation tools. The third benchmark for the industry sector is the **electrification rates** required for industry as a complete sector, for which we draw on insights from global IAMs.

## **5.1 Cement** kg CO<sub>2</sub>/tonne cement

The indicator assessed for cement is emissions intensity in terms of product produced –  $kg CO_2/tonne$  **cement**. The indicator considers production of traditional cement and novel cements. It does not account for material substitution nor efficiency. By focusing on the emissions intensity of the final product of cement, we analyse the possibilities for a production pathway compatible with the Paris Agreement. Further, it allows for the identification of the extent to which material substitution and efficiency is needed. The analysis of emissions intensities allows for a clear comparison between countries and regions.

Benchmarks for the cement industry are based on technological potential for mitigation and country specific circumstances. Benchmarks were defined by identifying key mitigation options, collating national data and analysing technical potential at the national level using a simple spreadsheet tool that accounts for uptake of various technologies and improvements.

# 5.1.1 Background

#### Origin of emissions

The benchmarks represent emissions reduction potential based on technical potential in combination with country-specific challenges and opportunities. Our first analytic step is to identify the current major sources of emissions and their corresponding mitigation options.

Cement emissions are dominated by those from clinker production (Figure 5-1), corresponding for about 90% of cement production emissions (Energy Transitions Commission, 2019a). The production of clinker requires high temperatures, traditionally produced from the burning of fossil fuels. In addition to that, the chemical process of calcinating limestone when producing clinker generates process emissions. Process emissions contribute to about 50% of cement emissions, while the burning of fossil fuels for thermal heat typically accounts for more than 40%. The remaining share of emissions come from indirect energy use (power consumption), which depend on the electricity fuel mix.



Figure 5-1. Flowchart of cement emissions and mitigation options

# 5.1.2 Methods

Here we explain the stepwise process of how we arrive at the final benchmarks. In a first step, key mitigation options are identified and assessed, followed by national historic data collection. Based on that, country-specific analysis is conducted.

#### Key mitigation options

Considering the significant share of cement emissions originating from clinker production (about 90%), key mitigation options aim at reducing the demand for clinker, which we refer to as the clinker-to-cement ratio (CCR), indicating the share of clinker used per part of cement.

#### **Clinker substitution**

One already established and widely applied method for reducing the CCR is through the use of clinker substitutes. Globally, current cement production has an average CCR of 75% (CSI, 2016a). Traditionally, examples of common clinker substitutes are fly ash and slag which allows for CCR as low as around 60% (achieved in China) (Wei, Cen, & Geng, 2018; Xu, Yi, & Fan, 2016), depending on required quality of the cement. However, since fly ash and slag are rest products from coal-fired power generation and steel production, their use in cement production in the mid- and long-term is not 1.5-compatible. More promising options exist, one of them being calcined clays combined with limestone, which could reach CCR levels of 40-50%, depending on required quality. Global availability of clay is abundant and found across the globe. The process still requires heat, but at significantly lower temperatures than for clinker production (ECRA, 2017a; Lehne & Preston, 2019a). Other options for clinker substitutes exist, with varying raw material availabilities and CCR reduction potential.

#### Decarbonisation of the thermal energy mix

By switching fuels used for heat generation, shifting away from fossil fuels to alternative fuels (AF), emissions can be significantly reduced. Some of the options, such as biomass and waste, are already being used, while other options, such as electric kilns and hydrogen, are not yet commercialised (Chan et al., 2019a).

Even though biomass for heat generation could technically replace 100% of fossil fuels, its use is restrained by the availability of sustainable biomass (Energy Transitions Commission, 2019a). Currently, highest rates of AF in the thermal energy mix, reaching 60% on average and up to 95% for individual plants, are seen in the EU (ECRA, 2017b). Also wastes of different kinds can be used for heat generation, ranging from municipal solid wastes and sewage sludge to industrial wastes.

The electrification of clinker kilns should technically be possible but faces some significant challenges. Firstly, the technology is not yet fully developed, and once it is, it will require significant amounts of clean power to reach and maintain the high temperatures. Similarly, hydrogen is being considered as a low-carbon fuel option but is also still at an early stage in terms of technology and market development (Material Economics, 2019a). Generally, with regards to decarbonisation of the thermal energy mix, it is important to keep in mind that this could only solve part of the problem. Even if the thermal energy mix were completely decarbonised, process emissions will still remain and would have to be combined with CCS or CCU to become carbon neutral.

#### **Novel cements**

Novel cements, or alternative binders, is the only mitigation option that offers the possibility of cement production that is completely independent of clinker. By using combinations of alternative raw materials as the binding component, the need for clinker as a binding agent is eliminated. There is a wide range of alternative binders under development, of which very few are yet commercialised. Their mitigation potential relative to traditional Portland cement varies from 10%, to alternative binders which could even absorb  $CO_2$  from the atmosphere (Lehne & Preston, 2019b). However, for novel cements to become successful, some key barriers need to be overcome, requiring significant research and development of pilot and large-scale demonstration projects, but also in terms of updating cement standards (Lehne & Preston, 2019b).

#### Carbon Capture and Storage and Usage

Carbon Capture and Storage (CCS) and/or Carbon Capture and Usage (CCU) is likely to be a necessary mitigation option for the cement industry.

Capturing CO<sub>2</sub> from cement production is somewhat more problematic than other sectors. Firstly, the exhaust gas has a relatively low concentration of CO<sub>2</sub>, which makes the capturing of it more complex and expensive. Through oxy-fuel technology an almost pure CO<sub>2</sub> stream of exhaust gas could be achieved, however this technology is still in the research/early pilot phase (ECRA, 2017b; Fleiter, Herbst, Rehfeldt, & Arens, 2019). At this stage, it has not yet been possible to capture all emissions; the highest achieved capture rate so far has been around 90%, making CCS only a near-zero emissions technology.

A second challenge for CCS is the transportation and storage of captured CO<sub>2</sub>. Cement plants are commonly located close to the geographical end-use location and are often not easily accessed. Possible storage locations vary significantly across regions, which further complicates transportation issues, requiring expansion of gas infrastructure. Questions around possible leakage issues and long-term storage can also be discussed.

If the discussed challenges could be overcome, CCS/U could play an important part in reducing emissions from the remaining clinker production, after having done what is possible in terms

oreducing the clinker demand. By combining CCS with low-carbon thermal energy fuels, an almost net-zero cement production could then be achieved.

#### Other mitigation options

Apart from the key mitigation options already discussed, further emissions reductions could be achieved through energy efficiency and the application of best available technology (BAT), including waste heat recovery and on-site power generation (ECRA, 2017b). As mentioned, additional mitigation options are material substitution and efficiency. These are further discussed in the assumptions section.



Figure 5-2. Mitigation measures in the cement sector and their corresponding indicators used in the bottom-up modelling

#### Constructing the model

Once the options for mitigation have been identified and assessed, they are linked to a quantifiable indicator (Figure 5-2) that can be incorporated into the excel tool. Historic data is collected for each country in terms of state of technology, thermal fuel mix and CCR to give a starting point for the model. This starting point plays an important role in how quickly best level practice levels can be reached.

In addition to the historic data, regional and country-specific projections are collected and compared to make an assessment of what is possible when considering country-specific limitations, such as availability of biomass and clinker substitution. Best practice examples set standards for what can be obtained in terms of energy efficiency.

Based on collected data and information, country-specific assessments are made to decide characteristics and achievements towards 2030. Equal levels of ambition are applied towards 2050, based on anticipated technology development and assumptions on technology market penetration rates for new and speculative technologies as well as for the energy supply mix. The final emissions intensity is calculated by multiplying the combined fuel emissions intensity by the final energy demand per tonne of cement, added with process emissions intensity, indirect emissions and CCS capture rate.

#### Main data sources

Historic data is collected from *Getting the Numbers Right* (GNR), a WBCSD initiative with global coverage (CSI, 2016b). The dataset has various levels of coverage across countries but is sufficient to be used as an estimate. Where needed, that data is complemented with inputs from individual studies.

Technical state of the art and current best practices are mainly collected from a few key studies including Material Economics study *Industrial Transformation 2050* (Material Economics, 2019b), Chatham House study *Making Concrete Change Innovation in Low-carbon Cement and Concrete* (Lehne

& Preston, 2019b), the EU Calculator (EUCalc, 2019), the Energy Transitions Commission study *Mission Possible* (Energy Transitions Commission, 2019a), ISI Fraunhofer study *Industrial Innovation: Pathways to deep decarbonisation of Industry* (Fleiter et al., 2019; ICF Consulting Services Limited & Fraunhofer ISI, 2019), Napp et al. study *The role of advanced demand-sector technologies and energy demand reduction in achieving ambitious carbon budgets* (Napp et al., 2019a) and the European Cement Research Academy synthesised technology paper *Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead, Revision 2017* (ECRA, 2017b). In addition to those, input has been provided by industry experts.

# 5.1.3 Key Assumptions

Here we explain the key assumptions underlying the model and explain our reasoning for the parameters chosen to define the benchmarks.

#### Biomass

From a completely technical perspective, it is possible for a clinker kiln to be fed by 100% biomass. In Europe, there are individual plants that have reached levels of 95% (ECRA, 2017b). However, it is important to stress other limitations referring to available amounts of sustainable biomass. There is high uncertainty when it comes to estimating how much sustainable biomass can be produced, which certainly is not unlimited. In addition, competition for this resource among other sectors is likely to further limit its use in the cement sector. In a study by the Energy Transitions Commission, it is estimated that about 20% of global energy demand for cement can be sustainably met from biomass by mid-century (Energy Transitions Commission, 2019a).

In (ECRA, 2017b) it is estimated that alternative fuels could supply 60% of cement production energy demand for cement in developed countries by 2050, also including wastes. In our analysis, we assume a similar level for all countries, assuming that waste management and collection will improve. Further, we assumed that about 50% of the alternative fuels mix consists of biomass, translating into 30% of the total energy demand. This is 50% higher than estimated in other work (e.g., Energy Transitions Commission, 2019b). We reason that biomass should be prioritised in hard to abate sectors, such as the cement industry.

It should also be stressed that we do not consider biomass to be a completely net-zero emitting fuel, taking into account emissions caused by land-use change. We have therefore applied a reduced emissions factor based on recommendations from a set of studies that goes deeper into this (Birdsey, Duffy, & Smyth, 2018; Johnson, 2009; Pichs Madruga et al., 2012; Valin, 2015). After doing so, we end up using an emissions factor that is 90% lower than gross emissions from biomass.

#### **Clinker substitutes**

Clinker substitution is an already proven and used mitigation method and is used to various extents in different regions across the world. China are leaders in this respect, achieving an average national clinker-to-cement ratio of 58% in 2017 (Wei & Cen, 2019). Such low levels have been realised thanks to high availability of fly ash from coal-fed power generation and slag from coal-based steel production. On the other side of the spectrum, countries like the USA have an average clinker-tocement ratio of about 90% (CSI, 2016b).

A range of emerging clinker substitutes are becoming available and increasingly used, of which one with most promising potential is a combination of calcined clay and limestone, also referred to as LC3 (Scrivener, 2019). With this, clinker-to-cement ratios of 50% can be reached, and even 40% has been achieved in a laboratory environment (Global Cement, 2019). The raw materials required for the production of LC3 cement is abundantly available across the globe. A certain level of thermal energy is still required for the calcination of the clay, however, it is much lower compared to that required in clinker production (600 and 1350 DC respectively). The fact that the process does not produce any

process emissions makes it possible to fully decarbonise, under the requirement that the thermal fuel mix is zero carbon.

In our analysis, it is assumed that clinker-to-cement ratios are improved rather rapidly, with the reasoning that it does not require investment in new technology but is rather a matter of collecting substitution materials. It is assumed that countries can achieve a clinker-to-cement ratio of 55% by 2030, using available stocks of fly ash and slag, while gradually developing methodologies for new substitution materials such as LC3. We assumed that a level of 50% should be reached in 2050.

#### Alternative binders

Shifting to alternative binders is one of the main mitigation measures in our analysis, but is simultaneously one of the main areas of uncertainty. There is a wide range of possible alternative binders, of which only one has been commercially proven (Lehne & Preston, 2019b). In this study we consider six different types of alternative binders, all with different emissions reduction potential. Some of these are limited by natural resource availability and some have not yet been proven to be producible at scale.

Other limitations regarding alternative binders relate to standardisation and resistance from consumers (Lehne & Preston, 2019b). The level of these limitations is unclear, illustrated by the variations in market penetration assumptions across different studies. To mention a few examples, the EU Calculator estimates that, in a very ambitious and transformational scenario, 20% of demand can be met by novel cements in 2050 (EUCalc, 2019). ECRA on the other hand, estimates that novel cements will only be able to supply "a few percent" of production of total production by mid-century (ECRA, 2017b). On the more optimistic side, studies like (Fleiter et al., 2019) assume levels of 50%. In our analysis we have chosen to take a rather optimistic view, but simultaneously communicating uncertainties and limitations, ending up at 30% of production in 2050, as a result from a combined bottom-up and top-down approach.

#### CCS

The fact that the production of cement includes both energy-related and process emissions complicates the decarbonisation of the sector. Completely decarbonising the thermal fuel mix will not affect the process emissions, which can only be targeted either through avoiding clinker production or by capturing the emissions. According to our analysis, there will still be a certain demand for clinker in 2050, which is why we also must investigate CCS possibilities (ECRA, 2017b; Fleiter et al., 2019).

At this stage, it has not been possible to capture all emissions; the highest achieved capture rate so far has been around 90%, making CCS only a near-zero emissions technology. In our analysis we have therefore assumed that a capture rate of 95% can be reached.

The potential risk in highlighting CCS as the one solution may dampen efforts in other solutions. In our analysis, we have taken discussed limitations into account (see Key mitigation options, section 5.1.2) and, to emphasise the uncertainties with regards to the success of CCS, analysed two different scenarios with different levels of CCS capture rates. The scenario taking a more sceptical view on CCS is based on the EU Calculator ambition level 4, which is based on a B2DS scenario (EUCalc, 2019). On the more pessimistic side among reviewed sources is ECRA which estimates that, in a very ambitious scenario, about 20% of production could be equipped with CCS, reaching 33% in an unrealistic scenario (ECRA, 2017b). However, to not surpass B2DS level, we assumed a level of 65% of plants equipped with CCS in our first scenario.

In a second scenario considered a future where CCS in cement production will be more successful. Drawing from studies investigating pathways towards net-zero cement, we assumed a level of 80%. In some of the reviewed studies, even higher rates are found (Fleiter et al., 2019; Material Economics, 2019b). However, in those cases, a top-down approach is taken, investigating the need of CCS to

achieve net-zero. Considering some of the challenges that CCS technology for cement production is facing, we would not confidently expect CCS to be applicable to 100% of cement plants, which is our reasoning behind a rate of 80% in the second scenario.

#### Thermal electrification

An additional area of uncertainty in terms of technical potential is the possibility to generate required thermal energy from electricity. Technically, it should be possible, but so far electric kilns are only in the research phase. If proven successful this would require substantial refurbishment of existing kilns (Energy Transitions Commission, 2019a). In our analysis we have assumed the highest level of ambition assumed in the EU Calculator, reaching 34% of thermal energy supply met from electric kilns in 2050.

#### **Material substitution**

One important factor with significant mitigation potential is the material efficiency and reduction of demand. Depending on the end-use, there are various options to replace cement with other materials. One example is the use of wood in buildings. This parameter is outside of the scope of this study. As we analyse emissions intensity of cement production, other materials are not considered in the product mix. Nevertheless, we stress this as an additional option for further reduction of emissions.

			2050		
Mitigation parameter	Unit	Developing	Emerging	Developed	All
Clinker-to-cement ratio	% (t SCM / t cement)	55%	55%	55%	50%
Energy efficiency (thermal)	GJ / t clinker	3.3 - 3.5	3.3 - 3.5	3.3 - 3.5	3.0 - 3.3
Alternative fuels share	(CJ / CJ) %	15 - 20%	20 - 43%	40 - 45%	55-60%
Electric kilns (electrification of thermal demand)	(CJ \ CJ) %	3%	4%	6%	34%
RE H2 (thermal)	(LD / LD) %	0.4%	0.5%	0.9%	6%
Novel cements	% (t novel / t cementitious)	2%	3%	5%	30%
CCS (low/high)	% plants equipped	10% / 12%	10% / 12%	10% / 12%	65% / 80%

#### Table 5-1. Key assumptions made in bottom-up modelling analysis

#### Table 5-2. Explanation of key assumptions

Mitigation parameter	Source/comment
Clinker-to-cement ratio	In the short term, countries with coal-fired power generation and coal-based steel making are assumed to use fly ash and slag to increase SCM share in cement production. Gradually, coal-fired power generation and coal-based steel making is phased out while new supplementary cementitious material (SCMs) are developed an increasing used, such as calcined clay combined with limestone (Global Cement, 2019; Lehne & Preston, 2019b).
Energy efficiency (thermal)	Developing and emerging economies are in front - better starting point. Best practice level is approximately 3.0 GJ/t clinker (Chan et al., 2019b). An increased use of biomass leads to an increased energy consumption due to higher moisture content in biomass (ECRA, 2017b).
Alternative fuels share	Based on estimates for developed countries in ECRA (ECRA, 2017b; EUCalc, 2019). It is assumed that all countries can reach such level. It is limited by sustainable biomass supply. Assumptions in this study surpasses estimates of sustainable biomass availability in ISI Fraunhofer study (Fleiter et al., 2019).
Electric kilns (electrification of thermal demand)	Assumption in 2050 corresponds to EU Calc ambition level 4 (EUCalc, 2019). High uncertainty as technology is not yet proven and faces significant market introduction barriers (Energy Transitions Commission, 2019a).
RE H2 (thermal)	Assumption in 2050 corresponds to EU Calc ambition level 4 (EUCalc, 2019). According to input from industry experts, hydrogen in cement production does not seem very promising.
Novel cements	Assumed to be 50% higher than EU Calc ambition level 4 for all countries. Few novel cements types are commercialised and faces various challenges. Nevertheless, it seems likely that some will be successful. Even if successful, some novel cement types are limited by natural resource availability (Chan et al., 2019b; Energy Transitions Commission, 2019a; Lord, Jones, & Sharma, 2017; Material Economics, 2019b).
CCS (low/high)	CCS coverage rates are analysed; one lower and one higher. The lower level corresponds to EU Calc ambition level 4, reaching 65% of plants equipped with CCS in 2050 (EUCalc, 2019). The higher level assumes a coverage rate of 80%, inspired by more ambitious studies (Fleiter et al., 2019; Material Economics, 2019b). In both analyses, CCS is assumed to reach a capture rate of 95% (Material Economics, 2019b).

#### Table 5-3. Assumptions on CCS/CCU capture rates and coverage

Scenario	% of plants equipped with CCS in 2050	Capture rate	% of emissions captured	% of emissions captured	Source
			2030	2050	
Low CCS	65%	95%	10%	62%	(EUCalc, 2019)
High CCS	80%	95%	12%	76%	(Fleiter et al., 2019; Material Economics, 2019b; Napp et al., 2019b)

#### 5.1.4 Cement Benchmarks

The model results (Table 5-4) show a moderately slow improvement in cement emissions intensity by 2030 that then accelerates with the majority of emissions reductions achieved between 2030 and 2050. This can partly be explained by an already well-established cement production infrastructure where plants have a long lifetime. Most new technologies are still in the research phase and slowly penetrate the market. As all countries will need to reduce emissions as much as possible by 2050, the results in this year are less scattered as compared to those of 2030.

None of the countries included in the modelling achieves full decarbonisation by 2050. As cement production results in a significant amount of process emissions, full decarbonisation can only be achieved through either CCS technology applied on all cement plants, a complete replacement of conventional cement by novel cements, or a combination of the two. Such transformation is challenging, but difficult to measure due to uncertainties around new technology development.

As already discussed, material efficiency and substitution are additional and important mitigation measures which are not accounted for in this study. Even though production could be reduced, a certain demand for cement will remain, especially in developing countries experiencing high rates of urbanisation and infrastructure expansion. Even so, material efficiency and substitution should be considered as vital mitigation strategies for the cement sector.

Our final benchmarks for the cement sector (Table 5-4) therefore reflect our modelling scenario and include all technical options that are currently considered reasonably viable to reduce the emissions intensity of production. However, efforts to develop novel approaches to reduce total cement emissions are ramping up with additional new ideas currently being trialled that go beyond the intensity indicator assessed here. As all residual CO<sub>2</sub> emissions in 2050 would need to be compensated by CDR, the industry should strive toward zero emissions intensity by 2050. Innovative



approaches, new processes and demand side management may get the industry at or close to this goal.

<b>Cement emissions intensity</b> kg CO <sub>2</sub> / tonne cement						
Country	Үеаг	low CCS	high CCS	% reduction (low CCS)	% reduction (high CCS)	PA Final Benchmark
	2015	615	615			
Global	2030	370	360	40%	40%	40%
	2050	90	55	85%	90%	85 – 90% [100%]¹
	2015	725	725			
USA	2030	345	335	50%	55%	50 – 55 %
	2050	90	55	85%	90%	85 – 90% [100%] <sup>1</sup>
	2015	570	570			
EU	2030	355	350	35%	40%	35 – 40%
	2050	90	55	85%	90%	85 – 90% [100%] <sup>1</sup>
	2015	560	560			
Brazil	2030	365	355	35%	35%	35%
	2050	95	60	85%	90%	85 – 90% [100%] <sup>1</sup>
	2015	570	570			
India	2030	390	385	30%	35%	30 - 35%
	2050	100	60	85%	90%	85 – 90% [100%] <sup>1</sup>
	2015	550	550			
China	2030	405	395	25%	30%	25 - 30%
	2050	90	60	85%	90%	85 – 90% [100%] <sup>1</sup>
	2015	620	620			
South Africa	2030	410	400	35%	35%	35%
	2050	95	60	85%	90%	85 – 90% [100%]¹
	2015	660	660			
Indonesia	2030	420	410	35%	40%	35 - 40%
	2050	90	60	85%	90%	85 – 90% [100%] <sup>1</sup>

Table 5-4. Benchmarks for cement emissions intensities and reductions

1. We set an aspirational benchmark of 100% emissions intensity reduction for all countries that may be achieved with innovative technologies and developments current being researched.

# 5.1.5 Recommendations for the cement sector

As discussed throughout the chapter, decarbonising the cement industry is a challenge and will require significant efforts in terms of investment, research and structural change. The need to find solutions for eliminating emissions from both fuel combustion and chemical processes further complicates the task. According to our benchmark results, reductions of 90% could be achieved by 2050, relative to 2015 levels, by scaling up ambition for every mitigation option. There is no single solution to decarbonising the sector but through combining existing options we reach very low emissions intensities. With additional efforts in material substitution and efficiency, the sector could achieve a net-zero status. In order to achieve this status, some key recommendations for the sector are:

A clinker-to-cement ratio of at least 60% by 2030 and 50% by 2050 should be achieved As informed by the literature review, and demonstrated by our analysis, an important first step is to minimise the demand for clinker and move away from traditional Portland cement. Clinker substitutes such as fly ash and slag can serve as a short-term solution, especially for countries generating a lot of coal-fired power as well as coke-based steel. In the medium to long-term, efforts should be put into developing a market for alternative substitutes such as calcined clay, including the updating of cement standards. According to our analysis, all countries should aim for a CCR of at least 60% by 2030, which should be improved to at least 50% by 2050. This is not only possible, but also would result in reduced expenditures on energy.

#### Increased investment in novel cements

Novel cements will be vital to the achievement of a Paris Agreement-compatible cement sector, but significant efforts are required with regards to investment in research and development, mapping of raw material availability and cement standards. All countries should prepare for such structural change in the sector.

#### Decarbonise the thermal energy mix

To decarbonise the remaining demand for traditional cement, a combination of mitigation measures must be considered, targeting both energy and process-related emissions. The main short-term option for reducing emissions from heat generation is to increase the amount of alternative fuels in the thermal energy mix.

To ensure the sustainability of the alternative fuel mix, caution should be taken with regards to the origin of biomass used. An assessment should therefore be made by each country, where sustainable biomass supply and distribution is planned across sectors. Further, improved waste collection management could provide sustainable fuels to the AF mix.

Based on this, all countries should aim to meet at least 60% of their thermal energy supply in the cement sector with alternative fuels. To fully decarbonise the thermal energy mix, additional options are needed, mainly translating into thermal electrification. From a mid to long-term perspective, investments in research and development for the electrification of the thermal mix should be prioritised.

#### Investment in and planning of CCS/U

Process emissions could only be tackled by a successful CCS/U development. There is an urgent need for research and development, and investments in large-scale demonstration projects. Individual countries should also make assessments of possible storage sites, logistics and transportation options.

#### All clinker kilns compatible with BAT standards by 2030

In terms of energy efficiency, all clinker kilns should be performing according to BAT standards by 2030. That is, the specific energy consumption should not surpass 3.2 GJ/tonne of clinker and should preferably achieve 3.0 GJ/tonne of clinker.

Keeping this in mind, the cement industry should strive to reach net-zero emissions by 2050 by implementing discussed mitigation options and by considering measures to reduce overall demand for cement.



Iron and steel kg CO<sub>2</sub>/tonne steel

As for other sectors we used a combination of global models and sectoral tools to derive the benchmarks. For the steel industry only limited analysis from global models is available, as most of those models do not model the steel sector explicitly, but rather industry as a whole.

We therefore developed a sector-specific analysis for the iron and steel industry, aiming to illustrate technical potential in country-specific contexts. A spreadsheet-based tool was used to analyse different technology routes and their potential to achieve carbon neutral steel production in 2050. Final benchmarks are expressed as **emissions intensities (kg CO<sub>2</sub>/t crude steel)** and are defined for 2030 and 2050. The two main factors determining variations across countries are current technologies used, i.e. the starting point, and the national availability of scrap steel. Apart from the recycling of scrap steel, other material efficiency and demand reduction measures have not been considered within the scope of the benchmarks.

For the electrification component, carbon emissions factors for the power sector are taken from power sector benchmarks outlined above.

# 5.2.1 Background

#### Production routes, origin of emissions and mitigation options

Blast furnace to basic oxygen furnace route (BF-BOF) is the highest emitting production steel route and is also the most commonly used globally today (70% of global production) (World Steel Association, 2019a). The need to reduce iron ore makes it an inherently energy-intensive process. The principal energy source in this process is coking coal which must first be converted into coke, requiring large amounts of energy. Energy efficiency and fuel switching options can only achieve limited emissions reductions as novel technologies are still partly dependent on coal (Bataille et al., 2018; Chan et al., 2019b). Improvements in efficiency have led to reductions of about 60% in energy required, but any further efficiency gains will be small (Lord et al., 2017).

The second most common route uses recycled scrap steel as feedstock. This allows the reduction step to be completely avoided along with the associated process emissions. The route is exclusively electricity-fed and could therefore be fully decarbonised under the condition that the power is produced from clean sources. In terms of energy, the scrap route requires about one third of the energy in the BF-BOF route (Willis et al., 2020). It is limited by the local availability and quality of scrap steel which vary significantly across countries. However, available scrap steel is not fully utilised in most places today (Bataille et al., 2018; ETC, 2019a).

An alternative to the blast furnace is the direct reduced iron (DRI) route, which is a fully commercialised technology. Despite the fact that emissions from the DRI route are significantly lower compared to those of the BF-BOF route, it is only used to a small extent today, supplying about 1% of global steel production (World Steel Association, 2019b). Currently, the use of this route is closely linked with local availability of natural gas, which is the traditionally main reduction agent. After the reduction, pig iron is fed to an Electric Arc Furnace (EAF) (the same as that used in scrap recycling). Natural gas can be replaced by biogas or hydrogen. There is also ongoing research on reduction of iron using electricity as a reduction agent (Bataille et al., 2018; Chan et al., 2019b; EUCalc, 2019). Under the condition that the electricity used for reduction or for producing hydrogen is clean, the DRI route has the potential to achieve full decarbonisation.

As international best practices, national projects in Austria and Sweden are aiming to produce fossilfree steel. The Swedish project HYBRIT aims to develop an existing method of natural gas-based direct reduction to run on pure and clean hydrogen. The Swedish company "Swedish Steel (SSAB) (partly owned by the government of Finland) is aiming at transitioning to zero carbon emissions steel by 2026 through use of hydrogen. This is an important element of the strategy for Finland and Sweden to become carbon neutral by 2035 (Finland) and 2045 (Sweden) (Mazengarb, 2020). Smelt reduction (DRI-smelt) is a novel technology that allows omitting the use of a blast furnace, by reducing iron directly with smelting. Technology project examples include HIsarna, COREX and FINEX (Denis-Ryan, Bataille, & Jotzo, 2016). This technology is still dependent on coal but does not require coking coal which reduces the energy demand. All in all, emissions can be reduced by about 20%, without CCS (Denis-Ryan et al., 2016). However, the high concentration of CO<sub>2</sub> in the exhaust gas makes DRI-smelt technology very suitable for CCS application, which could achieve emission reductions of up to approximately 95% compared to BF-BOF route.

In conclusion, each production route offers different mitigation options. However, only those that can be entirely electrified has the potential to achieve full decarbonisation, i.e. the scrap-EAF route, and DRI with hydrogen or through electrolysis using clean power. The scrap-EAF route is fully commercialised and practiced extensively across the globe. Even so, it could be further improved by recycling more steel and enhancing its quality. Between DRI with hydrogen and electrolysis, the hydrogen technology is far more developed. This technology could also contribute stabilising peaks from VRE power generation (Bataille et al., 2018; Vogl, Åhman, & Nilsson, 2018). The DRI electrolysis route is yet in the research phase and is not expected to enter the market until 2040-2044. The electrolysis route is expected to be more energy efficient than the hydrogen route (Bataille et al., 2018).

Looking beyond technology that can be completely decarbonised, novel technologies that could be almost decarbonised include various smelt reduction techniques. Still being coal dependent, emission reductions are achieved through higher energy efficiency. Fuel switching to cleaner fuels such as biofuel and hydrogen can also be achieved to some extent. However, this route would need to be combined with CCS to significantly reduce emissions.

CCS could also be an option for application on the BF-BOF route, however, it would be more costly and less efficient. To date, capture rates are far lower for the BF-BOF route compared to the smelt reduction route (EUCalc, 2019; McKinsey, 2018).

Our approach to developing the benchmarks in the iron and steel sector is based on a prioritising system where technologies are rated after their respective potential to fully decarbonise. Historical data is used to define a starting point. Calculations are based on assessments made on technology market introduction rates, combined with regional projections on country-specific parameters such as steel scrap availability and power sector emission factors.



Figure 5-3. Steel production routes and mitigation options

# 5.2.2 Methods

Considering the wide range of options there are in terms of technology routes in the steel sector, two certain things can be concluded; first, the optimal technology route for decarbonisation likely differs between countries, and second, there is no one single technology that will bring the sector to netzero on its own. Based on this, we composed two different scenarios to analyse the effects of different routes towards decarbonisation.

One common factor across both scenarios is the recycling rate of scrap steel, which varies across countries depending on the availability of scrap steel. Based on the benefits in terms of energy and material efficiency, as well as the potential for full decarbonisation, that comes with the scrap-EAF route, it was given highest priority in both scenarios when developing the benchmarks. Regional projections on steel scrap availability were collected and downscaled from published results where a steel scrap availability<sup>16</sup> assessment model (SAAM) was used (Xylia, Silveira, Duerinck, & Meinke-Hubeny, 2018). Where available, those data were supplemented by individual reports (Indian Ministry of New and Renewable Energy, 2019; Napp et al., 2019b; World Steel Association, 2019c).

In the first scenario, innovative low-carbon technologies are assumed to become successful, having a specific focus on hydrogen-based DRI and DRI-smelt with CCS, thus significantly increasing the electrification of the sector. An important driving factor in the first scenario is the early phase out of the BF-BOF route, which is completely phased out by 2050, leading to the sector becoming near independent on coke.

<sup>&</sup>lt;sup>16</sup> Scrap availability is referred to as the national available stock of scrap steel to be collected and recycled in the current year.

That is not the case in the second scenario where the BF-BOF route continues to be part of the technology mix and is only phased out in 2070, assuming that all new plants stay active until the end of their lifetime (about 50 years). Due to the current large stock of relatively new BF-BOFs, in particular in the major steel producing country China, there is a risk that new technologies will be disincentivised to avoid stranded assets. Using that as a narrative, the second scenario allows BF-BOFs to serve their complete lifetime. Doing so leaves less emissions reduction potential with production routes, and higher responsibility with CCS technology, which is a major mitigation measure in the second scenario.

CCS technology is used rather aggressively in the second scenario. More specifically, since smelt reduction only brings small emission reductions unless it is combined with CCS (20%), it is assumed that where smelt reduction technology is built, it is likely to be equipped with CCS by 2050. Further, it is assumed that the majority of the remaining BF-BOF plants, and all DRI-smelt plants, are equipped with CCS in 2050. Even though CCS on BF-BOFs yet does not achieve as high capture rates as on CCS with smelting technology, capture rates are assumed to advance to reach a similar level by 2050. While such advancements are made on the CCS technology side, the second scenario expects slower uptake of new low-carbon technologies such as hydrogen-based DRI, although still kept in the technology mix.

In each scenario, technologies are ranked according to the characteristics of the corresponding scenario and are used in that priority order up to a maximum limit. A maximum market penetration rate in 2050, as well as estimated market entrance year for each technology is defined based on literature review-based assumptions and input from industry experts (see provided references in Table 5). New technologies are introduced following an s-shaped curve, from which the market penetration rate in 2030 is identified. The phase-out of BF-BOF plants is determined according to current market share and follows an inversed s-curve towards the phase out year.

In both scenarios, the recycling of scrap steel is highest ranked and therefore always optimised. Following the recycling of scrap steel, the next technology in the ranking system is introduced and increased until its maximum market penetration rate is reached. As long as the demand is not satisfied, new technologies will be introduced in a similar manner. These ranked technologies all complement the demand met through existing BF-BOF plants that are being phased out according to an S-curve. Any remaining BF-BOF plants in 2030 and beyond are assumed to have improved energy efficiency and parts of coke replaced with charcoal.

CCS technology is used rather aggressively in the second scenario. Since smelt reduction only brings small emission reductions unless it is combined with CCS (20%), it is assumed that where smelt reduction technology is built, it is likely to be equipped with CCS by 2050. Further, it is assumed that the majority of the remaining BF-BOF plants, and all DRI-smelt plants, are equipped with CCS in 2050.

#### Data sources

National historic data on technology shares was collected from Word Steel *Steel Statistical Yearbook 2019* (World Steel Association, 2019b). National scrap steel availability was derived from Xylia et. al. *Weighing regional scrap availability in global pathways for steel production processes* (Xylia et al., 2018). Regional projections were scaled down to national as an estimate. Individual projections were used for the US (World Steel Association, 2019d), India (Ministry of New and Renewable Energy, 2019) and World (Napp et al., 2019b).

Mitigation portions, technical state-of-the-art and best practices are mainly collected from a few key studies including Material Economics study *Industrial Transformation 2050* (Material Economics, 2019b), the EU Calculator (EUCalc, 2019), the Energy Transitions Commission study *Mission Possible* (ETC, 2019b) and ISI Fraunhofer study *Industrial Innovation: Pathways to deep decarbonisation of Industry* (Chan et al., 2019b; Fleiter et al., 2019).

# 5.2.3 Key assumptions

The key assumptions behind the both scenarios are explained in detail along with corresponding sources are summarised in Table 5-5 and Table 5-6. BF-BOF traditional refers to coke-fed BF-BOF steel production which have not yet reached BAT energy efficiency performance. BF-BOF overall covers all types of such technology, including BAT, biomass-fed and combined with CCS. The parameter EAF-scrap refers to assumed market shares of EAF-scrap route, which is assumed to be similar to the national scrap availability. DRI-smelt covers all types of smelt reduction technologies. Note that smelt reduction with CCS is only one of the CCS options considered, as CCS is also considered for BF-BOF plants.

	Smelt-DRI CC	:S + H2	BF-BOF w CCS		
Technology	Parameter	Assumption	Priority	Assumption	Priority
BF-BOF traditional	Phased out in (year)	2030	9	2030	3
BF-BOF overall	Phased out in (year)	2050	8	2070	2
EAF-scrap	Market share in 2050	up to 7 - 79% <sup>17</sup>	1	up to 7 - 79% <sup>5</sup>	1
DRI-H <sub>2</sub>	Max market share in 2050	up to 30%	2	up to 15%	4
DRI-Electrolysis	Max market share in 2050	up to 6%	3	up to 6%	5
DRI-biogas	Max market share in 2050	up to 5%	6	up to 5%	8
DRI-natural gas	Max market share in 2050	up to 5%	7	up to 5%	9
DRI-smelt	Max market share in 2050	up to 25%	5	up to 0%	7
DRI-smelt w CCS	Max market share in 2050	up to 45%	4	up to 45%	6

#### Table 5-5. Key technology assumptions in the iron and steel sector model

#### Table 5-6. Steel sector key assumptions' explanations and sources

Technology	Comment
BF-BOF traditional	By 2030, all BF-BOF plants should have a BAT level performance.
BF-BOF overall	Assuming disincentivised by increasing CO2-prices.
EAF-scrap	Varies significantly across regions. Projections from (Xylia et al., 2018).
DRI-H2	Varies significantly in literature. EU Calc ambition level 4 is 15% in 2050. In Napp (2019) 10% in 2050. In material economics CCS scenario, 19% is still met through H2-DRI; corresponding share in their 'New Processes'-scenario is 35% (EUCalc, 2019; Material Economics, 2019b; Napp et al., 2019b).
DRI-electrolysis	Anticipated market introduction in 2040 (Bataille et al., 2018; Denis-Ryan et al., 2016). Anticipated market introduction in 2040 (Bataille et al., 2018; Denis-Ryan et al., 2016).
DRI-biogas	Limited by available supply of biogas and gas infrastructure. Likely to vary across countries. Not expected to play important role, as have been the impression after discussions with steel industry experts (ETC, 2019b).
DRI-natural gas	Generally, depend on national natural gas supply and infrastructure. Not expected to play an important role.
DRI-smelt	Already commercialised and is likely to expand penetration into market in the near-/mid-term as it is highly suitable for CCS application once reaching industrial scale (Bataille et al., 2018; Denis-Ryan et al., 2016).
DRI-smelt w CCS	In Napp et al. (2019), 50% of production is from integrated route with CCS; In Material Economics 'CCS'- scenario, 28%; CCS share in Material Economics 'New processes'-scenario is 9% (Material Economics, 2019b; Napp et al., 2019b). Assumed that all smelt reduction technology installed is equipped with CCS by 2050.

<sup>&</sup>lt;sup>17</sup> Scrap availability varies significantly across countries and regions. The displayed range illustrates the minimum and maximum projected scrap availability among the countries included in this study.

#### 5.2.4 Steel Benchmarks

The final benchmarks for each country are the ranges between the two scenarios modelled by the CAT team, with the exception that we extend the lower range to zero in 2050 for all countries. Some countries will find it more challenging than others to reach zero emissionsintensity but if all technological options were implemented it is theoretically feasible and should therefore be included in the benchmark of "highest plausible ambition".

In addition, we focus here on technical improvements that meet current demand forecasts for steel. Total steel demand could be reduced through substitution with other materials, which would enable the lower emitting production routes (e.g. recycled scrap) to meet a higher share of the demand and bring emissions intensities down further.

Factors affecting variations across countries in 2030 include: (a) share of remaining traditional BF-BOF, which is determined by the starting point, and (b) how quickly the power sector is decarbonised. Countries with the most ambitious ranges are those with higher levels of scrap availability, such as China and the EU, where 100% decarbonisation is achieved in 2050. The benchmarks are less stringent for countries with lower scrap availability, such as South Africa and Indonesia. The model does not include any international trade in steel but rather focuses on domestic production capabilities. International trade could, for example, allow those countries with low scrap metal availability to utilise scrap produced elsewhere.



# Table 5-7. Historic and data and final benchmarks for steel emission intensities

Steel emissions intensity kg CO <sub>2</sub> / tonne steel						
Country	Year	Min	Max	% reduction (min)	% reduction (max)	PA Final Benchmark
	2015	1850	1850			
Global	2030	1335	1350	25%	30%	25 – 30 %
	2050	0	130	95%	100%	95 – 100 %
	2015	1215	1215			
USA	2030	930	945	20%	25%	20 – 25 %
	2050	0	70	95%	100%	95 – 100 %
	2015	1275	1275			
EU	2030	680	700	45%	45%	45 %
	2050	0	75	95%	100%	95 – 100 %
	2015	1460	1460			
Brazil	2030	1305	1390	5%	10%	5 – 10 %
	2050	0	195	85%	100%	85 – 100 %
	2015	2360	2360			
India	2030	1280	1295	45%	45%	45 %
	2050	0	155	95%	100%	95 – 100 %
	2015	1980	1980			
China	2030	1290	1335	35%	35%	35 %
	2050	0	100	95%	100%	95 – 100 %
	2015	2295	2295			
South Africa	2030	1620	1630	30%	30%	30 %
	2050	0	215	90%	100%	90 – 100 %
	2015	1655	1655			
Indonesia	2030	1585	1600	5%	5%	5 %
	2050	0	190	90%	100%	90 – 100 %

# 5.2.5 Recommendations for the steel sector

All countries should aim for a net-zero steel industry by 2050. Our analysis provides a range of different routes to achieve full or near decarbonisation of the steel industry. There is no clear optimal route, but rather something that must be defined on a country-specific basis. Such assessment will depend on parameters such as steel scrap availability, demand projections, existing BF-BOF stock, captured carbon storage possibilities and power sector outlook. If applied at scale, the net-zero technologies proposed will put significant pressure on the clean power production, which is an important parameter that should be part of any net-zero steel industry strategy.

Key recommendations for the sector include:

#### Maximise the recycling of scrap steel

The benefits from maximising the scrap-EAF route are many. Environmentally, from the increased recycling rate and emissions reduction, as well as economically from the reduced energy demand. Jobs could also be created, induced by an improved recycling system. By optimising this route, the investment needed to decarbonise the remaining production could be significantly reduced. Countries with low scrap availability could explore options to import scrap steel.

#### No new BF-BOF plants

To avoid carbon lock-in, no new BF-BOF plants should be built. All other technology options consume less energy and produce lower emissions. Countries with existing BF-BOF stock should (a) improve energy efficiency according to BAT, and (b) prepare mid- and long-term strategies for BF-BOF phase out through either technology shift or refurbishment with CCS.

#### Invest in hydrogen-based steel production

Significant investment is needed in large-scale demonstration projects for the DRI-H2 route. Countries should also develop strategies to ensure sufficient clean power supply to meet projected rise in demand expected from required H2 production.

#### CCS – Planning and R&D

Where demand is not expected to be met from net-zero technologies, near-zero technologies should be considered. That could entail refurbishment of BF-BOF to DRI-smelt plants, including a clear plan for CCS application. More research is required in the CCS-field to improve capture rates and efficiencies.

#### Fuel switch for short-term improvement

In the short term, partial fuel switch to charcoal and/or hydrogen should be considered in the BF-BOF route, as well as biogas in the DRI route.

#### Material switch and demand reduction

Efficiency, in terms of materials as well as energy, should always be a prioritisation. Reducing the amount of steel that is produced allows low-carbon technologies to cover higher shares of the final demand. Apart from improving the recycling of scrap steel further measurements can be taken to reduce the overall demand – for example through material substitution. That would allow low-carbon technologies to cover larger shares of overall production.

# <mark>گ 5.3</mark>

#### **Electrification of Industry** Percentage of electricity in final energy demand of Industry

The cement and steel sectors are sizeable and emissions-intensive components of total industry but achieving decarbonisation of these sectors alone will not achieve the necessary industrial emissions reductions to ensure compatibility with the Long-term temperature goal of the Paris Agreement. This will require reductions across all facets of industry, and one broad-based indicator for benchmarking this is the total industry electrification rate.

Here we provide a top-down approach to deriving benchmarks for whole-of-sector electrification of industry in the chosen countries. These benchmarks reflect the fact that the relative ease of decarbonisation differs across sectors, for example the divergence in plausibility of steep decarbonisation rates in the steel and cement sectors, with no country seen as plausibly decarbonising their industry sector completely by 2050.

In order to achieve decarbonisation through electrification of a sector, a country's electricity system must simultaneously increase its share of non-fossil-based sources of energy. Therefore, two actions must occur in tandem, this benchmark should be twinned with our power system benchmark in order to ensure consistency with the Paris Agreement.

The Paris Agreement-compatible benchmarks for industry electrification are ranges that reflect a synthesis of the values in the chosen interval years (2030, 2040, 2050) of the 75<sup>th</sup> percentile across the Paris Agreement-compatible pathways analysed and the highest level of ambition found to be viable in the relevant literature.

We use regional results from the Teske et al. (2019) study on 1.5°C compatible energy scenarios to inform our electrification of industry benchmark as described in section 2.3.



#### **Results:**

The median and 75<sup>th</sup> percentile pathways for each country are illustrated by the solid and dotted blue lines respectively in Figure 5-4.<sup>18</sup> The values taken from relevant literature are represented by markers in each interval year. The key study utilised as a supplement to the downscaled IAM results is Teske et al. (2019) which provides regional 100% renewable energy scenarios compatible with limiting warming to 1.5°C.



Figure 5-4 IAM-based results for the electrification rate in industry including uncertainty ranges using different IAM model/scenario runs. The diamonds show results of the IEA B2DS scenario for comparison.

As with other sectors, there is a tendency for IAMs to underestimate the potential for high levels of mitigation actions, due to conservative or outdated technological assumptions (e.g. rapid decline in cost of solar PV, battery storage over recent years). For this reason, it is the 75<sup>th</sup> percentile, rather than the median downscaled IAM pathway chosen for inclusion in the benchmark range.

Final electrification rate benchmarks are outlined in Table 5-8 below. There is a clear correlation between countries with higher availability of scrap metal for use in steel production (e.g. China, EU, USA) and those with the highest upper bound in 2050, which, given the use of electricity in the steel recycling process, is to be expected. The exception to this is South Africa, however this can be explained by the already high starting point, near 40-45%, which is significantly higher than the remaining countries.

Of note is the fact that no country is expected to feasibly achieve a 100% electrification rate of their industry sector by 2050, a confirmation of the inherent difficulty in electrifying the cement sector, which is not expected to feasibly surpass 40% electrification by 2050 in any country analysed here, with an average of 34% (see Section 5.1.3).

<sup>&</sup>lt;sup>18</sup> The exception to this is South Africa, where the mean is taken rather than the 75th percentile due to equity considerations.

Share of electricity in Industry % electricity in final energy demand								
Country	Үеаг	IAM pathways mean	IAM pathways p75	ETP B2DS	Teske 1.5°C	DDPP 2°C	Other sources	PA Final Benchmark
	2030	32%	35%	22%	35%			35%
Global	2040	47%	56%	24%	45%			45-55%
	2050	47%	50%	25%	55%			50-55%
	2030	40%	50%	19%	36%*			35-50%
USA	2040	52%	72%	21%	50%*			50-70%
	2050	51%	69%	23%	53%*	33%		55-70%
	2030	49%	58%	24%	42%*			40-60%
EU	2040	60%	77%	24%	45%*			45-75%
	2050	61%	74%	25%	47%*			45-75%
	2030	29%	37%	15%	32%*			30-35%
Brazil	2040	36%	50%	16%	41%*			40-50%
	2050	38%	52%	17%	57%*	38%		50-60%
	2030	32%	39%	19%	34%	20%		35-40%
India	2040	43%	56%	21%	50%			50-55%
	2050	40%	47%	23%	53%	22%	44.5% <sup>19</sup>	45-55%
	2030	50%	57%	27%	45%	26%		45-55%
China	2040	72%	82%	29%	56%	33%		55-80%
	2050	74%	83%	31%	62%	39%%		60-85%
	2030	61%	68%	37%	33%*	43%		45-60%
South Africa	2040	73%	85%	41%	44%*	42%		45-75%
	2050	77%	87%	46%%	55%*	42%		55-75%
	2030	16%	18%		34%*	21%		20-35%
Indonesia	2040	27%	37%		42%*	29%		35-40%
	2050	23%	27%		50%*	35%		25-50%

Table 5-8. Share of electricity in industry

\* Regional Benchmark

<sup>&</sup>lt;sup>19</sup> THE ENERGY REPORT– INDIA 100% RENEWABLE ENERGY BY ,2050, http://awsassets.wwfindia.org/downloads/the\_energy\_report\_india.pdf

# 6 Buildings

# 6.1 General approach and scope

In the buildings sector we define benchmarks for a set of indicators that monitor energy demand and associated emissions from a set of end-use energy services. As with other sectors, our benchmarks are determined from a range of inputs; literature review, a bottom-up model of the buildings sector, and an analysis of 1.5°C compatible scenarios. Here we describe each of those different inputs separately and how they are combined to define the benchmarks.

The indicators included in our analysis are:

- Emissions intensity (kgCO2 / m<sup>2</sup>)
- Energy intensity (kWh / m<sup>2</sup>)
- Renovation rates (% stock renovated / year)
- New building standards (% Zero Emissions Buildings in new stock)

The indicators include all energy demand activities in buildings but exclude energy use and emissions associated with construction. Emissions associated with the construction industry are covered by the cement and steel benchmarks. Energy demand activities therefore include **cooling, heating (space and water), lighting, appliances and cooking**. In many countries, heating and cooling dominate energy demand and emissions, but not in all. Our analysis and indicators therefore include both direct and indirect emissions and we examine the residential and commercial (or services) sectors separately.

#### 6.2 Analysis

Three lines of evidence contribute to the final benchmarks; existing literature and targets, our own bottom-up modelling and analysis, and constraints on 1.5°C compatibility from global integrated assessment models.

# 6.2.1 Literature review

#### Key mitigation options in the buildings sector

Emissions in the buildings sector can be approached both through reductions in energy demand and decreasing the emissions intensity of energy use. Reductions in energy demand can be achieved through improving the efficiency of appliances (e.g. cookers, electrical equipment, lighting) and by reducing the heating and cooling demand of buildings by improving the building envelope. Emissions intensities can be reduced by electrification of heating, cooling and cooking accompanied by reductions in the emissions intensity of electricity supply (see the power sector). Full electrification of the energy supply is not required for full decarbonisation as several good options for on-site zero emissions energy also exist in many places, including solar thermal heating and geothermal heating.

Most of these interventions require action at the individual household level. The average building envelope can be improved through high standards of new buildings but will also require deep renovation of existing buildings. Deep renovation can achieve major reductions in total energy demand for heating and cooling while retaining thermal comfort levels. Similarly, a shift toward zeroemissions technologies will also require replacement of existing equipment in individual buildings. Heat pumps promise to be an effective solution to providing low energy-demand and low emissions for heating and cooling as they are extremely efficient and therefore minimise electricity demand.

#### How far can emissions and energy demand reductions go?

All end-use energy services could be completely decarbonised through known and existing technologies. At present, several cost and policy barriers are slowing this transition, but several studies have already explored the potential extent and pace of decarbonisation within the buildings sector.

For example, Langevin et al. (Langevin, Harris, & Reyna, 2019) found that improvements to the building envelope, building controls and installation of heat pumps provided the largest emissions reductions in the USA's buildings sector and, with these measures, achieved a 72-78% reduction in emissions by 2050.

Several analyses for the EU go even further and explore options for meeting the region's net-zero 2050 target. CLIMACT (Jossen et al., 2018) established a scenario that includes a minimum of 3% renovation rate and an average energy efficiency improvement of 75% by 2030. Such studies have already informed EU policy and through the Energy Performance Buildings Directive (European Parliament and the Council of the European Union, 2018), 3% of publicly-owned building floorspace should be renovated each year and all new buildings from 2020 should be nearly zero-energy.

New and renovated buildings meeting the Passive House standard of heating requirements of less than 15 kWh / m<sup>2</sup> / yr can now be found in many countries (Database, n.d.; Passive House +, 2018). These buildings demonstrate what is possible in terms of building standards and inform our building envelope improvements in our 'low energy demand' scenario (see below).

The IEA has taken a broader and comprehensive look at the buildings sector across all end-use services and countries. In the 'faster transition scenario' electricity shares increase to 53%, new coal and oil-fired boilers are phased-out by 2030, and total emissions from buildings are reduced to 1.2  $GtCO_2$ / yr in 2050 (IEA, 2019b). However, this scenario still includes 12% fossil fuel energy supply to buildings in 2050.

Few existing studies therefore identify pathways to full decarbonisation of the buildings sector by mid-century, but most agree on the most important mitigation actions; substantial improvements to the building envelope of renovated and new buildings, improvements in efficiency of appliances, and shifts toward low-energy, low-emissions heating and cooling technologies, such as heat pumps.

As the building stock in most countries has a long lifetime, early introduction of these standards and technologies is essential to avoid lock-in of high-carbon, high energy demand building infrastructure.

# 6.2.2 Bottom-up model

#### CAT building model

For the purpose of defining Paris Agreement-compatible benchmarks for the buildings sector, the CAT buildings tool has been adapted to include all buildings sector energy demand activities (excluding construction), renovation of existing stock, and emissions from all end-use energy services.

The buildings tool focuses on heating and cooling requirements as these are the dominant energy demand activities in major emitting countries, particularly in temperate climates where both heating and cooling is required.

Energy requirements and emissions are calculated for heating and cooling based on a building stock model that includes existing, renovated, and new buildings. For each building type, the heating/cooling requirements are calculated based on a building envelope factor, the heating/cooling degree days of the country, and the technology mix. Emissions factors are then used to calculate the emissions for each building type and technology mix.

Water heating is also calculated directly in the tool and depends on population (residential) and floor area (commercial). The calculations are not as complex as for heating/cooling but do take changing building stock and technologies into account and improved efficiencies and corresponding reduction in energy demand.

Energy demand from other activities (lighting, appliances, and cooking) are taken from the IEA B2DS scenario. Indirect emissions are calculated according to power sector emissions factors taken from the Paris Agreement-compatible benchmarks, except for cooking where the IEA B2DS scenario is used.

The model was parameterised for each country according to IEA energy use and emissions statistics. The results (e.g. total emissions) for 2015 are therefore fairly consistent with the IEA historic data and the model is therefore useful to explore options from that basis.

#### Mitigation options assessed

The CAT model prioritises mitigation for heating and cooling through **improvements to the building envelope** to reduce energy demand **and shifts toward zero-emission, more efficient technologies.** In practice, this means high renovation rates to improve building envelopes and high standard of building codes for new buildings. In terms of heating technology, there is a shift from fossil-based technologies toward heat-pumps, solar thermal, district heating, and electric heating (with some biomass). The pace of this shift is determined by the rates of renovation and the share of new buildings in the total stock.

We assume that all cooling is, and will be, electric and therefore will decarbonise at the same rate as the power sector.  $CO_2$  emissions from cooling therefore decrease rapidly in the coming two decades. We assume an increase in the share of floor space that is cooled, such that cooling is available in most or all areas where it is desired by 2050. The concurrent increase in energy demand is offset by improvements to building envelopes that minimise cooling needs. We do not explicitly account for increases in demand for cooling due to increasing global temperatures and rather focus on increased access to cooling.

Similar to cooling, our approach to mitigation in water heating also reflects a balance between efficiency improvements and greater access to services. In the residential sector, we assume that water heating demand per person converges to 700 kWh/capita in 2050. This implies substantial efficiency improvements and demand reduction in some countries (e.g. USA, EU), but allows for increased demand (alongside more efficient technology) in other countries.

Emissions reductions from other activities are according to the IEA Beyond 2° Scenario. As we use the power sector benchmarks and all lighting and appliances are electric, the model sees a full decarbonisation of these two end-uses by 2050. The B2DS scenario also assumes efficiency improvements, such as a shift to LEDs for lighting. The IEA B2DS assumes that some cooking still uses biomass and that this end-use is not fully decarbonised by 2050.

We do not focus strongly on behavioural changes in the model and rather assess the structural and technological changes that are needed. For example, heating and cooling requirements are set to comfortable levels and further energy savings could be made with lower thermostat settings in winter. However, with well insulated buildings the potential energy savings from lowering thermostat temperatures are reduced.

#### Model parameterisation

The CAT buildings tool is based on quite detailed country-specific information including floor areas, technology mix for heating, Heating Degree Days (HDD) and Cooling Degree Days (CDD), renovation rates, demolition rates, temperature requirements for heating and cooling, and socioeconomic data. Country specific data was collected for each country assessed, with much, but not all, coming from

the IEA (see separate section below on data sources). The model was parameterised for each country, particularly regarding building envelopes, such that 2015 emissions and energy demand across the separate activities is consistent with IEA data.

Improvements to **building envelopes** were applied such that passive house standards for heating and cooling are met by new and renovated buildings (<15 kWh/m²/yr). Renovating building envelopes is more challenging than achieving high standards with new buildings. Although very high standards can be met through deep renovation, this can be more challenging for some existing buildings than others depending on their initial construction, aspect, and location. We therefore assume that renovated buildings do not reach the same standard as new buildings but are 10% less efficient.

The **technology mix** of existing buildings follows data reported (Knobloch, Pollitt, Chewpreecha, Daioglou, & Mercure, 2019). Analysis from the same study also guides future technology mixes with the additional constraints that in each country:

- Current levels of district heating are maintained. We assume that district heating is decarbonised at the same rate as electricity.
- Biomass shares are substantially reduced, but not completely eliminated
- Current shares of electric boilers and geothermal energy are maintained. We assume that current shares indicate local capacity and preferences.
- Heat pumps and solar thermal make up the rest of the demand with the share of solar thermal based on (Knobloch et al., 2019).

As most of these options are zero (or very low) emissions, the choice of technology mix therefore does not strongly impact the final emissions intensity. Higher electrification rates allow benefits of decarbonising the power sector to propagate to the buildings sector more quickly but also put more pressure on the grid. Heat pumps offer highly efficient means of heating and therefore also impact total energy demand. Heat pumps are not, however, always easily implemented and alternative options, e.g. solar thermal, may be more practical in many cases. Multiple options for the heating technology mix therefore exist and the optimal solution is dependent on local (sub-national) conditions, such as suitability for district heating or geothermal energy.

Renovation in the model, and in our final benchmarks, refers to deep renovation and implies changes in the heating technology, increases in share of floor space cooled, and improvements to the building envelope.

#### **Energy demand scenarios**

To explore the impact of building envelopes on energy demand intensity, we explore two scenarios, one where the building envelope of new and renovated buildings is set to improve significantly, and a second where improvements focus on heating and cooling technologies with little improvements to the building envelopes. These two scenarios provide us with a range of energy intensity results and slight differences in emissions intensity.

#### Data sources

Data sources used for the CAT building model include:

- IEA building statistics including floor area, current emissions and energy demand, B2DS scenario for lighting, appliances, and cooking (OECD/IEA & IRENA, 2017)
- (Knobloch et al., 2019) technology mix for heating (current and future)
- HDD / CDD from CMCC-KAPSARC global degree-days dataset (Atalla, Gualdi, & Lanza, 2018)
- ▶ UN population data and projections (UN DESA, 2019)
- ▶ GDP from WDI (The World Bank, 2019)

# 6.2.3 1.5°C compatibility constraints

The CAT buildings tool allows us to evaluate the different options for reducing emissions from the buildings sector for different countries, but not to directly assess 1.5°C compatibility. To ensure that our benchmarks are 1.5°C compatible, we therefore compare our modelling results with global scenarios and emissions pathways that are 1.5°C compatible.

Available IAM results do not include combined direct and indirect emissions from the buildings sector. However, we are able to compare our results with direct emissions in the buildings sector from scenarios that are 1.5°C compatible and meet sustainability criteria. From those scenarios, we can learn that emissions reductions from buildings need to be deep and to happen quickly, with substantial reductions by 2030 and almost complete decarbonisation by 2040.

Using the mean across all scenarios, the **total emissions reductions from the sector should be at least 45% by 2030, 65% by 2040, and 75% by 2050 relative to 2020**. Indirect emissions should decrease more quickly, as the power sector benchmarks result in faster decarbonisation than the direct emissions reductions in the IAM scenarios. The reduction in total emissions from the CAT model varies across countries and scenarios, ranging from 10-60% in 2030, 70-95% in 2040, and 85-100% in 2050. Those countries with higher total emissions currently are required to achieve higher overall emissions reductions and we therefore consider the CAT model results as being broadly consistent with the IAM scenarios, absolute total emissions from the buildings sector should be **below 2 GtCO<sub>2</sub> by 2050**, assuming zero indirect emissions from a fully decarbonised power grid.

In the IAMs, total energy use in the sector does not increase between now and 2050. Energy intensity per m<sup>2</sup> decreases in all countries in our model and absolute energy demand also decreases in the EU, USA, and China. Other countries, with a more rapid increase in floor space and population from now until 2050, as well as implementation of measures to achieve better living standards (e.g. greater access to air conditioning in India) can expect an increase in total energy demand. However, high building standards in new buildings can help to limit that demand growth where either heating or cooling needs are high.

Based on our comparison with the IAM model results, we are confident that the benchmarks presented here are 1.5°C compatible.

# 6.3 Benchmarks

The CAT buildings tool model results are the only input source to our benchmarks because the tool combines all the energy demand end-uses and indicators in a consistent manner. However, the buildings tool is informed by multiple sources, as described above.

Global benchmarks are based on the country level benchmarks and were not calculated using the CAT buildings model tool.

Benchmark values are presented as reductions relative to historic data (2015) and are rounded to the nearest 5% for the intensity indicators. The model results in absolute terms and final benchmarks are presented in tables 6-1 to 6-3 below.



Using existing technologies, it is possible to completely eliminate emissions from buildings by 2050. To do so will require substantial investment in zero carbon (renewable or electric) heating and cooling sources and improvements to the building envelopes. Our benchmarks therefore reach close to zero emissions intensity for all countries in 2050.

Those countries where the benchmark is a range allowing for some emissions are those where new buildings in the coming years may produce residual emissions in 2050 and where emissions from cooking (burning biomass) are more difficult to eliminate.

The variation in percent reduction across countries is closely linked to the current situation within the country. For example, Brazil's benchmarks require a lower reduction rate in residential emissions because the emissions intensity is already very low compared with other countries assessed. It is low partly because the emissions intensity of electricity is already relatively low and, in addition, demand for heating and cooling is also low.

To be compatible with the Paris Agreement, substantial reductions in emission-intensity need to be achieved by 2030 and cannot be delayed to 2040 or 2050. Across the countries assessed, emissions intensity reductions by 2030 need to be 45 - 65% in the residential sector and 65-75% in the commercial sector. To do so will require immediate action in terms of energy efficiency, renovation, and implementation of high standards for new buildings.

Table 6-1. Model r	results and Paris	Agreement	compatible	benchmarks	for emissions	intensity of
buildings (kgCO <sub>2</sub> /	' <i>m</i> ²)					

<b>Buildings emissions intensity</b> kg CO <sub>2</sub> / m <sup>2</sup>					
Country	Үеаг	Residential Buildings	Commercial Buildings		
		PA Final Benchmark (% reduction from 2015 levels)	PA Final Benchmark (% reduction from 2015 levels)		
	2030	-	-		
Global	2040	90%	90-95%		
	2050	95-100%	100%		
	2030	65%	75%		
USA	2040	90%	95%		
	2050	100%	100%		
	2030	60%	75%		
EU	2040	95%	95%		
	2050	100%	100%		
	2030	50%	75%		
Brazil	2040	80%	95%		
	2050	95-100%	100%		
	2030	45-55%	70%		
India	2040	90%	95%		
	2050	95-100%	100%		
	2030	60%	65%		
China	2040	90%	90%		
	2050	100%	100%		
	2030	50%	70%		
South Africa	2040	90%	95%		
	2050	100%	100%		
	2030	-	-		
Indonesia	2040	-	-		
	2050	-	-		



The energy intensity per m<sup>2</sup> in each country include energy demand from all end-use services, space heating, space cooling, water heating, lighting, cooking and appliances. Energy demand for space heating and cooling are substantially decreased through improvements to building envelopes and installation of high efficiency heating and cooling technologies. Energy demand per capita for water heating converges across all countries; in some cases, this reflects efficiency improvements while in others improved access to water heating services.

The B2DS scenario includes a near complete shift towards efficient LED lighting by the 2030s resulting in decreasing energy demand for lighting across all countries. Despite assumptions regarding efficiency improvements, energy demand for cooking and appliances decreases less in the B2DS scenario, partly due to rebound effects. Behavioural changes could result in further deductions in energy intensity, particularly in those countries with high energy demand for appliance use (e.g. USA).

Local climate has a high impact on final energy demand between countries. Brazil has very low heating degree days and moderately low cooling degree days whereas the EU has a very high demand for heating. The USA and China have similar average climates with moderate demand for heating and cooling. India conversely has a low heating requirement but high potential demand for heating. Our model assumes improved access to cooling where there is demand for it, such as in India.

Because the impact of climate on energy demand is high, a global benchmark for energy intensity is not so meaningful and we therefore do not define a global benchmark for this indicator.

Buildings energy intensity kWh / m <sup>2</sup>					
Country	Үеаг	Residential Buildings	Commercial Buildings		
		PA Final Benchmark (% reduction from 2015 levels)	PA Final Benchmark (% reduction from 2015 levels)		
	2030	-	-		
Global	2040	-	-		
	2050	-	-		
	2030	25-30%	20-25%		
USA	2040	40-50%	30-40%		
	2050	45-60%	40-50%		
EU	2030	30%	20-25%		
	2040	50-55%	35-45%		
	2050	50-60%	40-50%		
	2030	20%	10-15%		
Brazil	2040	20%	15-25%		
	2050	20-30%	15-30%		
	2030	20-25%	10-15%		
India	2040	35-40%	20-25%		
	2050	40-45%	25-35%		
	2030	20%	10-15%		
China	2040	35-40%	25-30%		
	2050	45-50%	35-45%		
	2030	25%	25-30%		
South Africa	2040	35-40%	35-40%		
	2050	45%	45-50%		
	2030	-	-		
Indonesia	2040	-	-		
	2050	-	-		

#### Table 6-2. Model results and benchmarks for building energy intensity (kWh/m<sup>2</sup>)

The range for some countries is given by the two energy demand scenarios and reflects scenarios with different assumptions regarding improvements in building envelope standards (see methods above). The range is therefore higher for countries with a higher demand for heating and /or cooling.

Finally, it's worth noting that this indicator reflects energy demand per m<sup>2</sup>. We assume that total floor area increases in all countries and in some countries the total energy demand also increases (e.g. India, Brazil), whereas in others it decreases (e.g. EU, USA), while in others it is scenario dependent (e.g. China, South Africa).

#### 6.3.3 Renovation rates Percentage of buildings renovated per year

Renovation rates are inputs to the CAT buildings model and are modified to ensure that all stock is of a high standard by 2050. This includes upgrades to the building envelope and improvements to heating and cooling technologies. Modelling analysis showed that renovation rates of up to 3.5% were required to achieve these standards.

The USA and EU are expected to reach the maximum renovation rates at an earlier date than the other countries assessed. This is partly for equity reasons and partly because much of the stock expected to exist in 2050 has already been built. The EU and USA cannot rely on new buildings to improve the average energy and emissions performance but also need to prioritise improvements to the existing stock.

The renovation rate benchmarks are only set for 2030 and 2040 because renovation should be complete before 2050. However, if buildings constructed in the coming decade are not of a sufficiently high standard, continued renovation could help to minimise energy use and emissions in the latter half of the century. Some renovation is likely to continue in any case as older stock wears down.

#### **Renovation rates buildings** 5% % renovations / year Brazil 4% 3% 2% 1% No historical data 0% 5% China 4% 3% 2% 1% No historical data 0% 5% EU-28 4% 3% 2% 1% No historical data 0% 5% India 4% 3% 2% 1% No historical data 0% 5% Indonesia 4% 3% 2% 1% No historical data 0% 5% South Africa 4% 3% 2% 1% No historical data 0% 5% 🕮 USA 4% 3% 2% 1% No historical data 0% 5% World 4% 3% 2% 1% No historical data 0% 2010 2015 2020 2025 2005 2045 2050 2030 2035 2040

Table 6-3. Renovation rate benchmarks for commercial and residential buildings. (Benchmark values are rounded to the nearest 0.5%.)

Building renovation rates % of buildings renovated per year						
Country	Year	Paris Agreement Final Benchmark				
Clabal	2030	2.5-3.5%				
Global	2040	3.5%				
USA	2030	3.5%				
	2040	3.5%				
EU	2030	3.5%				
	2040	3.5%				
Brozil	2030	2.5%				
Didžit	2040	3.5%				
India	2030	2.5%				
IIIula	2040	3.5%				
Chipa	2030	2.5%				
Clinia	2040	3.5%				
South Africa	2030	2.5%				
South Affica	2040	3.5%				
Indonasia	2030	-				
Indonesia	2040	-				

# 6.3.4 New buildings standards

For the above energy and emissions intensity benchmarks to be met, new buildings need to meet high standards in terms of the building envelope and energy supply. More specifically, all energy demand end-uses must either be zero emissions and/or electric. Combined with decarbonisation of the power sector, emissions intensities of zero can be reached by 2050.

High thermal performance standards of buildings are needed to keep total energy demand lower and reduced the total electricity demand. Specific standards are dependent on the local climate and will be more important for regions of more extreme climate.

Emissions and total energy demand can be minimised by addressing energy used within buildings. All newly installed lighting in both residential and commercial buildings should be LEDs due to their high energy efficiency. Wherever possible, electrification of cookstoves allows for efficient, decarbonised cooking and all new appliances should meet high energy efficiency standards.

Our model recognises that some of these standards are easier to meet in some countries than others and allows for a transition from current to new standards. However, in OECD countries (including USA and EU here) there should be no delay in adopting best practice minimum energy performance standards. Our model allows for a five-year transition to higher standards in other countries.

New buildings standards are critically important because any stock built from now on that cannot be fully decarbonised in the next 30 years will need to be renovated; be that the building envelope or replacing carbon intensive technologies such as gas boilers.

The benchmark for new buildings is therefore that all (100%) new buildings should be Zero Emissions Buildings, where we define a Zero Emissions Building as one that either is, or can be, fully decarbonised when accompanied by decarbonisation of the power sector. This benchmark should be implemented now by the EU and USA and reached by 2025 at the latest by all other countries.

# 6.4 Key lessons and priorities for the buildings sector

The priority mitigation options for a country are dependent on local climate and current circumstances. For example, heating is the major building energy demand in the EU and can be reduced through high building performance standards for new and renovated buildings accompanied by widescale installation of heat pumps. India, on the other hand, could prioritise addressing cooling needs and reducing emissions from cooking.

- Improvements to the building envelope can lower total energy demand and reduce pressure on other sectors for electricity supply. However, it is most important to decarbonise the energy sources for cooling and heating with heat pumps providing a low emission, highly efficient option. Solar thermal energy, geothermal, electric boilers, and district heating are good options for complementing heat pumps with the optimal mix depending on local circumstances.
- Improvements to building envelopes could have major impact on energy demand savings in regions with high heating or cooling demand.
- In countries where much of the building stock in 2050 has already been built, high renovation rates and technology improvements are extremely important.
- In many countries, much of the building stock that will exist in 2050 is yet to be built. It's vital that the new stock is of a high standard and equipped with heating and cooling technologies that either are or can be zero emissions. Heat pumps, solar thermal water heaters and high thermal building standards are key to keeping energy demand and emissions low while providing comfortable living standards.



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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.

#### The Consortium



NewClimate Institute is a non-profit institute established in 2014. NewClimate Institute supports research and implementation of action against climate change around the globe, covering the topics international climate negotiations, tracking climate action, climate and development, climate finance and carbon market mechanisms. NewClimate Institute aims at connecting up-to-date research with the real world decision making processes.

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Climate Analytics is a non-profit climate science and policy institute based in Berlin, Germany with offices in New York, USA, Lomé, Togo and Perth, Australia, which brings together interdisciplinary expertise in the scientific and policy aspects of climate change. Climate Analytics aims to synthesise and advance scientific knowledge in the area of climate, and by linking scientific and policy analysis provide state-of-the-art solutions to global and national climate change policy challenges.

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