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Closing the gap to 1.5°: What can we learn from Marginal Abatement Cost Curves?

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Introduction

As part of the 2015 Paris Agreement, 196 countries signed an agreement to limit the increase in global average temperature to 'well below 2°C above pre-industrial levels' and 'pursue efforts to limit the temperature increase to 1.5°C'.

However, there is a significant gap between the warming implied by G20 countries' combined decarbonisation policies and the commitments of the Paris Agreement. The study assesses how G20 countries might close this gap and get back on track for a 1.5°C aligned trajectory.

Using marginal abatement cost curves (MACC), we evaluate the sectors and kinds of technologies which could deliver the required emissions abatement between now and 2030. We do this at the G20 level and for each member state in turn, assuming that abatement occurs where it is most economically efficient.

Contents

Acknowledgments

The authors would like to thank Quentin Bchini (Enerdata) and Esteban Drouet (Enerdata) for their help in the scoping of the sectors from Enerdata database used in this study. The report, however, only reflects the authors' methodological choices and views.

Executive summary

There is a significant gap between the ambition of countries' collective decarbonisation policies and the efforts required to be 1.5°C-aligned by 2030.[1] Based on our extensive prior work on net zero targets (see our Net Zero Atlas) we calculate that current policies imply an emissions level in 2030 that is 57% higher than necessary to remain on a 1.5°C trajectory (see exhibit 2). G20 countries—accounting for around 79% of global emissions[2]—specifically would need to reduce their emissions by 5.5% annually from 2019–2030 to get back on track.

This paper, therefore, aims to identify near-term potential to reduce emissions reduction in G20 nations—both in terms of sectoral breakdown and the kinds of technologies or activities needed to deliver it. We follow a three-stage research process that identifies emissions mitigation potential at both the G20 and national level:

1. **First, we define the total amount of additional abatement** required by 2030 for the G20—both on aggregate and at a national level—to get back on track with a 1.5°C -aligned trajectory. We do this by comparing:
    a. the emissions level resulting from their current mitigation policies with
    b. the amount of carbon emissions they could emit under a 1.5°C warming scenario—estimated with our proprietary Climate Liabilities Assessment Integrated Methodology (CLAIM) model[3].
2. **Second, we evaluate the capacity of economic sectors** to deliver the emissions reduction necessary to align with a 1.5°C trajectory. For each country, we use marginal abatement cost curves (MACC) from Enerdata, assuming a cost-efficient decarbonisation process, and aggregate to the G20 level.
3. **Finally, we group the abatement solutions into four categories** of mitigation technologies or activities:
    a. Ready-to-use decarbonisation technologies (e.g., renewables, electric vehicles),
    b. Energy and resource efficiency (e.g., building retrofitting, vehicle and industrial process efficiency, recycling),
    c. Early-stage decarbonisation technologies (e.g., hydrogen, carbon capture and storage),
    d. Population-wide behavioural changes (e.g. greater use of public transport or bikes, lower carbon diets).

This analysis suggests that if countries deliver their fair share of emissions reductions[4], and abatement occurs where it is most economically efficient, G20 countries already have a significant majority of the tools required to accelerate decarbonisation toward a 1.5°C trajectory:

[1] Following the 2015 Paris Agreement, countries have agreed to pursue efforts to keep global warming below 2°C above pre-industrial levels, while trying hard to limit the temperature increase to 1.5°C.

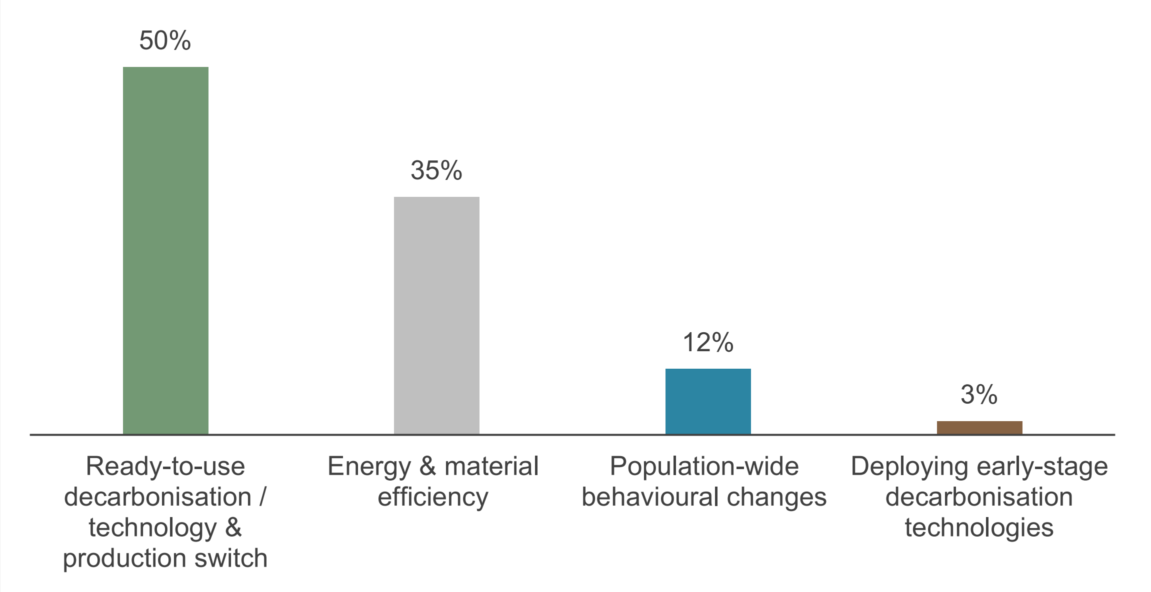
[2] Based on 2019 emissions from our database. Our historical GHG emissions inventories includes the land use, land-use change and forestry (LULUCF) sector. The emissions inventories from this sector are collected by IIASA based on UNFCCC and FAO reported emissions. The emissions from the other sectors are based on the Primap-hist database of the Potsdam Institute (mostly emissions from energy-use, industry and agriculture).

[3] For more details on our CLAIM approach, see Giraud *et al*. 2017 [HAL]

[4] Our 2030 potential abatement metric provides an indication of where abatement could theoretically happen most efficiently for each G20 member state by 2030 in circumstances where they remain aligned with a 1.5°C trajectory. We provide a sector-by-sector breakdown of the proportion of emissions reduction to be achieved by each sector for each member state, as well as by different types of abatement measures.

- As exhibit 1 shows, half of the abatement needed to get back on track at the G20 level could be met through ready-to-use decarbonisation technologies like renewables; and a further third of decarbonisation can be met by improving energy and resources efficiency.
- 12% of the emissions reductions could be attained through societal change, including transitioning to lower-carbon diets, increasing use of low carbon transport, and greater adoption of circular economy practices such as recycling and materials reuse.
- Only c. 3% of emissions savings would have to be achieved through accelerating the deployment of early-stage technologies, such as carbon capture and storage or low-carbon fuels, even if the full potential is more likely to be felt in the context of longer-term, 2050 net-zero targets.

Exhibit 1. Abatement potential across the G20 by activity type



Source: FTSE Russell & Beyond Ratings, August 2023.

- Using a sectoral lens, our analysis shows that the energy system could deliver the greatest proportion of near-term abatement potential (39%); industry could deliver 25%; and agriculture, forestry and other land use (AFOLU) provides a smaller percentage of the reduction (20%). Transport and buildings could be responsible for delivering a far smaller proportion by 2030, but the timeframes to replace building and vehicle stocks are particularly long and the rewards of pre-2030 investment are most likely to be reaped in the decades that follow. These sectoral results at G20 aggregate level are broadly aligned with the last IPCC report.[5]

Interpreting these findings at a G20 member state level is nuanced. Countries that are more heavily reliant on fossil fuel-intensive energy systems can typically achieve a greater proportion of their abatement by transitioning to renewable energies and transforming their energy system specifically. In contrast, for countries with a less carbon-intensive electricity mix, other solutions can deliver a higher proportion of abatement, mainly through energy and resource efficiency, but also to a lesser extent demand-side behavioral changes.

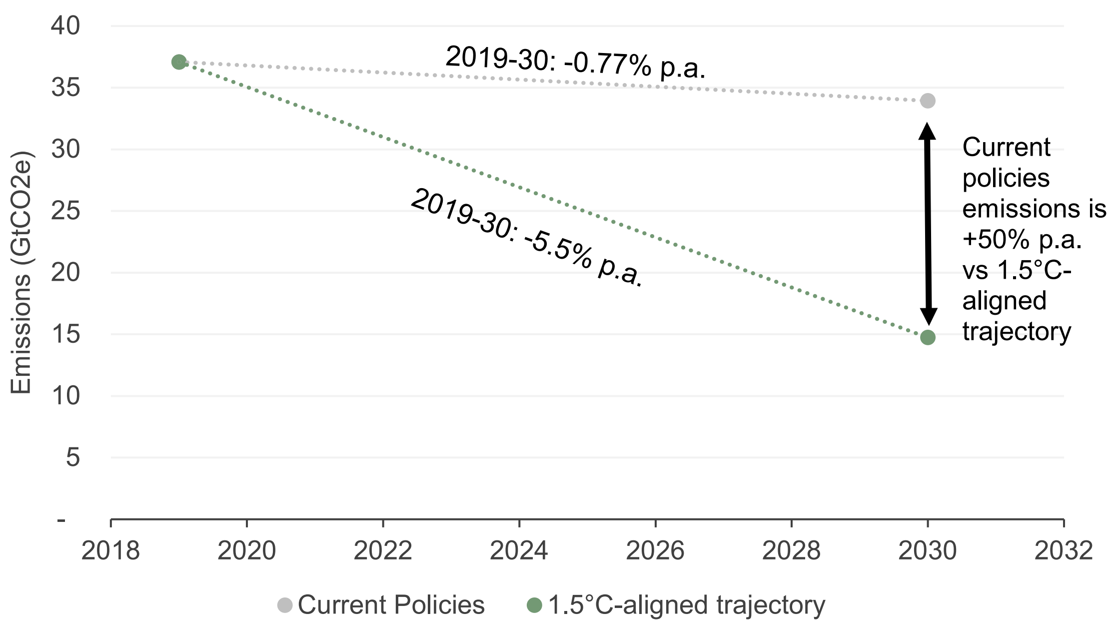
[5] IPCC - Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (2022) [IPCC]

Section 1: Getting back on track for 1.5°C by 2030

All G20 countries have now made public emissions-reduction commitments as part of their Nationally Determined Contributions (NDCs)—all by 2030, and even more stretching Net Zero Targets by 2050.[6] G20 countries' collective current climate policies nonetheless still fall significantly short of these global climate targets, even if they have become gradually more aligned with the Implied Temperature Rise on a 2.7°C trajectory at COP27.[7]

To get back on track for a 1.5°C trajectory will therefore require significant near-term decarbonisation of the global economy over and above what is implied by current policies. We calculate that on aggregate G20 countries will be required to decrease their GHG emissions by 5.5% annually until 2030 (starting from 2019) to track toward this.[8] Based on these calculations, the emissions level in 2030 that we can expect from current policies is 57% higher than what is necessary to remain on a 1.5°C trajectory (see exhibit 2).

Exhibit 2. Implied 2030 emissions levels in the G20: Current Policies vs. 1.5°C aligned trajectory[9]



Source: FTSE Russell & Beyond Ratings, August 2023.

[6] For a full summary of G20 emissions reduction targets, please see FTSE Russell, 'COP27 Net Zero Atlas'.

[7] See the implied temperature rise of the G20 illustrated on the figure 3 of the COP27 Net Zero Atlas.

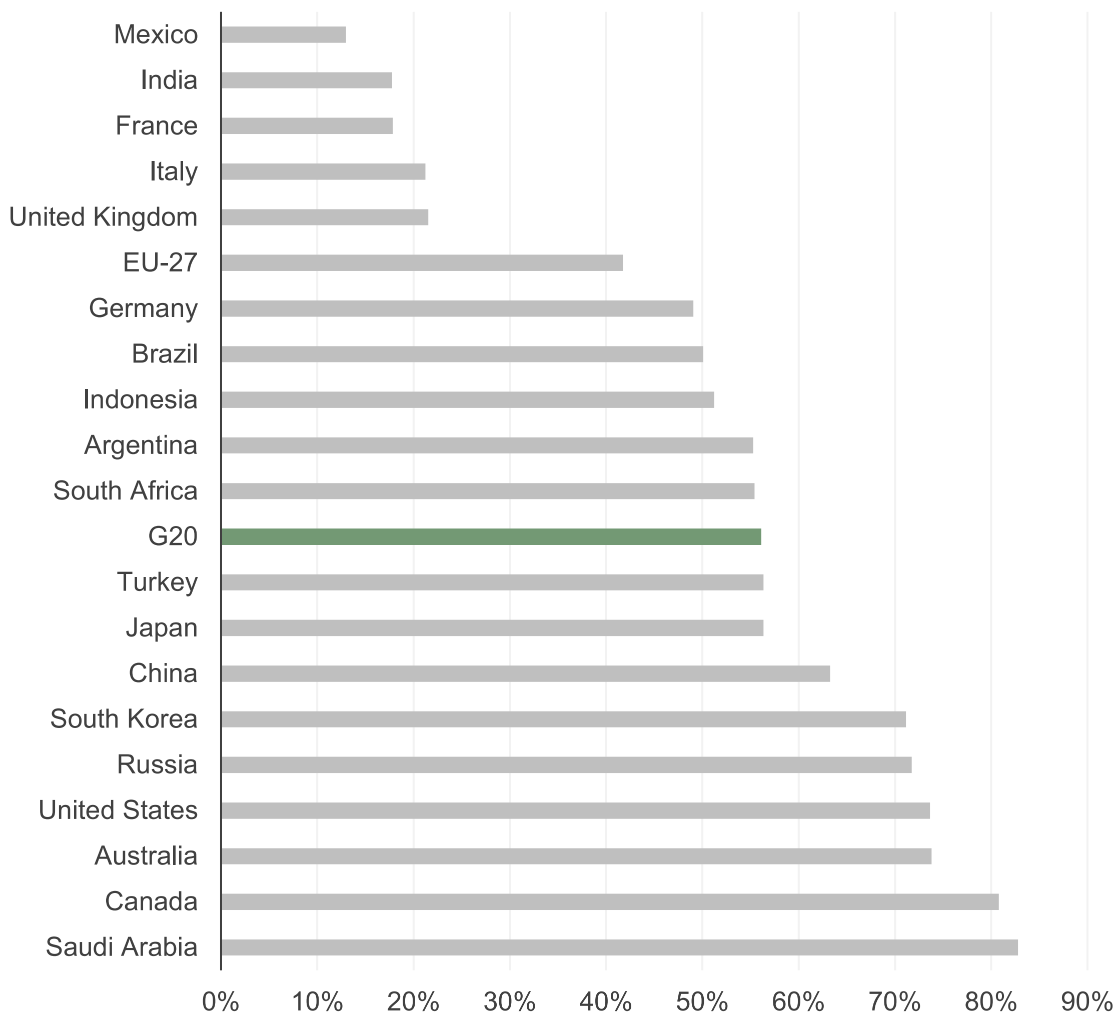
[8] 2019 emissions are from our database. Our historical GHG emissions inventories includes the land use, land-use change and forestry (LULUCF) sector. The emissions inventories from this sector are collected by IIASA based on UNFCCC and FAO reported emissions. The emissions from the other sectors are based on the Primap-hist database of the Potsdam Institute (mostly emissions from energy-use, industry and agriculture). See appendix for information on how we construct Current Policies and 1.5°C-aligned trajectories.

[9] The 1.5°C-aligned trajectories are achieved with the CLAIM methodology which deliver each country carbon budget (amount of CO2 a country can still emit to be aligned with a specific target).

The data presented in exhibit 3 highlights a significant 'ambition gap' for all G20 countries between the decarbonisation implied by their current policies and what is required to remain on a 1.5°C trajectory by 2030. The highest ambition gaps are found in Saudi Arabia (83%) and Canada (81%), followed by Australia and the United States—which both have gaps of 74%.

On the other hand, our results show that some G20 countries' projected 2030 emissions are closer to being on track for 1.5°C, either because they still have low per-capita emissions and large remaining carbon budgets (such as Mexico and India), or because they are relatively carbon efficient economies aggressively cutting their near-term emissions (such as France or the UK). Nevertheless, even these countries would need to step up their efforts significantly to track toward a 1.5°C trajectory in 2030.

Exhibit 3. Estimated gap in 2030 between the emissions level implied by current policies and the level required to remain on a 1.5°C trajectory



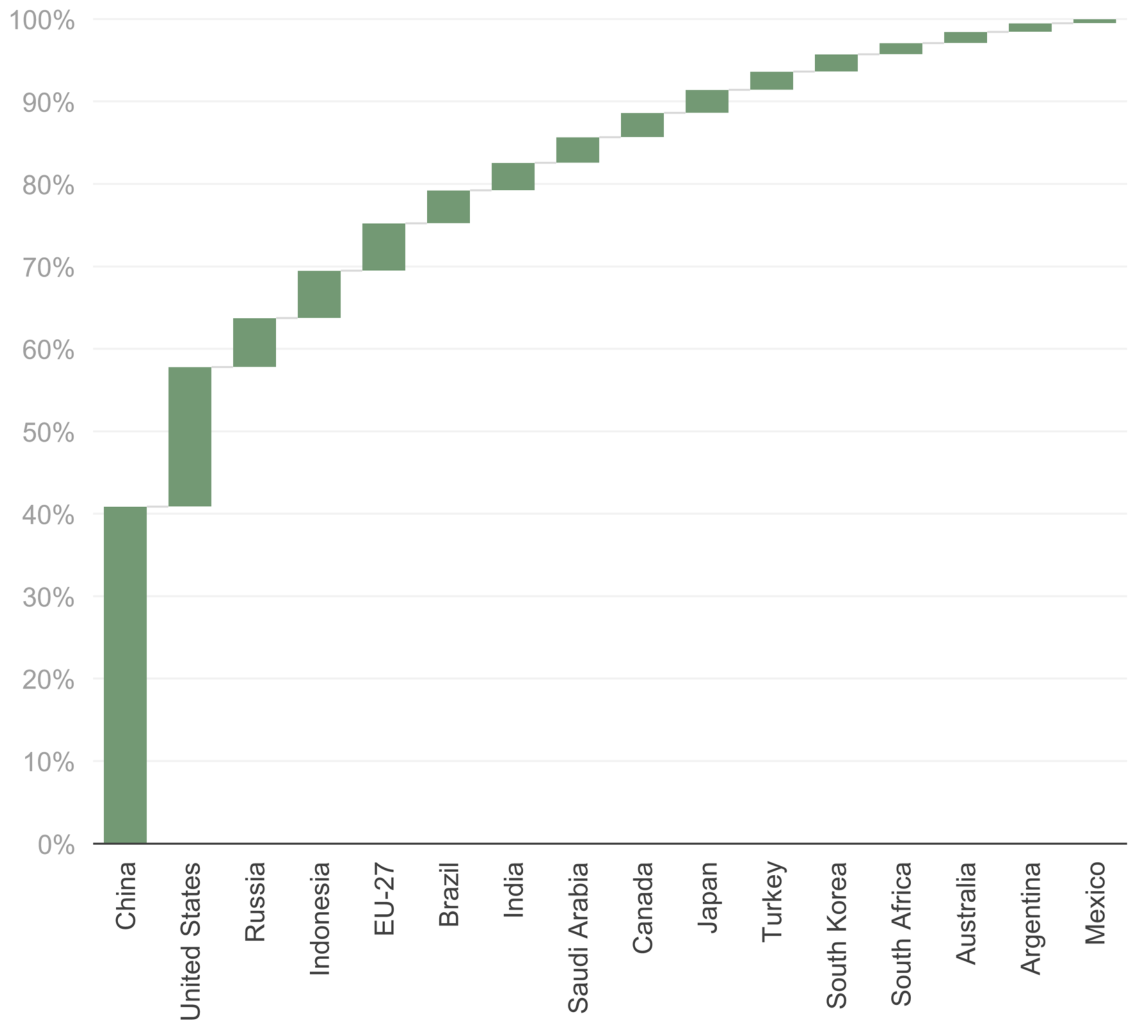
Source: FTSE Russell & Beyond Ratings, August 2023. See appendix for more details on author's calculation.

Reader's note: The gaps reflect the ambition of countries' climate policies but also the emission level they should reach to align with a 1.5°C scenario. This level is estimated through our CLAIM approach[10] that defines carbon budgets at country level according to their climate and economic profile (historical emissions, energy intensity, GDP/capita, etc.). The 2030 emissions per capita level that is implied by existing policies is a good indicator of the magnitude of effort required to 'get back on track'.

[10] For more details on our CLAIM approach, see Giraud *et al*. 2017 [HAL]

In absolute terms, China and the US stand out. Due to their size and relatively carbon intensive economies, these two countries account for almost 60% of G20 countries required additional GHG emissions reductions by 2030 to close the gap to a 1.5°C trajectory (see exhibit 4).

Exhibit 4. Distribution of required absolute emissions abatement between 2019 and 2030 across G20 member states[11]



Source: FTSE Russell & Beyond Ratings, August 2023.

[11] This is calculated as total abatement required for each member state between 2019 and 2030 as a percentage of total overall abatement at the G20 level. See appendix for information on how we construct Current Policies and 1.5°C-aligned trajectories.

Section 2: Which measures can close the gap?

Decarbonising entire economies will require policymakers to pull the right levers in the right sequence. The measures chosen and the order in which they are deployed may differ markedly from country to country depending on their economic profile, political institutions and fiscal health.

To better understand the path ahead for each G20 member state, we use marginal abatement cost curves (MACC) to analyse the decarbonisation potential of different abatement measures on a sector-by-sector basis. This approach considers the economic cost of avoiding a ton of carbon under certain conditions and assumes that abatement occurs where it is most economically efficient. Although highly stylised, this approach provides interesting and consistent results on mitigation potential. (See the appendix for a full methodological summary.)

Our analysis reveals that implementing ready-to-use decarbonisation technologies could deliver half of the abatement required across the G20 by 2030 (see exhibit 5). These include a suite of well-known decarbonisation measures with mature technologies and established production supply chains that could be rolled out at scale with adequate capital funding. The largest ticket items in this group are switching to low-carbon electricity sources (e.g., renewables, such as solar and wind power), as well as widespread uptake of low-carbon transport through electric vehicles.

Rolling out well-understood energy and resource efficiency measures, including more efficient buildings but also more carbon-efficient land use, for example, can deliver around a third of abatement across the group. There are significant opportunities to improve the energy efficiency of various parts of the economy—most notably through retrofitting buildings, improving vehicle and industrial process efficiency measures, land-use change and recycling.

Far smaller abatement potential exists through promoting population-wide behavioral changes and early-stage decarbonisation technologies. Demand-side evolution—particularly lifestyle changes—presents opportunities in some specific countries to nudge consumers toward lighter personal vehicles, greater use of public transport or bikes, lower-carbon diets, and reduced waste creation. We estimate this could be responsible for just under a tenth of abatement in the G20.

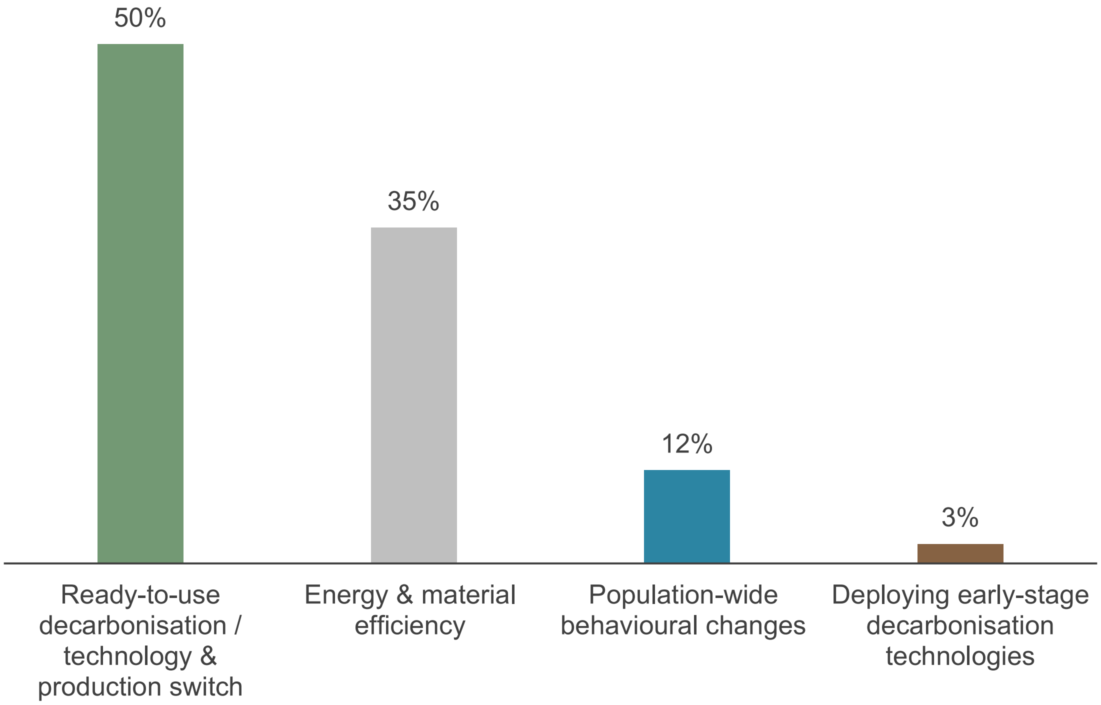
Most tricky to achieve are emissions reductions driven by the deployment of current early-stage decarbonisation technologies. For example,

- carbon capture storage (CCS),
- carbon dioxide removal (CDR),
- decarbonisation technologies for heavy vehicles,
- shipping and aviation, and
- low-carbon fuels.

Technologies like these are not currently mature enough for widespread adoption, but with proactive planning and implementation they could have considerable post-2030 mitigation potential. Even though the short-term benefits in emission reduction may be relatively low, it is important to invest significantly in these solutions, particularly through research and development, to leverage their potential in the context of longer-term Net Zero targets.[12]

[12] See for instance IEA, Net Zero by 2050 – A roadmap for the global Energy Sector [IEA]

Exhibit 5. Abatement potential across the G20 by activity type



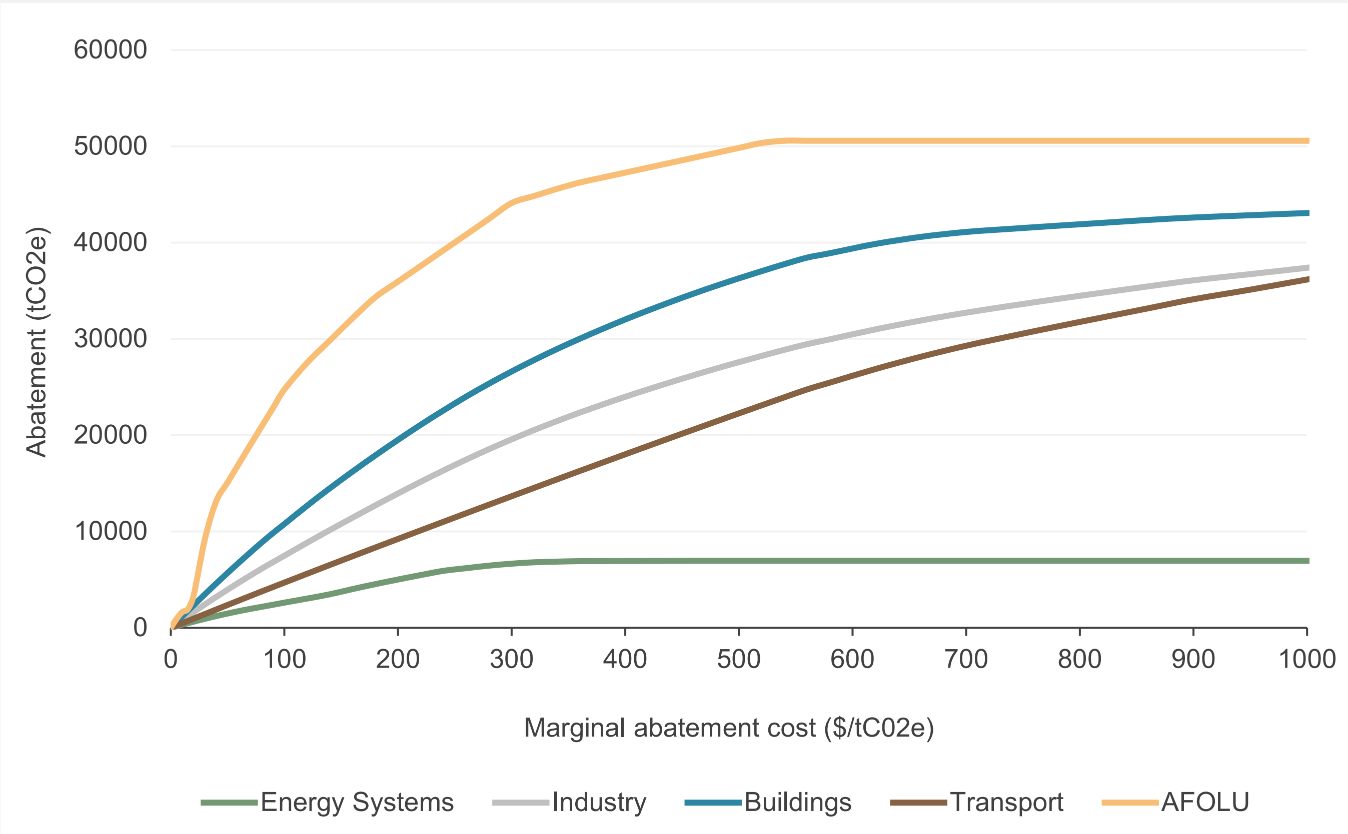
Source: FTSE Russell & Beyond Ratings, August 2023.

Box 1. Marginal abatement cost curves (MACCs)

A marginal abatement cost curve (MACC) is a graphical representation that illustrates the relationship between the cost of reducing emissions (abatement) and the quantity of GHG emissions abated. It represents the incremental cost of achieving an additional unit of emissions reduction beyond a baseline level.

Specifically, MACCs show the marginal cost of reducing GHG emissions for different mitigation options. They can be used as a tool to identify the least expensive ways to reduce emissions. The mitigation options can be categorised by sector, as in the Enerdata curves that we use in this study; or by technology, as in the famous McKinsey curve[13].

Exhibit 6. France's GHG abatement cost curve



Source: FTSE Russell, August 2023, based on MACC from Enerdata.

Exhibit 6 shows sectoral abatement potential at different levels of marginal abatement cost, based on Enerdata and Frank et al (2021).[14] Interestingly, our study shows that the AFOLU sector could be particularly critical for France's transition towards a low carbon economy - for instance through the implementation of land management and agricultural practices designed to increase carbon storage from biomass and soil.

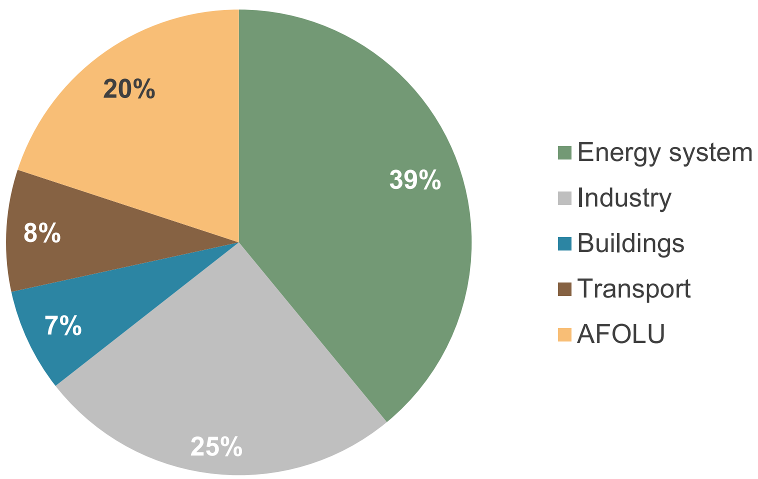
[13] In 2007 McKinsey developed the first abatement cost curves to showcase the potential of reducing greenhouse gas emissions across different sectors.

[14] See: Enerdata - Marginal Abatement Cost Curves

Section 3: The sectoral perspective

In each G20 nation, the mitigation measures that can deliver the required abatement differ, so interpreting these findings at member state level is nuanced. The type of mitigation solutions available to individual member states depends largely on each country's specific circumstances—for example, its energy mix, available resources, policy frameworks, and the focus it puts on different sectoral decarbonisation.

Exhibit 7. Sectoral distribution of required abatement for the G20 on aggregate



Reader's note: author's calculation – see appendix for more details

Source: FTSE Russell & Beyond Ratings, August 2023.

Energy systems

Energy systems possess by far the most sectoral abatement potential by 2030. We estimate they represent more than 39% of the total potential in the G20. Due to the growing use of coal-fired power generation at global scale, GHG emissions from energy systems have continued to increase in recent years, rising by 1.9 $GtCO_2e$ between 2010 and 2018.[15] At the same time, decarbonising electricity will be important in the coming years. Electrification is recognised as a critical enabler to decarbonise other activities like transport or heating.

Fortunately, renewable technologies are rapidly maturing, widely available, and highly competitive.[16] In that context, switching energy source for power generation from fossil fuels to renewables[17] is the most powerful and cost-efficient lever to reduce emissions in the next decade.[18]

This is particularly true for countries where carbon intensive fossil fuels are still dominant in the energy mix such as China, Australia or South Korea. They rely heavily on coal for power generation. South Africa, for example, produces about 90% of its electricity from coal.[19] Not

[15] Lamb *et al.*, 2021, A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018, [ERS]

[16] According to IRENA, for instance "56% of capacity additions for utility-scale renewable power in 2019 achieved lower electricity costs than cheapest new coal plant", see [IRENA]

[17] And to a lesser extent other decarbonised sources such as nuclear energy

[18] See the Summary for Policymakers – IPCC Sixth assessment report - Figure: SPM.7 (ipcc.ch)

[19] Climate Transparency, 2022, [CT]

surprisingly, we estimate that energy systems could comprise 58% of South Africa's total abatement by 2030, the highest in the G20 (see exhibit 8).

Oil- and gas-producing countries, such as Saudi Arabia, Russia or the United States, also have significant abatement potential in this area, given their heavy reliance on their own fossil fuel reserves for domestic power generation. About half of their efforts to align with a 1.5°C trajectory in 2030 could come from energy systems.

Beyond power generation, reducing methane 'fugitive' emissions[20] from coal, oil and gas production has significant abatement potential. For instance, we estimate that lowering these fugitive emissions could represent almost 25% of Saudi Arabia's emission reductions for 2030.

Various countries have already vowed to phase-out coal from power generation. For instance, the United Kingdom has set a particularly ambitious deadline of October 2024 to remove unabated coal from the UK's energy mix, while Canada and Chile have set similar commitments on different timeframes for 2030 and 2040, respectively.[21]

Industry

Industry has the second highest abatement potential in the G20. We estimate it represents more than 25% of total potential. Both the limited availability of decarbonisation technologies and the increasing demand for industrial goods, particularly from emerging economies, will put pressure on the sector and its capacity to deliver emission reductions.

Despite this, there is significant room for emissions abatement, mostly from energy-efficiency measures. Highly industrialised countries such as Germany, China, Japan and South Korea have the strongest potential (see exhibit 8). Material efficiency and enhanced recycling are other effective mitigation options in the next decade.

According to some studies, the Net Zero roadmap of the sector would already suppose no new carbon-intensive industrial installation[22] as it implies lock-in effects given the typical lifetime of these installations. One of the main challenges in that regard is to accelerate the development of alternative technologies, like those based on green hydrogen and carbon capture storage (CCS), to enable the implementation of the new decarbonised production capacities as soon as feasible.

Agriculture, forestry and other land use (AFOLU)

The agriculture, forestry and other land use sector represents the third highest abatement potential in the G20. We estimate it represents around 20% of the global potential. The sector's emissions increased significantly during the last few decades.

AFOLU can be an important and highly cost-efficient abatement option, particularly for G20 countries with large agricultural and forestry sectors. In Indonesia and Brazil, we estimate the abatement potential of the sector represents almost half of total potential (see exhibit 8). A priority is to reduce deforestation that leads to cropland development. To align with a 1.5°C pathway, global levels of deforestation should fall by 70% by 2030 relative to the 2019 level.[23] This

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[20] Methane fugitive emissions refer to the unintentional release of methane gas into the atmosphere during various stages of the production, transportation, and use of natural gas, oil, and coal. Fugitive emissions occur due to leaks or unintended releases from equipment, pipelines, storage tanks, or other infrastructure associated with the extraction, processing, and distribution of these fossil fuels.

[21] For the UK, see UK Government, Press release. For Canada – see Canadian Government, Press release. For Chile, see Chilean Government, Press release.

[22]See Kuramochi, T. *et al*., 2018, Ten key short-term sectoral benchmarks to limit warming to 1.5°C, Climate Policy

[23] Nascimento, L. *et al*., 2021, Tracking climate mitigation efforts in 30 major emitters: Economy-wide projections and progress on key sectoral policies [NCI]

mitigation option can deliver a large amount of emission reductions with a very low associated abatement cost.

Buildings and transport

Somewhat surprisingly, we estimate the additional abatement potential from the buildings and transport sectors (7% and 8%, respectively) represent a comparatively small amount of the G20 total. This typically reflects larger and cheaper emissions reductions potential through the energy or land use sectors.

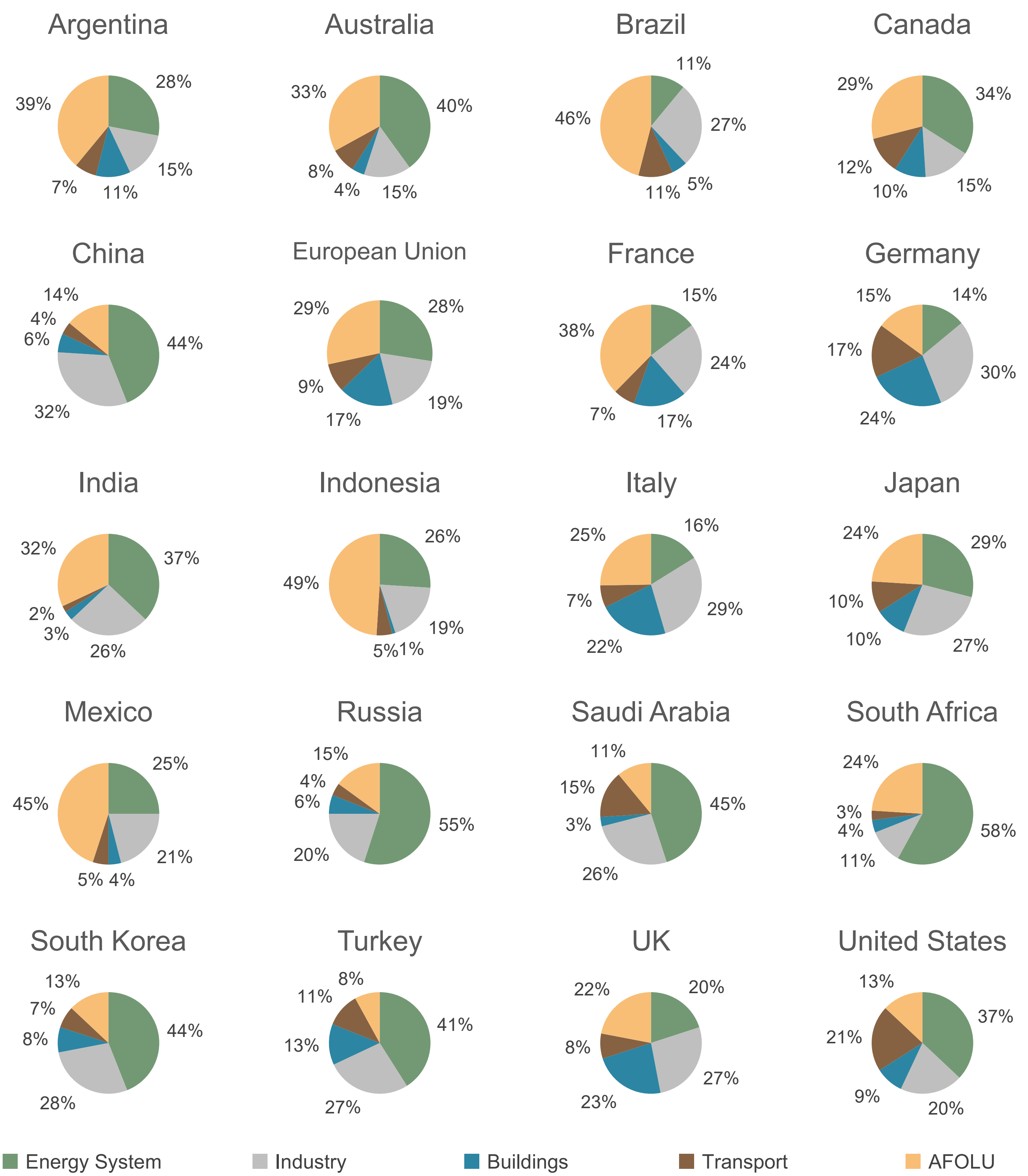
Although the building and transport sectors have a relatively low share in total abatement until 2030 for the G20, they do require attention, particularly for countries currently on track to rapidly decarbonise their power sector. For example, this is the case for several advanced G20 economies, such as Germany, UK, and the US. There, buildings and transport sectors are relatively important to deliver additional emissions reductions accounting for 30–40% of the overall mitigation potential.

In addition, timeframes to replace buildings and vehicle stocks are particularly long and require a strong acceleration in investments—e.g., through policy instruments, such as target dates to phase out sales of combustion engine vehicles.[24] Together, these sectors require one-third of total investments needed to align with a 1.5°C trajectory by 2030 according to GFANZ estimates.[25]

[24] a number of countries have set these target dates such as Norway by 2025; Israel, Iceland, Sweden, Denmark and The UK by 2030; and many others (examples taken from Nascimento, L. *et al*., 2021 [NCI]).

[25] See Race to Zero, Financing Roadmap [GFANZ]

Exhibit 8. Sectoral mitigation potential in G20 countries, at a glance



Source: FTSE Russell & Beyond Ratings, August 2023.

Appendix: Methodology

Our methodology in three steps

1. **Calculating the gap to 1.5°C at country level**

   The initial phase of our methodology involves evaluating the extent to which each G20 country needs to reduce its greenhouse gas emissions to be in line with the 1.5°C warming scenario. This assessment is made in addition to the reduction efforts already established through existing policies. Our analysis defines the level of effort required by each country by comparing:

   i. emissions level resulting from their current mitigation policies to the
   ii. amount of carbon emissions they could emit under a 1.5°C warming scenario. This evaluation is based on projected outcomes for the year 2030.

$$\begin{aligned}&\boldsymbol{Gap}\\&= Emissions\ level\ in\ 2030\ resulting\ from\ their\ current\ mitigation\ policies\\&- Emissions\ level\ in\ 2030\ required\ to\ be\ on\ 1.5°C\ warming\ scenario\ trajectory\end{aligned}$$

The 'current policies' emissions trajectories are constructed by the NewClimate Institute and IIASA. They provide annual emissions estimates from 2021 to 2030. Both institutes have a long history of estimating the impact of current policies on future GHG emissions. The methods used for developing the current policy scenarios are presented in detail in Nascimento *et al*. (2021).[26] See also our COP26 Net Zero Atlas[27] or COP27 Net Zero Atlas[28] for more details. For France, Italy and Germany, which are only available in aggregated form as part of the EU27 in the NewClimate and IIASA datasets, we use the reference scenarios produced in the framework of the 'Fit for 55' package.[29]

The countries' 1.5°C carbon budgets are estimated based on our proprietary CLAIM model.[30] It uses a statistical approach to simulate millions of possible 'country shares' according to their climate and economic profile (historical emissions, energy intensity, GDP/capita, etc.). The model provides likely carbon budgets allocations consistent with a 2°C scenario whose global budget comes from the MESSAGE-GLOBIOM model used in the IPCC 's assessment reports.

2. **Calculating the sectoral potentials to fill the gap**

   Once the 1.5°C gaps are estimated, the second phase is to evaluate the capacity of economic sectors to deliver emissions reduction to fill these gaps. For each country, we use *s* 'marginal abatement cost curves' (MACC) to assess the sectoral abatement potential based on an economically efficient decarbonisation process. The optimisation consists of:

   i. assessing the sectoral emissions reduction implied by different levels of carbon price implemented uniformly in the whole economy,[31] giving the shape of the MACC curve for each sector; and

[26] Nascimento, L *et al*., 2021 [New Climate Institute]

[27] The COP26 Net Zero Atlas, FTSE Russell [FTSE Russell]

[28] The COP27 Net Zero Atlas, FTSE Russell [FTSE Russell]

[29] EU Reference Scenario 2020 [European Commission]

[30] For more details on the CLAIM methodology and the Implied Temperature Rise indicator, please see our paper: How to measure the temperature of sovereign assets, FTSE Russell [FTSE Russell]

[31] This estimation step is done internally by Enerdata through with the POLES model that ensures consistency of mitigation options across sectors. MACCs can also be estimated through surveys of businesses, case studies, or historical data on abatement costs. See for instance, Pathways to a low carbon economy, 2009 [McKingsey]

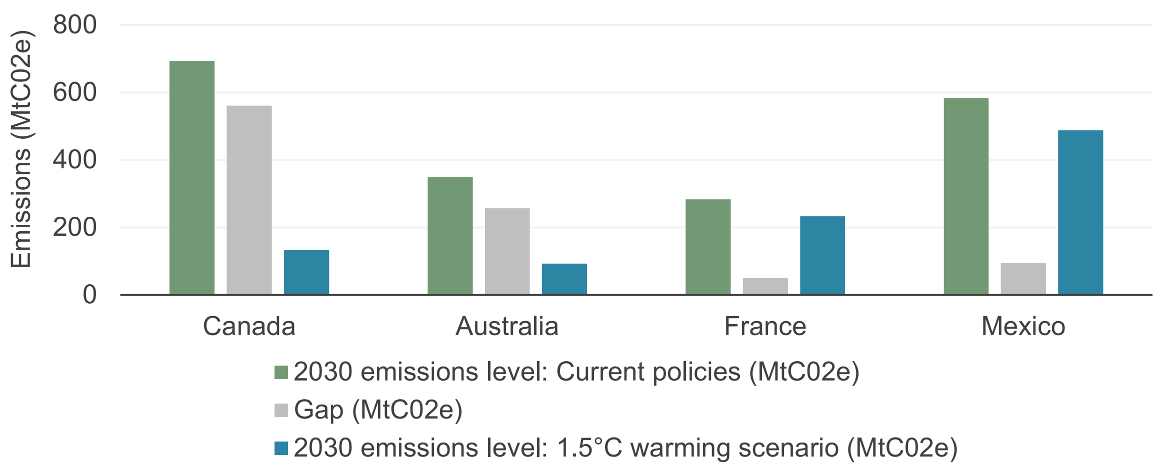
ii. minimising the abatement cost to achieve a certain global level of emission reduction (in our case filling the gap between current policies and 1.5°C), which eventually gives a volume of emission reduction by sector to achieve the target in the 'cheapest' way.

We rely on the MACCs provided by Enerdata[32] for the energy systems, industry, buildings and transport sectors, and based on Frank *et al*., 2021,[33] for the agriculture, forestry and other land use (AFOLU) sector. Key methodological steps:

- Enerdata provides a MACC for a standalone 'non-CO_2' sector that we reallocated to our energy systems, industry, buildings and transport sectors.[34] For instance, fugitive methane emissions from fossil energies production or F-Gas from industrial activities were reallocated respectively to energy systems and industry.
- As the Enerdata's MACC do not cover agriculture and land use sectors, we used the study from Frank *et al*. (2021) to incorporate these sectors and cover the full breadth of the economy. The resulting MACCs for the AFOLU sector were available for aggregated regions (such as Latin and Central America or Middle East and Africa). We used the World Bank database of agricultural land[35] and forest area[36] for downscaling to G20 countries level.

The integration of the AFOLU sector in the optimisation process led to a readjustment of its MACC so that the share of this sector in global mitigation efforts was aligned with usual results in the literature. In particular, we aligned our result at the aggregated G20 level on the meta-analysis done in the IPCC 6th assessment report[37] (see exhibit 10 for results).

Exhibit 9. Gap between current policies and 1.5°C-aligned scenario emissions in 2030



Source: FTSE Russell & Beyond Ratings, August 2023.

Illustrative example with Canada

Exhibit 9 illustrates the method outlined above: Canada's current policies imply that it will reduce its emissions to 693 MtCO2e by 2030, which is four times higher than the implied emission level for a 1.5-degree trajectory. Thus, the additional volume of GHG to abate would be 561 MtCO2e.

[32] See: Enerdata - Marginal Abatement Cost Curves
[33] Frank *et al*., 2021 [ERL]
[34] More details on the methodology are available on request.
[35] Agricultural land (sq. km) | Data (worldbank.org)
[36] Forest area (sq. km) | Data (worldbank.org)
[37] Figure: SPM.7 (ipcc.ch)

To achieve carbon neutrality by 2050, we estimate that a marginal carbon price of $860/tCO2e would be required.

3. **Categorising mitigation actions**

   The latest report from the IPCC (IPCC AR6 2022[38]) presents various mitigation solutions categorised by their abatement potential (measured in GtCO2e per year) and cost of abatement (in $/tCO2e) for the year 2030 (see exhibit 12). These solutions are grouped by the IPCC across five sectors: AFOLU, industry, energy, buildings, and transport.

   i. We take this analysis one step further, grouping those mitigation solutions into the following four mitigation activity categories (see exhibit 10):

      - **Ready-to-use decarbonisation technologies/ technology and production switch:** *Ready-to-use decarbonisation technologies* refers to the various methods and technologies aimed at reducing or eliminating carbon dioxide emissions from human activities, particularly those associated with the burning of fossil fuels (e.g., renewables energy, development of electric vehicles).

        Technology and production switch refers to the transition from high-carbon or carbon-intensive technologies and production processes to low-carbon or carbon-neutral alternatives. It involves adopting and using cleaner technologies and changing production methods to reduce greenhouse gas emissions (e.g., fuel switching, enhanced use of wood products, reduce emissions of fluorinated gas).

      - **Energy and resource efficiency** focuses on optimising the use of energy and resources to achieve the same level of output or service while consuming less (e.g., energy management system, building retrofitting, vehicle and industrial process efficiency, recycling, and circular economy). Here, we include land-based mitigation solutions where land is used in a more ‘carbon-efficient way’ (afforestation, forest management, etc.).

      - **Population-wide behavioural changes** refer to significant shifts in the attitudes, actions, and habits of a large group of people within a given population (e.g., use lighter personal vehicles, greater use of public transport or bikes, lower-carbon diets, and reduced waste creation).

      - **Early-stage decarbonisation technologies** refer to innovative and promising technologies that are still in the early stages of development, testing, and commercialisation with more considerable mitigation potential post-2030 (e.g., hydrogen, carbon capture and storage, carbon dioxide removals, etc.).

[38] Figure: SPM.7 (ipcc.ch)

Exhibit 10. Classification of mitigation activities

Category	Activity
Demand-side behavioural changes	Reduce food loss and food waste
	Shift to sustainable healthy diets
	Avoid demand for energy services
	Shift to public transportation
	Shift to bikes and e-bikes
Early-stage decarbonisation technologies	Carbon capture and storage
	Bioelectricity with CCS
	Fuel efficient heavy duty vehicles
	Electric heavy duty vehicles
	Carbon capture with utilisation and storage
	Cementitious material substitution
	Feedstock decarbonisation, process change
Energy & resources efficiency	Shipping-efficiency and optimisation
	Aviation- energy efficiency
	Reduce CH_4 emission from coal mining
	Reduce CH_4 emission from oil and gas
	Reduce CH_4 and N_2O emission in agriculture
	Reduce conversion of natural ecosystems
	Restoration, afforestation, reforestation
	Forest management, fire management
	Efficient lighting, appliances and equipment
	New buildings with high energy performance
	Improvement of existing building stock
	Energy efficiency
	Material efficiency
	Enhanced recycling
	Reduce CH_4 emission from solid waste
	Reduce CH_4 emission from wastewater

Category	Activity
Ready-to-use decarbonisation / technology & production switch	Bioelectricity
	Biofuels
	Wind energy
	Solar energy
	Nuclear energy
	Hydropower
	Geothermal energy
	Carbon sequestration in agriculture
	Onsite renewable production and use
	Enhanced use of wood products
	Fuel efficient light duty vehicles
	Electric light duty vehicles
	Fuel switching (electricity, natural gas, bio-energy, hydrogen (H_2))
	Reduction of non-CO_2 emissions (Industry)
	Reduce emission of fluorinated gas

Source: FTSE Russell & Beyond Ratings, , August 2023, based on Figure: SPM.7 (ipcc.ch)

ii. Based on our grouping by four activities and the IPCC's grouping by five sectors, we have a total of 20 combinations of sectors and categories, each with its corresponding mitigation potential (in GtCO2e/year) and cost of abatement (in $/tCO2e).

For each combination of sector and category, we calculate what we term an 'allocation key'. This is the proportion of abatement potential for a specific category that comes from that sector.

$$Abatement\ potential\ of\ a\ category\ of\ a\ sector\ (\%) = \frac{Abatement\ potential\ of\ a\ category\ of\ a\ specific\ sector\ (\frac{GtCO2e}{year})}{\sum Abatement\ potential\ of\ the\ 5\ sectors\ (\frac{GtCO2e}{year})}$$

For example, the 'ready to use decarbonisation and production switch' technologies in the energy sector have a mitigation potential of 8.98GtCO2e/year. The mitigation potential of all the mitigation solutions is equal to 29.52GtCO2e/year. Then, those technologies represent 86% of the abatement of the energy sector.

Those allocated keys are presented in exhibit 11.

Exhibit 11. Sectoral allocation key based on the IPCC meta-analysis from AR6[39]

	Energy & material efficiency	Population-wide behavioural changes	Deploying early-stage decarbonisation technologies	Ready-to-use decarbonisation / technology & production switch
Energy	14%	0%	0%	86%
AFOLU	53%	30%	0%	17%
Buildings	51%	26%	0%	24%
Transport	19%	20%	16%	45%
Industry	52%	0%	5%	43%
Total	35%	12%	3%	50%

Source: FTSE Russell & Beyond Ratings, August 2023.

iii. For each country and each category/sector, we multiply sectoral potential to fill the gap (previously calculated in step 2, i.e., the share of abatement per sector for each country) by this allocation key to get the abatement potential of a category of a specific sector:

$$\begin{aligned} &\textit{Abatement potential of a sector within a category for a country } (\%) \\ &\quad = \textit{Allocation key of this category and this sector} (\%) \\ &\quad * \textit{Abatement potential of this sector for this country} (\%) \end{aligned}$$

Illustrative example with France

The energy and material efficiency technologies represent 52% of the industry abatement potential (allocation key). Based on exhibit 10, industry represent 26% of French's abatement potential. Then, industry accounts for 13% of the abatement potential among the energy and material efficiency mitigation solutions.

The allocation key is based on the IPCC meta-analysis from AR6.[40]

Exhibit 12. Sectoral mitigation potential compared with IPCC

	Energy system	Industry	Buildings	Transport	AFOLU
This study (based on Enerdata and Frank et al. 2021)—G20	39%	25%	7%	8%	20%
AR6 IPCC*—World	40%	23%	7%	11%	20%

Source: FTSE Russell & Beyond Ratings, August 2023, based on Figure: SPM.7 (ipcc.ch)

[39] Figure: SPM.7 (ipcc.ch) and Exhibit 10 in this appendix
[40] Figure: SPM.7 (ipcc.ch) and Exhibit 10 in this appendix

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