CLIMATE ANALYTICS

Real zero: delivering a fossil free future

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About Climate Analytics

Climate Analytics is a global climate science and policy institute. Our mission is to deliver cutting-edge science, analysis and support to accelerate climate action and keep warming below 1.5°C.

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Summary

Due to continued reliance on fossil fuels globally, global warming is now likely to exceed 1.5°C relative to pre-industrial levels by around 2030. We will need to reverse that warming and bring temperatures back down below 1.5°C as quickly as possible, which will require rapid and far-reaching cuts to greenhouse gas emissions, starting immediately. However, debate remains about the best strategy by which to reduce emissions.

Climate science has identified that achieving net zero will be critical to achieving our climate goals. Global warming will stop when we reach net zero CO_2 emissions and start to fall again as we reach and sustain net zero greenhouse gas (GHG) emissions. Stemming from Article 4.1 of the Paris Agreement, net zero has become embedded in global climate decision-making and accountability. In particular, net zero has emerged as a dominant framework for national and corporate climate action, with 70% of all countries, and over 60% of the world's top 2000 companies pledging to achieve net zero by or around mid-century.

But not all net zero goals are created equal. As originally intentioned, these national and corporate climate action net zero goals are laudable – reducing greenhouse gas emissions to as close to zero as possible, with any remaining emissions being compensated for by negative emissions. But in practice many national and corporate climate pledges envisage large-scale continued combustion of fossil fuels, with the resulting emissions compensated for by CCS and CDR.

This approach contrasts with real zero: the complete elimination of fossil fuels by replacing them with zero-carbon alternatives, rather than compensating for them with offsets, carbon dioxide removal or carbon capture and storage (Figure ES1).

Overreliance on CCS and CDR, while neglecting the primary pillar of climate action – phasing out fossil fuels, is a high risk climate strategy. CCS has fundamental technological, infrastructural and geophysical limits which will make deploying it at scale highly challenging, prohibitively expensive and prone to failure. Meanwhile any CDR which is successfully deployed needs to be prioritised to drive temperature reductions, rather than enable the continued combustion of fossil fuels.

If we are to achieve net zero CO_2 emissions at the global level before 2050, and net zero GHG soon after, then in most sectors we will need to achieve real zero – the complete elimination of fossil fuels – before 2050. The viability of real zero is only growing over time as zero-carbon technologies rapidly advance and mature, and their costs fall.

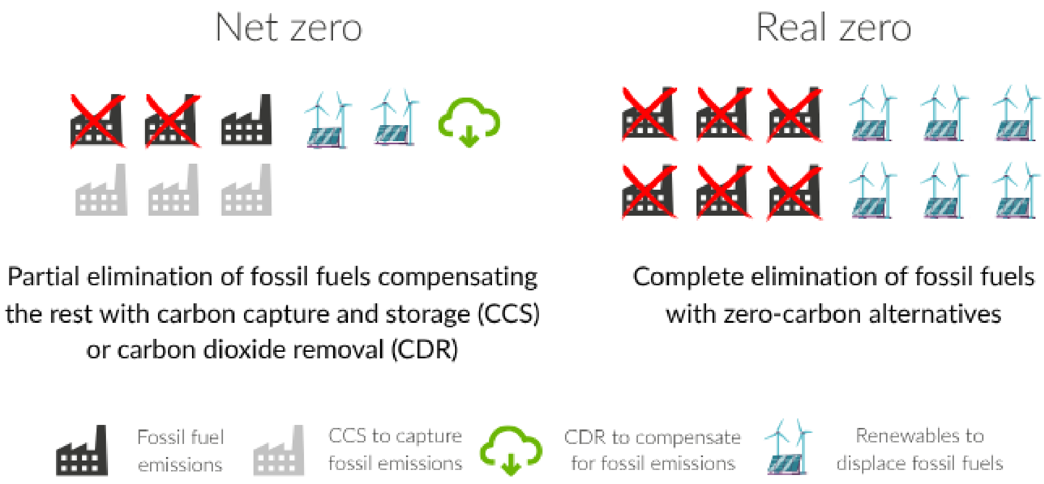

Figure ES1: The difference between real zero and net zero emissions goals

This report explores the technical feasibility of real zero in key sectors of the economy, assessing when different sectors could fully eliminate fossil fuels, and the key technologies and measures which are needed to do so.

The report covers five key sectors of the energy system – trucks, steel, shipping, power and light-duty vehicles.

Drawing on two key lines of evidence – the latest energy and emissions pathways from global integrated assessment models (IAMs), and a review of sector-specific and bottom-up modelling of transformation pathways – the report assesses the current state of knowledge on the feasibility of real zero in the literature, and provides initial estimates of the dates by which real zero could be reached in leading regions.

- **Our analysis suggests that real zero trucking could be achievable as early as 2040 in leading regions, particularly Europe, with global real zero achievable by 2050.** Electrification is the dominant lever for achieving real zero in the trucking sector, due to their clear economic and technical superiority of electric vehicles over alternative zero-emissions vehicles in the majority of use cases.
- **The earliest dates of real zero for steel are 2040 in some IAM scenarios.** This is over a decade ahead of what is perceived as possible in the broader literature, none of which reports real zero by 2050. This could be due to bottom-up studies underestimating the competition for scarce CO_2 storage resource, differences in the level of ambition assessed, or variations in the representation of the steel sector between different modelling approaches. While further investigation is needed, **we suggest that real zero steel by 2040 could act as a stretch target for the sector, with real zero by 2050 as a threshold for which there is more confidence.** A real zero steel sector would require the rapid deployment of zero-carbon measures for primary steel production, the leading option of which would be to use green hydrogen as a reducing agent. Alongside expanded secondary steel production, green hydrogen and electricity will be key drivers of a real zero steel sector.
- **International shipping could achieve real zero by 2050**, with both IAMs and shipping-specific literature identifying this as a technically feasible goal. Ammonia emerges as one particularly promising zero-carbon fuel, although other options such as direct electrification for shorter-distance trips and biomethanol could also contribute.
- **Real zero in light-duty vehicles is achievable by the early 2040s, with very deep reductions possible even earlier.** Again, electrification is at the heart of the transition.
- **Real zero in the power sector is achievable by 2040,** with six different IAM frameworks able to achieve this goal by or during the 2040s. As electricity is the key driver of real zero in many other sectors, cleaning up the power sector is critical to achieving real zero across the full system. Wind and solar emerge as the backbone of a real zero power sector.

It is important to note that in all instances that this report argues that real zero can be achieved by a certain date, this should be interpreted as *at that date or earlier*.

This initial analysis demonstrates that a fossil free energy system is a very real possibility for key sectors within the next 20 years. If leading regions can achieve real zero at or around the 2040s, then leading companies within these regions should be aiming to achieve real zero even sooner, with the first real zero companies achieving this goal in the 2030s and with a growing consortium of real zero companies by 2040.

Companies that embrace real zero will position themselves at the forefront of the emerging zero-carbon economy. Meanwhile, those that continue to rely on CCS/CDR risk being competitively disadvantaged as zero-carbon alternatives become increasingly cost-effective. The transition to real zero is not a distant aspiration, but an immediate and tangible opportunity.

Three small letters can make a world of difference. "Net" zero is not the same as zero. It is time to shift focus from net zero to real zero in as many sectors as possible, as quickly as possible.

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Acronyms

AER	Annual Efficiency Ratio
BET	Battery Electric Trucks
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CAGR	Compound Annual Growth Rate
CCS	Carbon Capture and Sequestration
CCUS	Carbon Capture, Utilisation, and Sequestration
CDR	Carbon Dioxide Removal
DCS	Distributed Control System
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EEOI	Energy Efficiency Operational Indicator
ERS	Electric Road System
ETC	Energy Transition Commission
GCAM	Global Change Assessment Model
GHG	Green House Gas(es)
HYBRIT	Hydrogen Breakthrough Ironmaking Technology
HYFOR	Hydrogen-based Fine-ore Reduction
HFCT	Hydrogen Fuel Cell Truck
IAM	Integrated Assessment Model
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
IMAGE	Integrated Model to Assess the Global Environment
IMO	International Maritime Organisation
IPCC AR6	Intergovernmental Panel on Climate Change's Sixth Assessment Report
LDV	Light Duty Vehicle
LNG	Liquid Natural Gas

LSFO	Low Sulfur Fuel Oil
MCS	Megawatt Charging System
MDO	Marine Diesel Oil
MPP	Mission Possible Partnership
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PBS	Possible But Stretching
PV	Photovoltaic
REMIND	REgional Model of Investment and Development
SZEF	Scalable Zero-Emission Fuel
T&E	Transport and Environment
ULCOS	Ultra-Low CO_2 Steelmaking
UMAS	University Maritime Advisory Service
UNFCCC	United Nations Framework Convention on Climate Change
WITCH	World Induced Technical Change Hybrid
ZET	Zero Emission Truck

Introduction

The importance of reaching real zero

We need to bring emissions down to zero to tackle the climate crisis. The science is clear – global warming will stop at the point that we reach zero CO_2 emissions and temperatures will begin to fall again as we reach and sustain zero total greenhouse gas emissions (IPCC, 2021, 2022).

But how should we reach zero? Most existing targets and policy frameworks are focused on the idea of "net zero". This is a state where any remaining residual emissions are balanced out by removals. The Paris Agreement commits signatories to collectively achieving net zero greenhouse gas (GHG) emissions, with Article 4.1 setting out the goal of achieving a "balance of sources and sinks" in the second half of the century.

Net zero is a critical concept when looking at global emissions (Allen et al., 2009). First, when looking at total GHG emissions, there are certain residual non-CO_2 emissions (such as methane emissions from agriculture), which will be impossible to reduce fully to zero. Therefore, reaching zero global greenhouse gas emissions, as required by the Paris Agreement, and as critical for driving long-term temperature decline, will always mean reaching *net* zero GHGs. This will require negative CO_2 emissions compensating a remainder of unavoidable non-CO_2 emissions. Second, while in the long-term it may be possible to fully eliminate all CO_2 emissions and reach real zero CO_2 emissions, by mid-century it is likely that some residual CO_2 emissions will remain, which would need to be counterbalanced by carbon dioxide removal (CDR). Reaching net zero CO_2 emissions by or around 2050, and net zero greenhouse gas emissions soon after are clear milestones that were identified by the IPCC in sequential reports (IPCC, 2018, 2022).

However, net zero is no longer simply a scientific concept or a global milestone. The framing of "net zero" has proliferated, with hundreds of countries, sub-national governments and increasingly corporations signing up to reach net zero by mid-century or soon after. Over 60% of the world's top 2000 companies have pledged to reach net zero, including several fossil fuel majors (Net Zero Tracker, 2025).

In some of these transition plans, fossil fuel demand is reduced somewhat from today's levels, but remains substantially above zero. Any remaining fossil fuel combustion is addressed by carbon management, which means deploying either fossil carbon capture and storage (CCS) or CDR. In the first case, CCS captures and stores the emissions from fossil fuel combustion. As CCS capture rates will never be 100%, in order to reach net zero some residual emissions would need to be compensated for by technological CDR approaches such as bioenergy with CCS (BECCS), direct air carbon capture and storage (DACCS) or nature-based CDR such as afforestation/reforestation (A/R). In some sectors, such as transport, applying CCS to moving emissions sources is not possible. Here carbon management would involve using CDR to compensate for all remaining fossil fuel emissions.

Relying heavily on fossil CCS and technological or nature-based CDR, is a substantial risk for a range of reasons.

First, both CCS and technological CDR are (broadly) nascent sets of technologies, with very limited deployment to-date. Both face a wide range of hurdles to their successful deployment, including substantial technological complexity, high costs, geo-physical limitations such as limited CO_2 storage space, constraints on water availability and more (Byers et al., 2016; Gidden et al., 2025; Grant et al., 2022; Kazlou et al., 2024; Lane et al., 2021; Malhotra & Schmidt, 2020).

Fossil CCS has a very poor track record, with over 80% of demonstration projects over 1990–2020 ending in failure (N. Wang et al., 2021), and as some technological CDR approaches rely on CCS as a component, they are likely to face similar deployment challenges. There are similarly significant limitations to the scale of nature-based CDR that is possible (Deprez et al., 2024; Fesenmyer et al., 2025; Y. Wang et al., 2025). Therefore, betting on a large CCS and CDR resource that can be used to enable continued fossil demand is a highly risky and questionable strategy.

Second, if CCS/CDR approaches are successfully scaled, some of these approaches, particularly BECCS and A/R could have significant negative impacts on food prices, biodiversity and broader sustainability concerns if deployed at large scale (Deprez et al., 2024; Heck et al., 2018).

Third, compensating for fossil CO_2 emissions with nature-based CDR fails to account for the fact that carbon sequestered in forests and soil is only temporary, and can be lost back to the atmosphere for several reasons. In contrast, the warming impact of fossil CO_2 emissions is essentially permanent. Using temporary removals to offset permanent warming is erroneous accounting, and undermines efforts to reduce temperatures (Dooley et al., 2022).

Finally, if we do manage to scale CDR technologies, we will need it to bring temperatures back below 1.5°C. It seems increasingly certain that we are set to head into of a period of overshooting the 1.5°C temperature limit (Reisinger et al., 2025). In this scenario, minimising the extent and duration of overshoot becomes critical to reducing the risk of irreversible tipping points and climate impacts. Bringing temperatures back down will require deep reductions in non-CO_2 emissions and scaling up CDR to the maximum levels that are achievable within sustainable bounds. However, given the constraints on CDR deployment, there will not be enough CDR deployed to both bring temperatures down and offset continued large-scale fossil fuel consumption. As a result, it is essential that fossil fuel production and use is cut to the very lowest levels possible, and as fast as possible. Allowing fossil fuel use to continue will otherwise fundamentally undermine efforts to reduce long-term temperatures.

If we are to achieve global net zero, we therefore need to achieve real zero in most sectors. Real zero means fully eliminating fossil fuels, rather than relying on CCS or CDR to compensate for their continued use. Large-scale CCS and CDR deployment, by enabling continued long-term use of fossil fuels in a wide range of sectors, could undermine our ability to achieve net zero GHGs at the global level, as committed to by the Paris Agreement.

A growing set of voices across academia, civil society and industry are coalescing around real zero as a way to reset the climate action debate. By committing to actually eliminating fossil fuels, we can avoid reliance on risky fossil CCS, and free up CDR to deploy to bring temperatures back down, rather than merely offsetting the tail end of a fossil economy.

Real zero: a feasible target, an economic opportunity

Aiming for real zero can help drive transformative change towards a fossil-free economy.

As the cost of renewables and batteries continues to decline rapidly, the feasibility of achieving real zero in many contexts is only growing. In sector after sector which were traditionally deemed “hard-to-abate”, where fossil fuel use was “unavoidable”, zero-carbon technologies are becoming increasingly competitive. In 2015, real zero was a niche exception in a few cases, but now it is a real possibility for many sectors in the energy system. While some residual cases still hold out, the current pace of innovation in fossil-free technologies suggests that the feasibility frontier of real zero will only expand to more sectors in the coming years.

However, feasibility is a multi-faceted concept. It is one thing to identify a pathway to a fossil-free system which is technically possible. It is another to demonstrate that it is economically viable for a company concerned with its bottom line. In all of this, the role of policy and consumer demands and expectations also play a critical role.

In this report and the accompanying analysis on the economic feasibility of Real Zero using case studies (Climate Analytics, 2025), we provide initial findings that suggest real zero is not a pipe dream – but a technically feasible and economically desirable goal that can serve as the North Star for corporate climate action in a wide range of sectors.

In this report, we assess the existing evidence on the technical feasibility of reaching real zero in five key sectors of the energy system – road freight, steel production, international shipping, power generation, and light-duty passenger transport. Using both top-down and bottom-up modelling and literature as key lines of evidence, we assess how fast these sectors can reach real zero, and the technologies which can drive the achievement of real zero. We demonstrate that real zero is feasible within techno-economic constraints and can be achieved in the early 2040s in many sectors. Leading corporations within these sectors who want to reap the benefits of a real zero set-up should therefore aim to achieve deep reductions in fossil fuel use by the early 2030s, with real zero targets around 2040, and in some cases before.

In the accompanying report – *Real zero: an opportunity, not a cost* – on the economic feasibility of real zero, we dive into the detail on the economics of achieving real zero. Looking in-depth at the transition to battery electric trucks in Europe, green steel in Japan and green fertiliser in India, we assess the economic opportunity of real zero and compare it to alternatives such as a business-as-usual case, or a corporate net zero strategy which focuses on reducing emissions but not necessarily reducing fossil fuel demand. We highlight the huge prize to be gained by a transition to a fossil-free system – with vast operational cost savings from renewable electrification, reduced exposure to volatile fossil fuel markets, and the potential to benefit from a "first mover" advantage. Many real zero strategies require large-scale up-front investment. But investments are not necessarily costs – if they unlock significant advantages.

The economic opportunity of real zero is also a function of the policy context in which a corporation operates. Supporting and enabling policies that can bring down the cost of capital, provide a market for green products, level the playing field with fossil incumbents by pricing their externalities and more. The case studies in the economic analysis also highlight the places where supporting policy is needed to unlock the economic opportunity of real zero.

Three small letters can make a world of difference. “Net” zero is not the same as zero. At the corporate level, we need to shift focus from net zero to real zero in as many sectors as it is possible to do so. This series of reports begins to outline the feasibility and desirability of the real zero transition at the corporate level.

While further analysis can help refine our understanding of the pathways to a fossil-free economy, it is also time for action. Companies seeking to lead the transition to a new economy have a key role to play – setting ambitious real zero targets and getting down to business on the task of reshaping their supply chains, technology portfolios and business models to align with the coming zero-carbon world. Latecomers may see their economic competitiveness seriously undermined.

Methods summary

This report aims to identify dates by which real-zero could be reached in key energy system sectors, and the technologies and fuels that could eliminate fossil fuels in these areas. To do so it draws on two key lines of evidence, which are deep mitigation pathways from integrated assessment models (IAMs), and an in-depth review of sector-specific transition pathways from energy system models, industry roadmaps and the wider literature. These are summarised further below, with more detail in the Methods Annex.

Real zero: evidence from the global pathways

IAMs are a key line of evidence in setting global, regional and sectoral climate ambition, and have been used in a wide range of settings to inform on mitigation strategies. Two key strengths of IAMs for the purpose of this work are that they:

- **Capture sectoral interlinkages.** IAMs model the full energy system, incorporating both supply-side (e.g. electricity generation, hydrogen production) and demand-side sectors. This means that they can help map out the connections between sectors, such as the need for green hydrogen to help decarbonise primary steel production. While these interlinkages are sometimes represented in relatively coarse detail, IAMs offer the potential to better interrogate inter-sectoral linkages better than standalone sectoral modelling.
- **Represent high-ambition energy transitions.** In this report, we focus on assessing the "leading edge", by which we mean the fastest pace at which fossil fuel demand could be reduced to real zero in different sectors. We are therefore exploring the feasibility frontier of sectoral transitions. While the feasibility frontier in a sector is inherently unknown, the more ambitious a pathway is, the closer it likely comes to the feasibility frontier. The IAM pathways that we assess all attempt to limit peak warming to very low levels.[1] As such, they push the

[1] The majority of the scenarios we assess are compatible with limiting warming to 1.5°C with low overshoot, i.e. the C1a scenario classification from the IPCC's AR6 report. However, where alternative pathways show faster pathways to real zero in a particular sector, we still incorporate their insights, even if they have slightly higher total fossil fuel consumption and temperature outcomes.

energy system transition as fast as possible (within their constraints) to reduce emissions. This means that the sectoral transitions are likely to be closer to the feasibility frontier than pathways which take existing (inadequate) climate and energy goals such as NDCs and net zero targets as the starting point to define ambition.

We review the literature to identify the latest energy and emissions pathways produced by IAMs that can inform pathways to real zero. We look at sources provided since the IPCC's AR6 assessment, to ensure we are capturing the latest scenario evidence.[2] The full list of sources covered is highlighted in **Error! Reference source not found.**.

Source	Models captured
Edelenbosch *et al* (2024)	IMAGE 3.3
Soergel *et al* (2024)	IMAGE 3.3, REMIND-MAgPIE 3.2-4.6
Fuhrman *et al* (2024)	GCAM 7.2
NGFS (2024)	GCAM 6.0, REMIND-MAgPIE 3.3-4.8
Van Heerden *et al* (2025)	IMAGE 3.3, REMIND 3.0, WITCH 5.0, COFFEE 1.5
Schreyer *et al* (2025)	REMIND 3.3
(Climate Analytics and PIK, 2025)	REMIND 3.5

Table 1: Global pathways assessed in this report

Not all IAMs provide sufficiently granular data to assess whether they are reaching real zero in each sector (for example some IAM pathways only report total transport emissions and energy, not the sub-sectors of trucks, light duty vehicles and other modes). Therefore, not every reviewed IAM contributes to the analysis for every sector.

For each IAM pathway, we also applied a variable prioritisation tree. This means that if a pathway reports fossil fuel demand in a sector, this is taken as the measure of a pathways' progress towards real zero. If this data is missing then our methodology infills this data using emissions data, followed by the use of proxy variables such as demand

[2] We do not include the IPCC AR6 database, as very few models provided sector-specific information on trucks, shipping, steel or light-duty vehicles, and therefore the utility of this dataset for the analysis is limited.

for solids as a proxy for the demand for coal. For more details see the Methodology Annex.

In some of the IAM pathways we assess, action to peak and rapidly reduce emissions starts in 2020. This is because many IAMs model the world in five-year timesteps, and so it is only post-2025 that they will be able to recalibrate to capture the real-world outcomes of the early 2020s, in which global fossil fuel demand and emissions remained stubbornly high. To account for this, we exclude any pathways in which the change in fossil fuel demand in 2025 falls significantly (more than 5%) below the best estimate of 2025 levels, which we construct using International Energy Agency (IEA) data that covers the period up to 2023. This filtering is applied at the level of each sector. For more details see the Methodology Annex.

It is important to note that, with the exception of Schreyer et al. 2025, the pathways produced by these models do not look explicitly to achieve real zero in any particular sector, or region. Instead, each model optimises global emissions reductions under a set of constraints (for example, the availability of CCS, or limits to the growth rates of zero-carbon technologies). Sectoral and regional reductions are then achieved if, when and where the costs to reduce emissions is lower than elsewhere. The large variety in inputs and optimisation assumptions for each modelled pathway leads to the variations in the sections below of where and when real zero is reached. By contrast, if the models were driven by constraints on specific sectors and regions, in many instances real zero could be achieved earlier. In that sense, in all instances that this report argues that real zero can be achieved by a certain date, this should be interpreted as *at that date or earlier*. An earlier real zero date in any sector would always be preferable to provide some hedging against decarbonisation setbacks in other sectors.

Real zero: evidence from sectoral and national roadmaps

While IAMs are a key line of evidence in guiding global climate action, IAMs also have a series of limitations. As multi-regional, multi-sectoral models exploring energy-economy-land-use developments out to 2100, these models have to make steps to simplify their representation of individual sectors. While IAMs are increasingly including reflecting the diversity of technologies available in key sectors (Krey 2014, Keppo *et al* 2021), their sectoral resolution is still sometimes below that of more detailed sector- or region-specific modelling work.

We therefore complement the IAMs with a second line of evidence, which is a review of the literature on decarbonisation that comes from sector-specific and regional/national roadmaps. We conduct a wide literature review for three key sectors of **trucks, steel** and **shipping**, and extract the most ambitious decarbonisation pathways per sector to compare and contrast with the IAM results. Table 2 summarises the literature reviewed.

We do not conduct a literature review for the power sector and the light-duty vehicle (LDV) sector. This is because these are sectors where the evidence base on the potential for achieving real zero is most well evidenced, including by both IAMs (Luderer et al., 2021), bottom-up sectoral studies (Brown et al., 2018) , and approaches which take a more hybrid approach (Climate Action Tracker, 2023, 2024). As such, we here present the results from the IAMs alone as a first assessment of the feasibility of achieving real zero. Future work could complement these sectors alongside a wider literature review.

Sector	List of studies reviewed	Key studies highlighted
Trucks	*(Basma & Rodríguez, 2023b; ETC, 2023; ICCT, 2020; Mission Possible Partnership, 2022; Net-Zero America, 2021; UIRR & d-fine, 2022)*	*(Basma & Rodríguez, 2023b; ETC, 2023; Mission Possible Partnership, 2022; Transport & Enviroment, 2022)*
Steel	*(Bataille et al., 2024; Chang et al., 2023; Durga et al., 2024; Hebeda et al., 2023; Kumar, 2022; Making Net-Zero Steel Possible: An Industry-Backed, 1.5°C-Aligned Transition Strategy, 2021; Net Zero Emissions Guide - Steel and Aluminium, 2023; The State of the European Steel Transition, 2025; OECD, 2025; Vercoulen et al., 2023; Yu et al., 2021)*	*(Bataille et al., 2024; Durga et al., 2024; Hebeda et al., 2023; Mission Possible Partnership, 2022; Net Zero Emissions Guide - Steel and Aluminium, 2023; The State of the European Steel Transition, 2025; OECD, 2025; Yu et al., 2021)*
Shipping	*(Smith et al., 2025, MMMCZCS, 2022, Transport & Environment, 2025, SBTi, 2023)*	*(Smith et al., 2025, MMMCZCS, 2022, Transport & Environment, 2025, SBTi, 2023)*

Table 2: Sectoral and regional decarbonisation roadmaps reviewed for this report.

Trucks

Global trucking activity has reached an all-time high of 32.8 trillion tonne-kilometres in 2023 and is projected to double by 2050(World Economic Forum, 2024). In 2023, medium and heavy-duty trucks produced about 1.9 gigatonnes of direct CO_2 emissions, which accounted for about 5% of total global CO_2 emissions and over a quarter of all road transport emissions, despite representing less than 4% of vehicles on the road (World Economic Forum, 2024a).

While the sector has achieved a 14% improvement in emission intensity since 2019 through advances in fuel efficiency and logistics, it remains heavily dependent on fossil fuels, with diesel providing 96% of trucking energy use and low emissions fuels (largely biofuels) making up the remaining 4% (World Economic Forum, 2024b).

The key options to eliminate fossil fuels from trucks involve a range of zero-carbon technologies, including battery electric trucks (BETs) and hydrogen fuel cell trucks (HFCTs). Meanwhile, the competing view would involve continuing to use internal combustion engines (ICEs), and compensating for these emissions via CDR.

Global pathways

Our review identifies three different models that provide data on deep decarbonisation of the trucking sector, which are the GCAM (Global Change Assessment Model), IMAGE (Integrated Model to Assess the Global Environment) and REMIND modelling frameworks. We distinguish between different versions of REMIND due to the significant developments in modelling of deep electrification that have been made over recent years in these modelling frameworks (Muessel et al., 2025).

Figure 1 highlights the overall results for the trucking sector across these different models. The figure shows, for each model, the reductions in oil demand for trucks seen across all regions shown in grey dots.[3] The three most ambitious regions per model are then highlighted in coloured markers, which helps to identify the leading edge of how fast different models can achieve real zero.

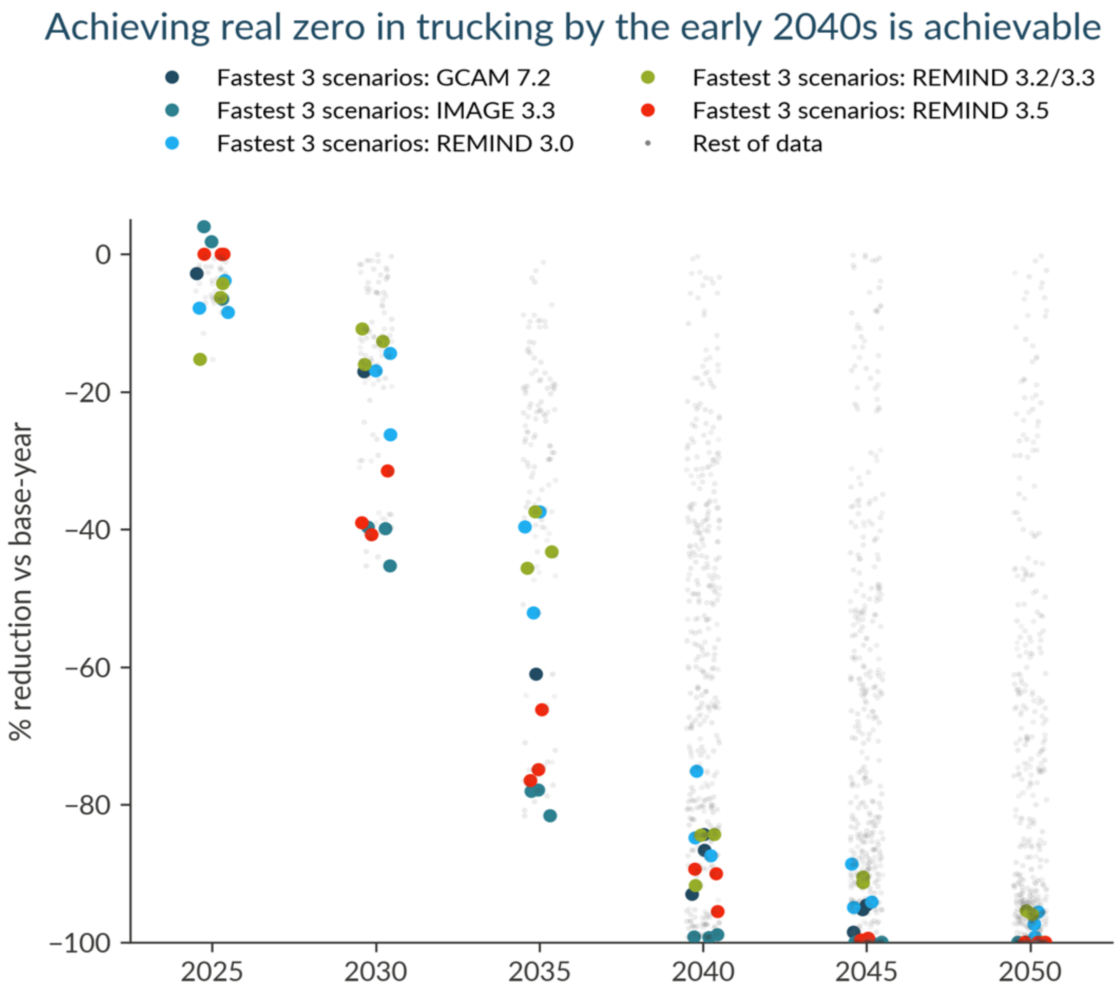


Figure 1: Achieving real zero in the trucking sector – evidence from the global pathways

[3] Where models do not report oil demand, we take emissions from the trucking sector as a proxy for oil demand

Rapid and deep reductions in oil demand for trucking are achievable. By 2035, the most ambitious models suggest oil demand could drop between 60% and 85%. Meanwhile, by 2040 all models can achieve between 80–100% reduction in oil demand in trucks in leading regions.

Figure 2 highlights how many models achieve real zero in each region, and how many regions achieve real zero in each model. We define real zero here as achieving greater than 99% reduction in fossil fuel consumption, relative to the base-year of the scenario. The most ambitious model (in this case the IMAGE 3.3 model), achieves real zero in the trucking sector by 2040. The model reaches real zero in two regions in 2040 (Europe and the Pacific OECD) and achieves real zero in all further regions globally by 2045 – except for Greater China. Meanwhile by 2045 two versions of REMIND (REMIND 3.2/3.3 and REMIND 3.5) also reach real zero in trucks in Europe, while REMIND 3.5 also reaches real zero in North America and the Rest of the OECD regions. By 2050 all five reviewed models have achieved real zero in Europe, GCAM has achieved real zero in all modelled regions, and IMAGE and REMIND 3.5 have achieved real zero in a wide range of regions.

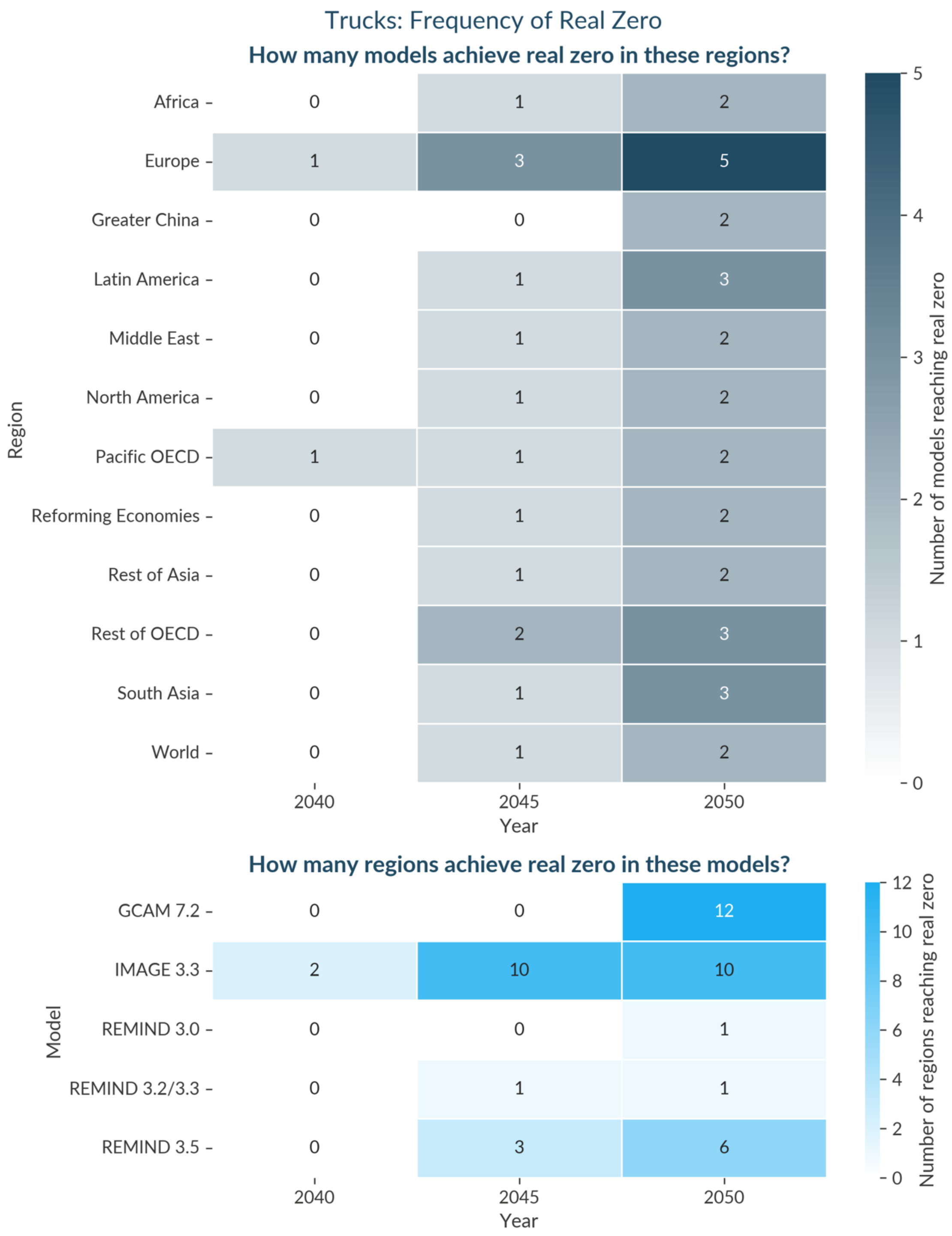


Figure 2: Frequency at which different regions and models achieve real zero

There is therefore some evidence in current integrated assessment modelling that trucks could achieve real zero by 2040 in leading regions (particularly the EU) and increasing evidence that real zero is achievable in more regions throughout the 2040s.

This is shown in Figure 3, which highlights the ambition frontier for emissions reductions in the trucking sector across the reviewed IAMs pathways. This graph shows, for any given reduction in oil demand, how many times the five models achieve a given reduction. As each model can report data for multiple regions and multiple scenarios, we look for the most ambitious outcome in each model/region pair, looking across all scenarios. This prevents one model which has many scenarios featured in the database from overly biasing the results of the analysis. If a particular model achieves a certain reduction in a particular region (across any of the scenarios assessed), this counts as this model achieving this reduction.

While in 2040 only two regions achieve real zero (and only in the IMAGE 3.3 model), by 2050 there are over 20 model-region combinations which have achieved real zero in the trucking sector, increasing our confidence in the feasibility of a fully fossil-free trucking sector pre-2050.

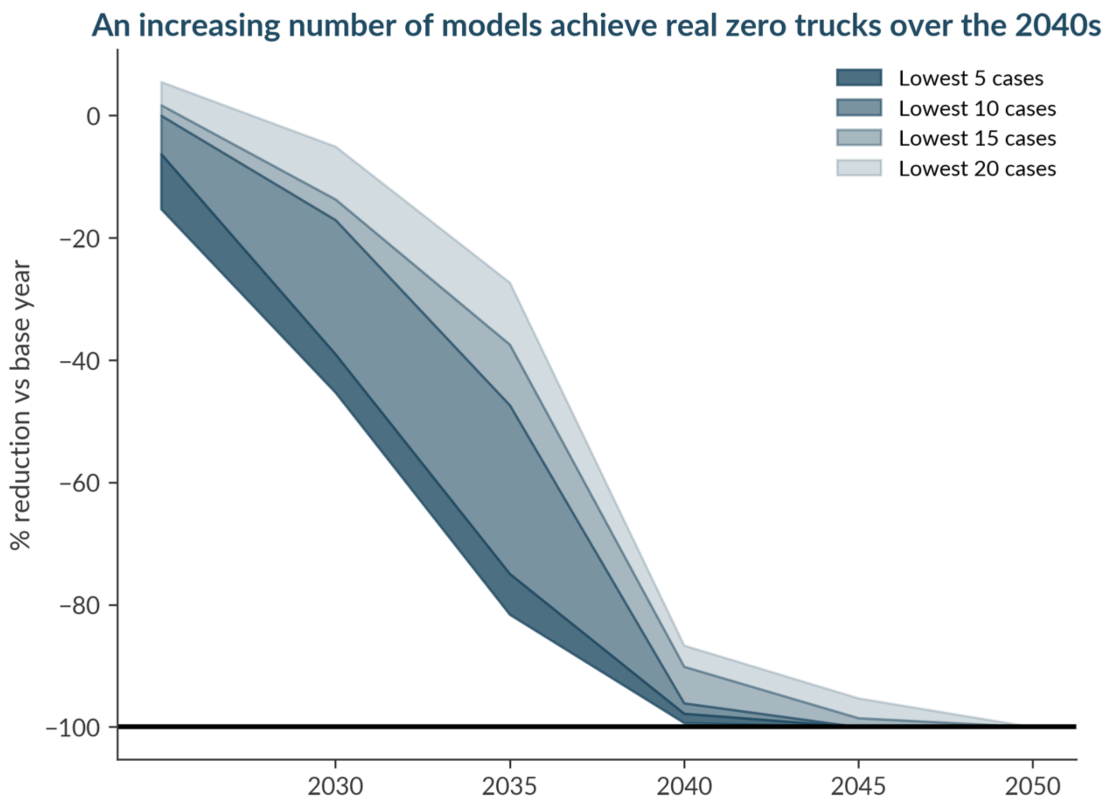


Figure 3: The ambition frontier for achieving real zero from trucking – evidence from the global pathways

Figure 4 shows the fuel mix that delivers real zero across the reviewed models. While there is a variation in this fuel mix across models, most models see electricity as the dominant energy carrier in decarbonising the trucking sector. The REMIND modelling framework suggests that electricity could meet 80–100% of final energy demand in trucks, with a much smaller component provided by hydrogen or remaining liquid demand from biomass or synthetic fuels. Meanwhile the GCAM model has a higher share of hydrogen in the final energy mix, reaching up to 40% of final energy demand, but still sees electrification as the dominant route. The outlier in this set of models is the IMAGE model, which relies almost entirely on hydrogen for truck decarbonisation, with a small component of biomass. As discussed later, this is very likely be a significant overestimate of the role of hydrogen within trucking, given the very rapid progress in battery technology occurring currently, and the strong benefits of electrification over hydrogen.

It is likely that a real zero trucking sector can be delivered primarily (and indeed entirely) by electrification.

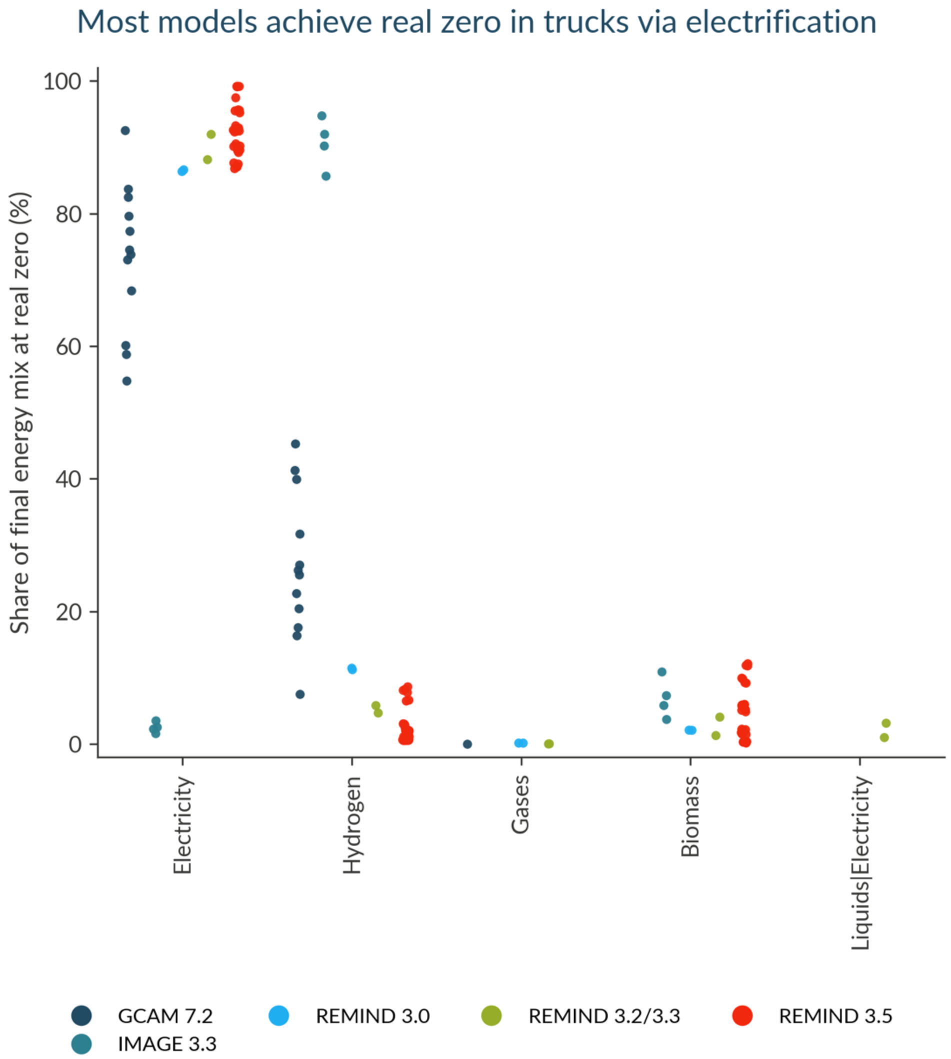


Figure 4: The fuel mix that delivers real zero in trucking – evidence from the global pathways

Literature review

Recent technological and policy assessments reveal heavy duty trucking decarbonisation pathways reach real zero a few years later than IAM projections suggest.

Pathways to real zero from the literature

We assess a wide range of scenarios that explore truck decarbonisation (see Table 2 in Methods). We then focus on a set of four key studies which demonstrate the potential for reaching real zero in the trucking sector. These are the Mission Possible Partnership (MPP)'s study, two Europe-focused reports from Transport and Environment (T&E), the

Energy Transition Commission (ETC)'s analysis of the global trucking sector and analysis from ICCT.

The first from Mission Possible Partnership achieves complete heavy-duty vehicle decarbonisation by 2050 in four key regions – Europe, US, China and India. Zero emissions trucks (i.e. battery electric trucks and hydrogen fuel cell trucks) achieve parity with their fossil counterparts, supported by a carbon price up to $250/t CO_2 (Mission Possible Partnership, 2022). Globally zero emissions trucks (ZET) sales increase to almost 40% of total sales in 2035 and 100% by 2040, resulting in a fully zero-emissions fleet by 2050. Achieving this across Europe, China, United States, and India requires significant infrastructure deployment of 1.4 million to 1.8 million overnight depot chargers as well as 400,000 to 700,000 high-speed chargers for Battery Electric Trucks (BETs) and up to 19,000 hydrogen refuelling stations by 2030 (Mission Possible Partnership, 2022). The MPP scenario relies on a diverse mix of hydrogen and BETs. We explore the technology mix further in the following section – but the key point to make here is that this scenario shows a pathway which scales up zero-carbon alternatives in order to eliminate sales of diesel trucks by 2040, and has a fully zero-carbon rolling stock by 2050 (**Error! Reference source not found.**).

The potential for real-zero in trucking by 2050 is further supported by analysis from Transport & Environment. Their 2022 report presents two scenarios for Europe – a central scenario which achieves 65% ZET sales by 2030 across all truck categories in Europe, and an accelerated scenario which achieves 100% ZET sales by 2030. This report does not consider an accelerated stock turnover for trucks and so assumes that diesel trucks have a lifetime of around 14-18 years (Transport & Enviroment, 2022). Despite this, the central scenario achieves a 95% CO_2 emission reduction by 2050 compared to 1990 levels, and the accelerated scenario a 98% reduction. The central scenario still leaves 0.9 million diesel trucks operating in 2050, about 13% of the fleet with an average age of 21 years making up the remaining 5% of emissions (Transport & Enviroment, 2022). Meanwhile the accelerated scenario achieves 100% ZETs before 2050.

Meanwhile ETC's 2023 Possible but Stretching (PBS) scenario also achieves full truck decarbonization by 2050, here at the global level, by coupling aggressive ZET adoption with accelerated fleet retirement policies. ZET adoption following an S-curve based on total cost of ownership decisions between ICEs, BETs, and HFCTs, with the vast majority of the trucking sector shifting to electric trucks. A critical enabler for achieving the 2050 target is reducing ICE vehicle lifespans through forced retirement policies of complete ICE use bans by 2044 in developed economies and progressive phase-outs by 2050 in developing economies (ETC, 2023).

Finally, ICCT 2023, which evaluates the technological and regulatory landscape in European trucks, places the earliest date of 100% ZET sales at 2040. This 2040 date for new fleet decarbonisation is achieved under a modelled scenario in which emissions from new trucks fall 60% by 2030, 90% by 2035, and 100% by 2040, cementing voluntary pledges from primary manufacturers (Basma & Rodríguez, 2023b). Achieving 100% ZET sales by 2040 could lead to a fully decarbonised rolling stock by 2050, as long as it is accompanied with policies to accelerate the retirement of ICE trucks, as in the ETC's analysis.

The share of sales that come from ZETs across the reviewed literature is shown in Figure 5.

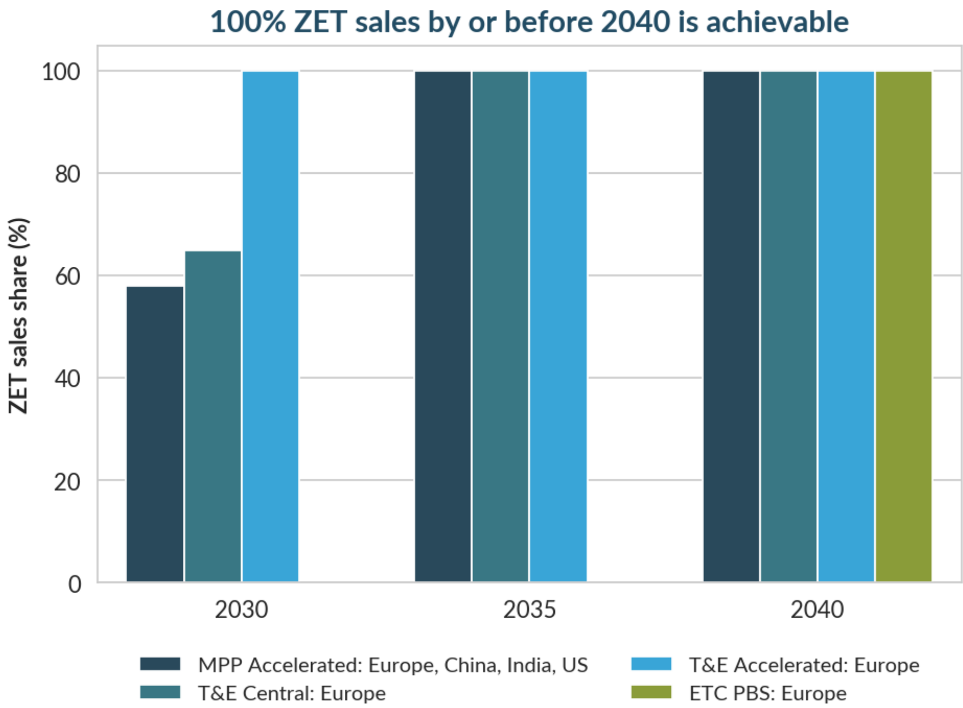


Figure 5: New zero emission truck sales targets by policy milestone year in the reviewed literature

Technology pathways to real zero

Due to their relative cost and maturity when compared with other technologies, BETs are expected to dominate the zero-emission truck market, with a potential small role for hydrogen fuel cell trucks (HFCTs) in certain long-distance segments (Basma & Rodríguez, 2023b; Mission Possible Partnership, 2022).

Battery Electric Trucks are the dominant lever for real zero in trucking

The sales of BETs exceeded 90,000 in 2024, with year-on-year growth of 80% – reaching 2% of total sales worldwide. 80% of these sales were in China, where sales have more than doubled between 2023 and 2024 (IEA, 2025b).

BETs offer many advantages that make them the primary driver for truck decarbonisation across applications – predominantly through economic competitiveness, with capital expenditures and operating costs through reduced fuel and maintenance expenses becoming increasingly competitive in some markets (Basma & Rodríguez, 2023b; Mission Possible Partnership, 2022).

The technological revolution in batteries is reshaping the trucking sector. A 30% drop in battery prices for commercial vehicles since 2020 has enabled significant range extensions without proportional cost increases accelerating market adoption. Battery packs sizes have increased by about 70% while their cost has only increased by about 20% (IEA, 2025b). The falling cost per kWh has enabled economically viable truck electrification. Meanwhile, improvements in battery size and truck efficiency are also extending the range of electric trucks. According to OEM's specifications, from 2019 to 2025, BET battery sizes increased by 120% (242kWh to 532kWh) while their nominal driving ranges improved by 233% (150km to 500 km) enabling substantially greater range per unit of battery capacity (Ragon, 2025).

As well as the rapid technological progress in batteries, electric trucks have a range of further advantages:

- Energy efficiency. Electric trucks can recover energy through regenerative braking, consume no energy while idling, and have much higher efficiency converting final energy to actual useful energy (distance travelled). As a result, electric trucks are around three times more efficient than their diesel equivalent on average (Ragon, 2025).
- Technological simplicity. Electric drive trains have fewer moving parts than internal combustion engines and hydrogen fuel cell vehicles, leading to reduced service requirements and lower operational downtime (Mission Possible Partnership, 2022).
- Operational simplicity. Predictable charging schedules, as well as centralised and repeated routes which enable easier infrastructure planning, as well as the rapid diversification of truck models available make the switch to electric trucking even easier.

- Long-haul options. Some long-haul electrified options have indicated they can reach up to 800km/day without significant drawbacks and may reach total cost of ownershi parity with diesel between 2025-26 for predictable routes which return to a base. (Basma & Rodríguez, 2023a).

The result of these factors is that, where electrification is a viable option, it will likely be the dominant technology. Battery truck sales are already growing rapidly, while hydrogen sales remain relatively low (Figure 6). This charge is being driven by China, which represented over 80% of global electric truck sales in 2024 (IEA, 2025b).[4]

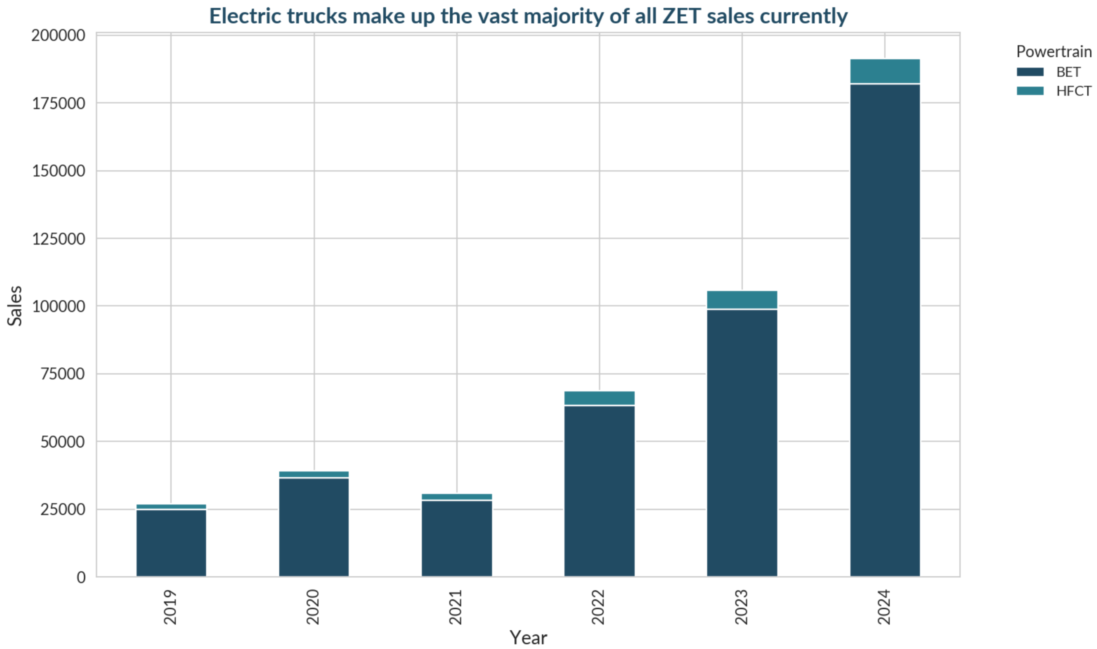


Figure 6: IEA Zero Emission Truck Sales by Powertrain 2019 - 2024. Data Source: (IEA, 2025b)

The dominance of BETs over hydrogen in real-world commercial decision-making is a clear sign of their superiority over alternative zero-carbon options.

Longer distance trucking

In the very longest distance trips (>800km/day), BETs face more significant constraints around the size of the batteries that would be needed. This can lead to a large weight and volume penalties of up to 10.2 times that of ICE equivalent designs(Basma & Rodríguez, 2023b; IEA, 2025a). However, this represents only a small segment of overall truck demand – making up only 3% of kilometres travelled in the EU (Basma &

[4] China shows remarkable market volume, even despite facing longer cost parity timelines due to cheaper diesel trucks. This is partly overcome by China's technological dominance of the BET space, with the world's most mature zero emission trucking ecosystem with almost 450 electric truck models available (IEA, 2025a; Mission Possible Partnership, 2022).

Rodríguez, 2023b). And even here, a range of options exist that could potentially enable the electrification of trucks.

One possible path to electrify very long-distance trucking is battery swapping, allowing for rapid refuelling by exchanging depleted batteries for fully charged ones at dedicated stations. This has demonstrated operational success in China especially when routes are fixed and minimising downtime is critical (IEA 2025). However, this would require standardised batteries across manufacturers and could have high infrastructure costs and logistical complexities associated with battery inventory and ownership (Rogstadius et al., 2024). Therefore, while battery swapping might play a niche role in closed and predictable logistic operations, it may not play a dominant role in long haul trucking without a collaborative, large-scale focus on buildout.

Electric Road Systems which supply electricity to trucks in motion such as via overhead cables, in-road conductive rails, or inductive charging could substantially reduce the need for large onboard batteries and could play a role in cross border long haul electrification (Rogstadius et al., 2024). Electric Road Systems can be cost-competitive with diesel and hydrogen solutions on high-traffic corridors (Deshpande et al., 2023). However, rollout could be challenged by high upfront infrastructure costs, and a need for standardisation and coordination across countries-

Megawatt Charging Systems could also enable over 800km/day long haul electrification, as they provide extremely high charging power (up to 3.75 MW) and allow charging under an hour (during driver rest breaks for example) (IEA, 2025a). Despite addressing the main operational challenge of increased charging time this still forces trucks to carry large batteries and requires the roll out of Megawatt Charging Systems infrastructure which requires grid upgrades and careful monitoring of peak electricity demand.

As seen above, there are a wide range of options that could help enable electric trucks to compete with hydrogen in the longest distance segments. While these challenges may be overcome, hydrogen trucking could potentially play a niche role in these long distances. HFCTs have operational advantages through their rapid refuelling capabilities (10-20 minutes) and the higher energy density of hydrogen, which enables longer ranges without any payload penalties and supporting increased daily utilization (Rout et al., 2022).

However, against this HFCTs also have a wide range of disadvantages. They are significantly less efficient that BETs, and they face higher fuel costs as well as specialised infrastructure requirements for hydrogen refuelling networks (IEA, 2025a). Currently HFCTs are significantly behind electric trucks in the race to market, with total cost of ownership parity with diesel trucks only set to be reached around 2035-36 – almost a decade behind battery trucks (Basma & Rodríguez, 2023a).

In addition, hydrogen trucks would need to compete with alternative use-cases such as fertilizer and chemicals manufacturing and primary steel production for a potentially scarce supply of green hydrogen. Given the potential that renewable hydrogen will remain a scarce resource, at least in the medium-term, there is a need to prioritise hydrogen for use-cases where alternatives are scarce or less well developed (such as primary steel production). Given the progress being seen in electric trucks, the large-scale consumption of hydrogen in the trucking sector is unlikely to represent a robust decarbonisation strategy.

Summary

The global pathways assessed in this report achieve real zero increasingly through the 2040s, and by 2050 a large number of different models are able to achieve real zero in a wide range of regions. In these models the EU is often a leading region on the road to real zero. Meanwhile the broader literature reviewed generally achieves real zero at the earliest by 2050, and this includes studies that focus on the EU alone, provide global coverage, or look at a range of major regions.

This gives us confidence that **real zero in trucking can be achieved by 2050 at the latest, and likely in the 2040s in leading regions** (such as the European Union). Importantly, leading trucking companies will not move at the regional average but could likely go faster than the average by some years. As such, companies who wish to position themselves at the front of the transition to real zero should be aiming to set targets for complete decarbonisation by around 2040 at the latest.

In terms of the fuel mix that achieves real zero in trucks, there is still some variation in the reviewed IAMs and bottom-up literature. However, direct electrification via batteries shows clear economic and technical advantages in most use-cases, and is likely to dominate. Hydrogen trucks are unlikely to play a significant role in truck decarbonisation, due to the technical and economic superiority of electric trucks in almost all use cases. They could however potentially play a role for the very longest distance segments, although we note that even here further progress in battery innovation and alternatives such as battery swapping or electric roads could further undermine their role.

Steel

The steel sector (including both primary and secondary production) was responsible for 7-9% of global GHG emissions in 2024 (Torres-Morales & Swalec, 2024). Between 2025 and 2027, the sector is forecasted to increase steelmaking capacity of up to 6.7% – around 165 million tonnes (Mt) of new steelmaking capacity. Of that increased capacity, nearly 40% is expected to utilise the emissions intensive blast furnace/basic oxygen furnace (BF-BOF) production process (OECD, 2025).

In the 2019-2023 period, steel demand increased by 1.2% while emission intensity increased by 0.6%. The increase in emission intensity is primarily due to the increase in steel production in high-emission regions (Net-Zero Industry Tracker 2024 - Steel, 2024). However, steel supply has outstripped demand over that same time, and the OECD expects the annual excess to grow approaching 2030 (OECD, 2025). The excess capacity in the steel market, coupled with maturing zero-emissions production processes, open up potential pathways toward deep emissions reductions in the sector.

The main real zero options for steel production involve producing primary steel and secondary steel via fossil-free routes, of which the major options include direct reduction using hydrogen followed by an electric arc furnace (EAF) for primary production, and recycling scrap steel in an EAF for secondary production. In contrast, the alternative pathway that continues to use fossil fuels would involve fitting CCS to the existing BF-BOF process, or running a direct reduction furnace via fossil gas, again equipped with CCS.

Global pathways

Our review identifies four different models that provide data on deep decarbonisation of the steel sector, namely GCAM, IMAGE, PROMETHEUS and REMIND, as can be seen in Figure 7. We distinguish between different versions of GCAM and REMIND due to the significant developments in modelling made over recent years in these modelling frameworks (Pehl *et al* 2024, Fuhrman *et al* 2024).

Figure 7 highlights the overall results for the steel sector across these different models. As with trucks, the figure shows reductions in fossil fuel demand in steel per model and per different time horizon, highlighting the most ambitious three scenarios per model.

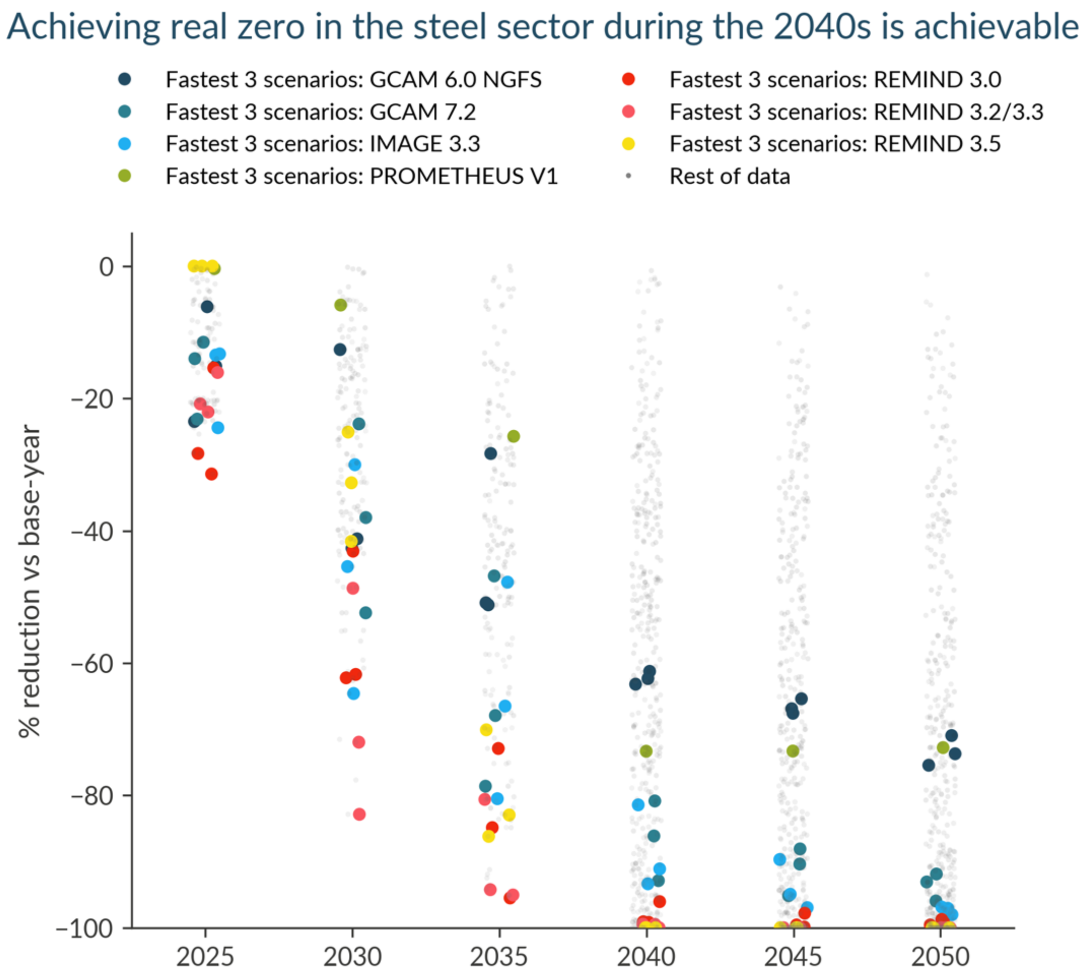


Figure 7: Achieving real zero in the iron and steel sector – evidence from the global pathways

Rapid and deep fossil fuel reductions in the steel sector are achievable, according to our model research. By 2040, across all regions and all models, the majority of the models (with the exception of PROMETHEUS) exhibit some pathways that are able to reach ambitious reductions, ranging between 67 and >99% on a global level.

The first panel in Figure 8 shows how many models achieve real zero steel in each region over the 2040s. The second panel shows how many regions achieve real zero in each model. REMIND 3.5 achieves real zero in the steel sector in 2045 globally, while reaching real zero in four regions by 2040, namely Latin America, North America, Europe and Rest of the OECD. Meanwhile, REMIND 3.0 also reaches real zero in two regions by 2040, and REMIND 3.2/3.3 reaches real zero in eight regions. By 2050 all

REMIND models have achieved real zero globally, whereas IMAGE, PROMETHEUS and GCAM achieve lower reduction levels, thus not achieving the real zero threshold (99%).

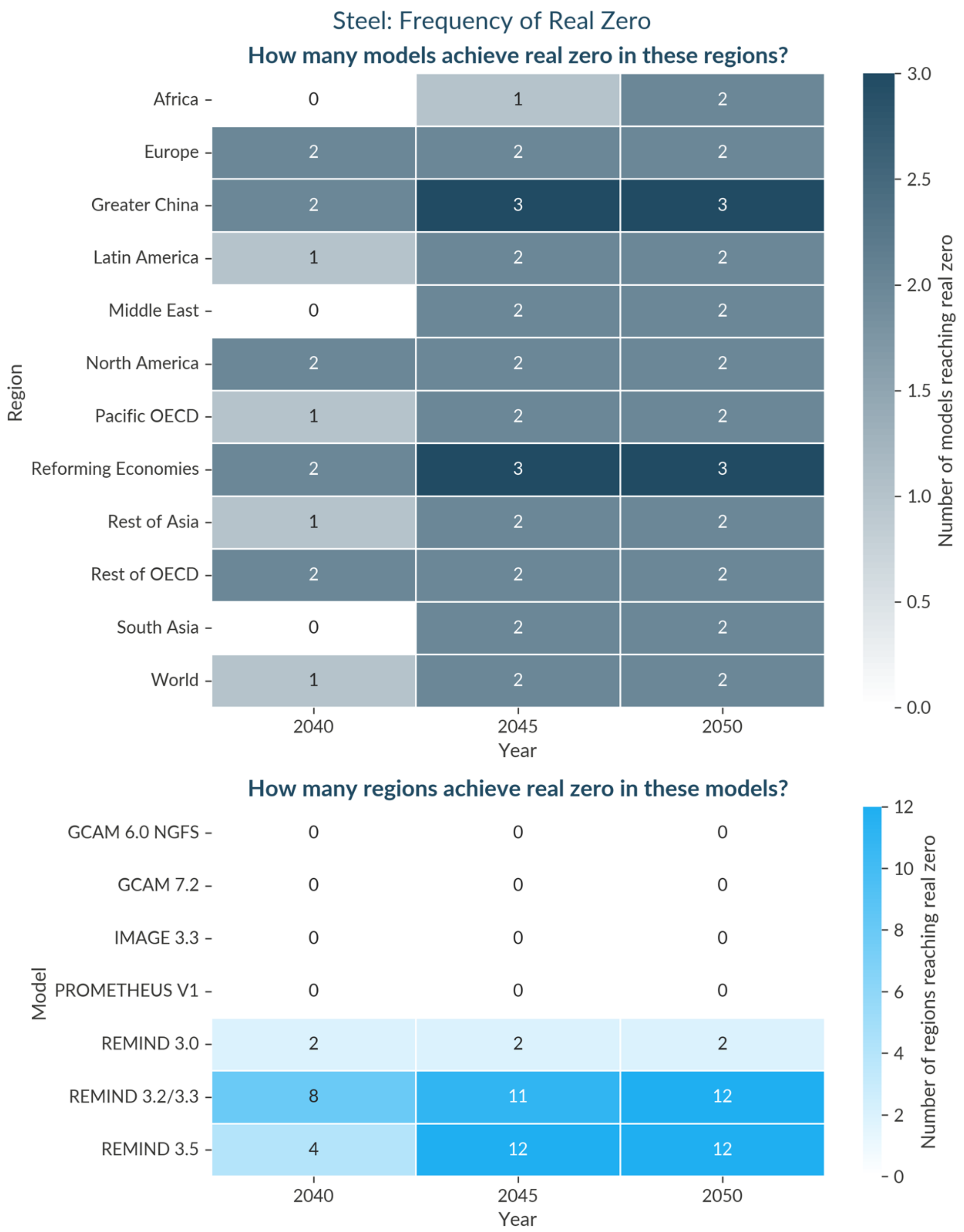


Figure 8: Frequency of real zero in each region and model in the steel sector

The increasing confidence in models' ability to achieve real zero by 2050 is shown in Figure 9. The models that achieve full real zero are all from the REMIND family. However, it is important to note that both GCAM 7.2 and IMAGE 3.3 achieve very close to real zero steel sector during the 2040s, with the most ambitious GCAM 7.2 scenarios achieving reductions of up to 92% in 2040 and over 95% by 2045, and the most ambitious IMAGE 3.3 scenarios achieving reductions of over 95% by 2040 and up to 98% in 2050. While this is not a fully real zero steel sector, with a modest acceleration of zero-carbon steel production, these models would be able to achieve a fully real zero steel sector. The number of regions and models which achieve >95% reductions in fossil fuel demand in steel is shown in Figure A1 (see Annex).

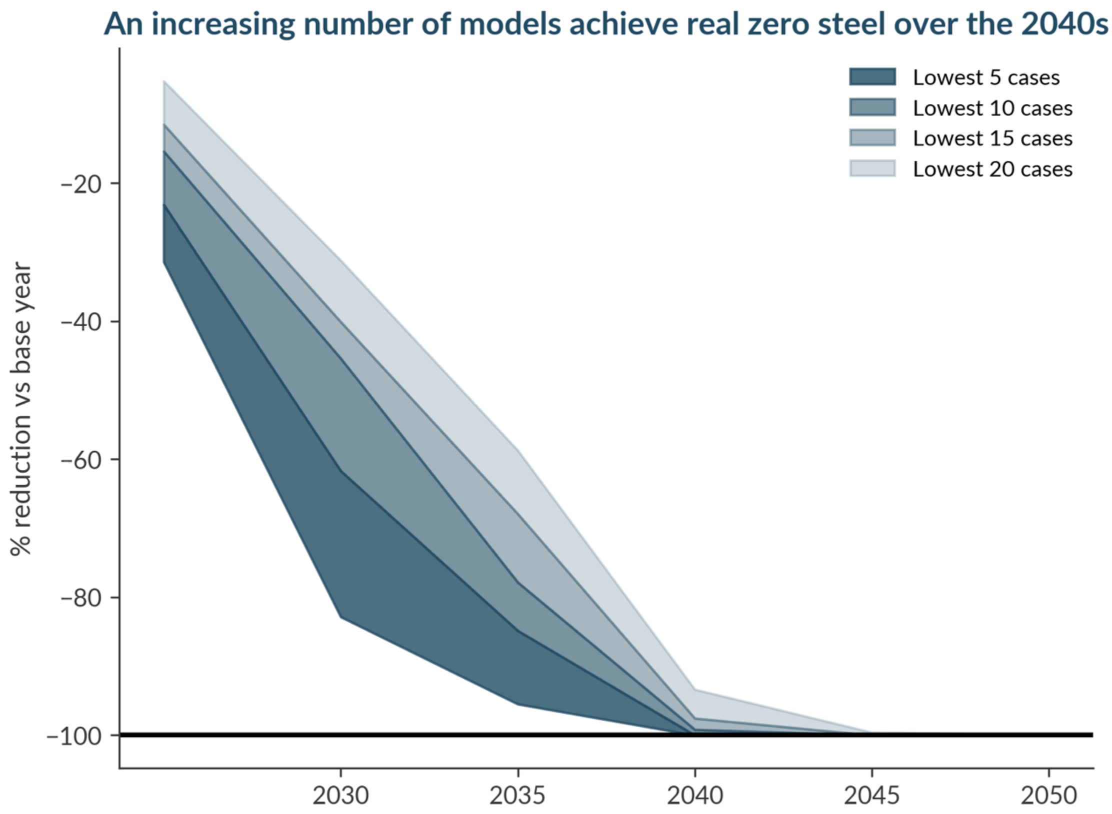


Figure 9: The ambition frontier for achieving real zero steel – evidence from the global pathways

How can we decarbonise the steel sector towards real zero

There are a range of different methods that can be used to produce steel, with a key distinction being between primary and secondary production. While secondary production takes scrap steel as an input and recycles this to produce steel via an electric arc furnace (EAF), primary production takes iron ore as an input, reduces this to produce iron via a range of possible processes and then converts this iron to steel, whether via an EAF or other methods such as the basic oxygen furnace (BOF).

In the case of secondary steelmaking, decarbonising the electricity supply would reduce the majority of emissions (except for minor process emissions associated with use of graphite electrodes and slag formers). This makes decarbonising secondary steel and expanding the overall share of secondary steel production a low-hanging fruit in the transition to a zero-carbon steel sector.

However, it will not be possible to transition entirely to secondary steel production to meet all global steel demand. This is partly because secondary steel production is constrained by the availability of scrap steel. While in some advanced economies there is a large amount of scrap steel available, in many emerging markets, current and future steel demand will substantially outstrip scrap availability, meaning that primary steel will continue to have a critical role in the future steel mix. Secondly, over time impurities such as copper and tin can accumulate in secondary steel, which means that it cannot be used in products for which a high purity is required. This means that, while a growth in secondary steel production is a key element in steel decarbonisation pathways, there remains a critical role for primary production, and the need to develop real zero compatible primary steel production routes.

However, decarbonisation pathways for the primary steel making are more complex. Producing iron from iron oxide is the most energy and emission intensive step of the process. This is the the key source of emissions in the primary steel production process because of the use of coking coal for high temperature heat and as a chemical feedstock (Rumsa et al., 2025).

While the primary steel manufacturing process has remained unchanged for centuries, the source of carbon has moved from biomass to coal. Some national sectors have been able to adapt to different feedstocks. In countries where natural gas is relatively cheap, iron oxide is reduced in a direct reduction vertical shaft furnace, which uses a mixture of carbon monoxide and hydrogen as the reducing agent. The reaction is carried out below the melting point of iron and the resulting product is referred to as direct reduced iron (DRI), which can then be fed into an EAF to produce steel. Meanwhile in India, the non-availability of coking coal has led to the adoption of a novel production pathway where thermal coal (local or imported) is mixed with iron ore concentrates, lumps or pellets and reduced to DRI in rotary kilns.

An alternative to these fossil-based reduction methods of iron ore is the use of hydrogen as a reducing agent. Hydrogen has better reduction kinetics compared to carbon monoxide, and the reaction can occur at a lower temperature (Boretti, 2023). A pilot facility was built by the HYBRIT consortium to show feasibility. A large number of steelmakers are pursuing this pathway, and natural gas based vertical shaft furnaces are being modified to use 100% hydrogen as the reducing agent. In a completely decarbonised production system, the thermal energy required to heat the reactants and to supply the energy required for the chemical reaction is supplied by electricity. Hydrogen is produced from water electrolysis and could be produced on-site or imported.

While vertical shaft furnace based DRI production has picked up pace in recent years, it comes with its own set of challenges. The vertical shaft furnace reactors require iron ore pellets as input and the high temperature operation limits their flexibility, which in-turn increases the cost of upstream investments such as solar, wind, batteries, hydrogen storage, and transmission grid upgrades among others. Alternative reactor concepts are being developed to circumvent some of these challenges. Fluidised bed reactors are being developed by POSCO, which can use iron ore fines as an input (POSCO, n.d.). Hydrogen-based fine-ore reduction (HYFOR), which uses hydrogen plasma to reduce the iron ore, is being developed by Primetals and other consortium members (Spreitzer et al., 2022). HyIron has developed small scale distributed iron production system which uses an electrically heated rotary kiln and hydrogen as a reducing agent (*Home - Green Iron - Zero Emissions | HyIron*, 2019).

The use of electricity to reduce the iron ore using high temperature and low-temperature electrolysis is another technological pathway under development. This method, however, is at a lower technology readiness level. While the use of CCUS has been explored for both the BF-BOF and the natural gas based DRI-EAF route, the majority of these projects have been unsuccessful (*Steel CCUS Update: Carbon Capture Technology Looks Ever Less Convincing | IEEFA*, n.d.). The risks associated with continued fugitive methane emissions further reduce the suitability of these technology alternatives (Yu-Ting Chang, 2025).

Figure 10 provides an overview of the different routes for decarbonising the steel sector.

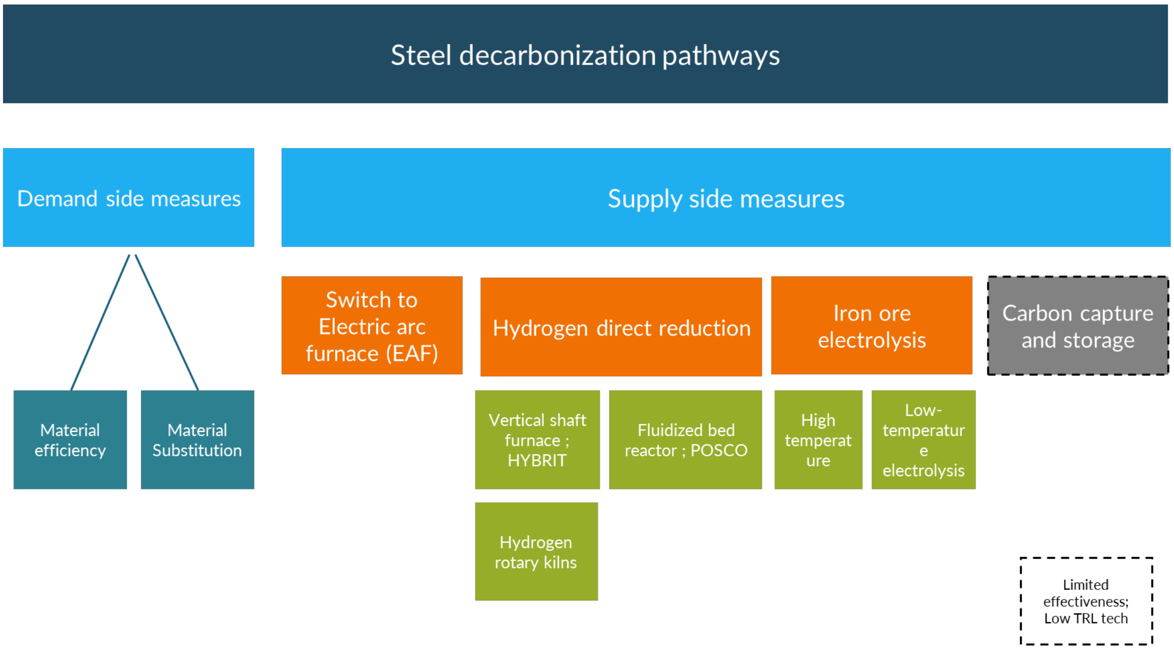


Figure 10: Demand-side and supply-side measures for decarbonising the steel sector

What decarbonisation pathways dominate the models

The IAMs we reviewed that reach real zero largely rely on a mix of electricity and hydrogen as the key inputs to the steel sector, with biomass playing a minor role (see Figure 11).

A two-pronged approach is required, using EAFs to produce secondary steel from recycled scrap, and using hydrogen-DRI in combination with EAFs to produce primary steel. In both approaches, electricity provides the energy to drive the process, while in the primary steel production, hydrogen acts as the reducing agent, rather than a fuel.

Green hydrogen and electricity are the key inputs to a real zero steel sector

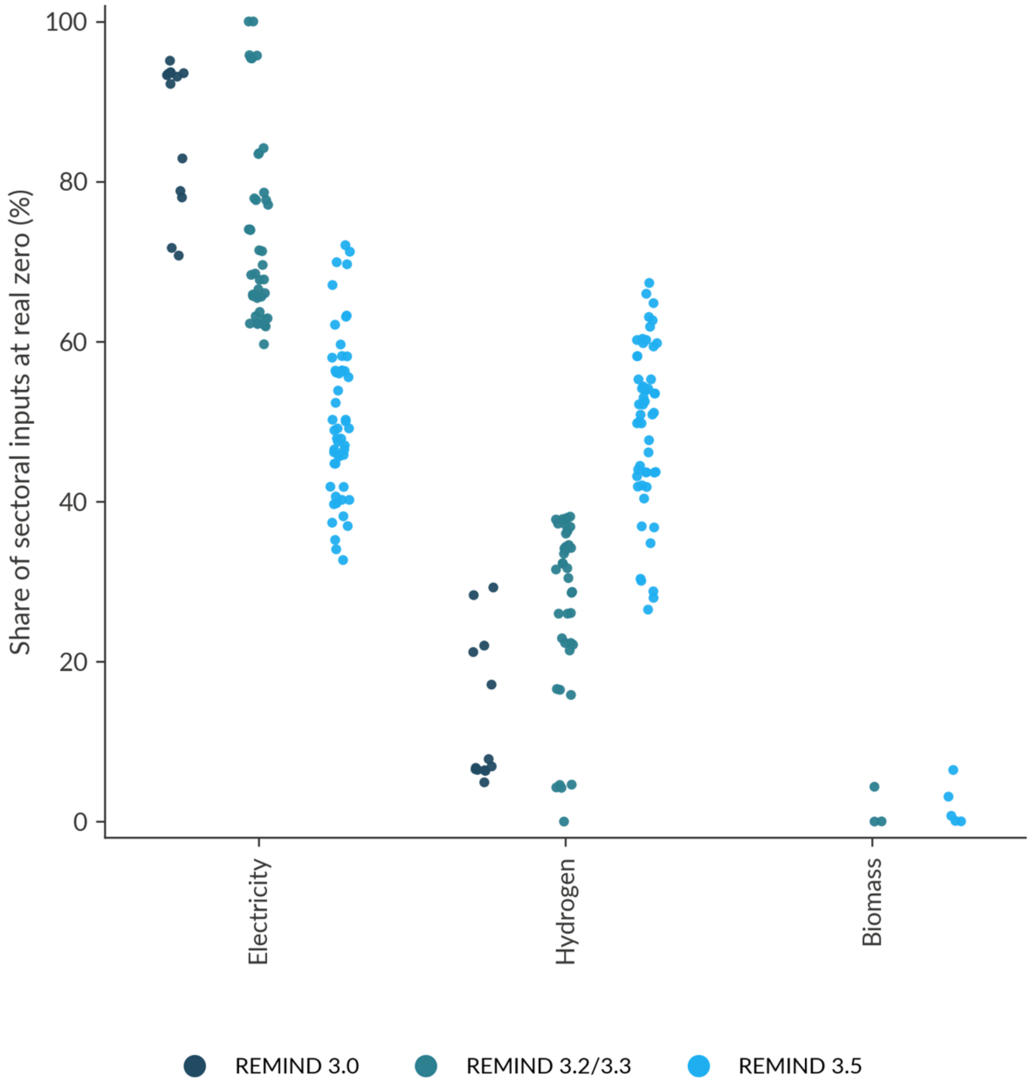


Figure 11: Sectoral inputs breakdown for real zero – evidence from the global pathways

In some modelled regions in REMIND 3.0–3.3, electricity can provide up to 100% of the final energy mix, representing a sector in which secondary steel production dominates, and there is very limited primary production. On average in REMIND 3.0–3.3, hydrogen provides around 20% of total inputs to the real zero steel sector. While this means there is still a role for primary steel production in these scenarios, it would also require noticeable reductions in primary steel production in many regions, and a significant transition towards secondary steel production. As discussed in the Summary, it is unclear whether these reductions in primary production are actually achievable in all regions, given the limited availability of scrap steel in key emerging and developing economies, and the need for primary steel in particular use cases.

However, it is also possible to achieve real zero in the steel sector with a greater role for primary steel production. The most recent REMIND 3.5 model shows relatively lower electricity shares coupled with increased hydrogen levels. In all regions achieving real zero, hydrogen provides at least 25% of the total sectoral inputs, and up towards 70%. This would enable a higher level of primary steel production than in the previous REMIND versions which rely more exclusively on electricity for steel production. This is a more likely outcome for the steel sector, which would enable growth in demand for primary steel in key markets to be met. This highlights that real zero in the steel sector is still possible with higher levels of primary production, but emphasises the importance of scaling real zero production routes for primary steel, as well as accelerating the growth of secondary steel production where possible.

Literature review

As described above, the latest IAM pathways demonstrate that deep and rapid decarbonisation of the steel sector is possible. These findings are also reflected in a review of relevant literature. However, while the literature and the IAMs reach similar conclusions regarding emissions reduction pathways overall, country and region specific studies offer a more nuanced perspective on the pathway to real zero.

Global pathways to real zero from the literature

Existing literature incorporates both global modelling of the steel sector transition and in-depth analysis of regions and countries with significant steel production. Of the global studies, the estimated emissions reductions possible by 2050 (Figure 12) are generally lower than those demonstrated by the IAMs.

Each of these studies modelling the global transition incorporates CCS technologies into initial estimations. The level of reductions directly attributable to CCS is defined in each study (either in the literature itself or in the publicly available source code). This report discounts CCS-attributed reduction from each study to arrive at 'real-zero' reduction levels.

Global studies reviewed:

- Net Zero Industry's study *Facility Level Global Net-Zero Pathways Under Varying Trade And Geopolitical Scenarios* analyses facility-level data to estimate emissions from the steel industry could fall almost **90% globally by 2050**, when excluding the contribution of fossil CCS (Bataille et al., 2024).
- Scenarios from the Mission Possible Partnership models transition pathways considered varying rates of development for key green-steel production pathways. These scenarios estimate emissions reductions of around **90%**

globally by 2050 without the use of CCS (Making Net-Zero Steel Possible: An Industry-Backed, 1.5°C-Aligned Transition Strategy, 2021).

- A joint study from E3G and the Pacific Northwest National Laboratory estimated emissions reductions of around **83% globally by 2050** without the use of CCS (Yu et al., 2021).
- The IEA's Net Zero scenario achieves emissions reductions of **79% by 2050**, when excluding the contribution from CCS (IEA, 2024).

The reductions in emissions (excluding any reliance on CCS) are shown in Figure 12.

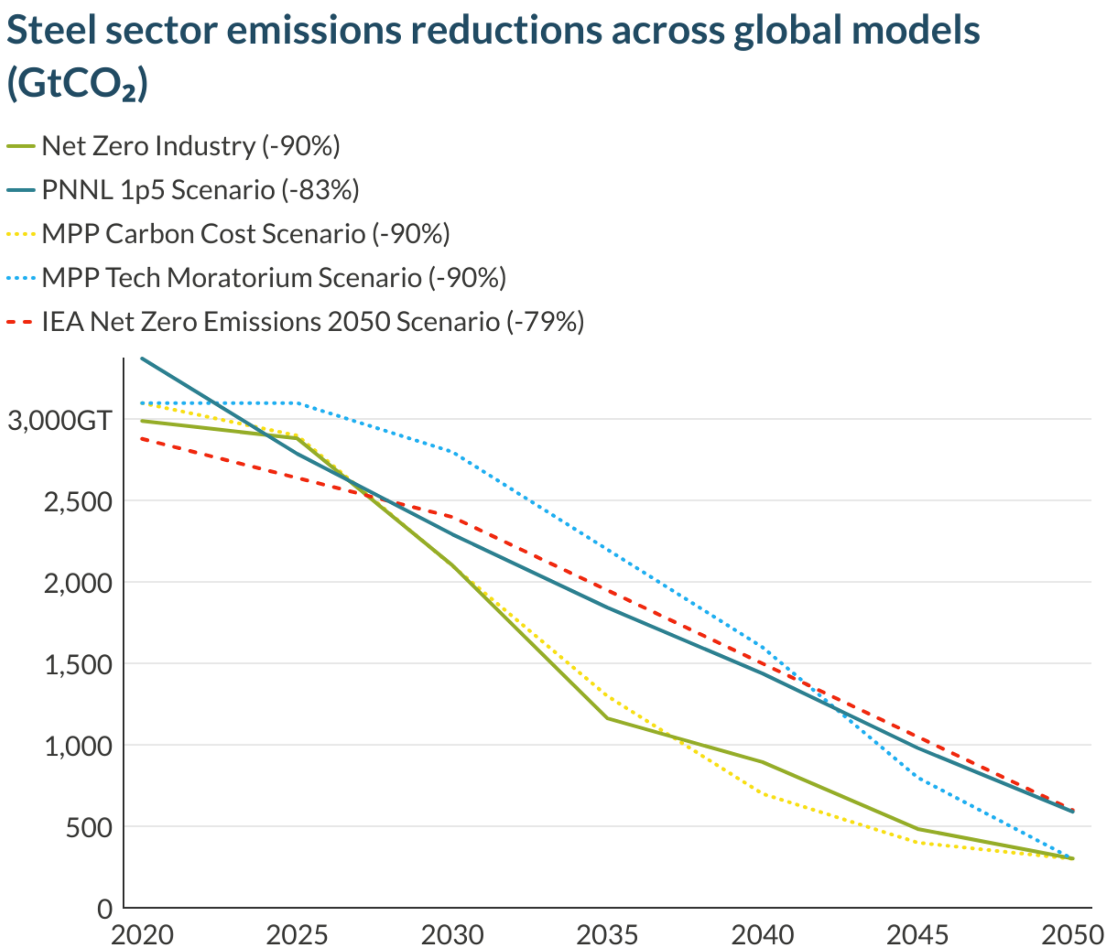


Figure 12: Modelled reduction pathways of aggregated models from existing literature.

Regional pathways to real zero from the literature

While analysing abatement through a global lens is a useful approach, the transition pathway for the steel sector will likely vary significantly across regional and national levels. Of the regional studies reviewed, the steel sectors in United States and European Union emerge as the most ambitious reduction contenders.

- Durga, Speizer and Edmonds (2024) model a steel sector pathway in the US that does not make use of any CCS abatement. They determine that conventional BF-BOFs can be fully phased out by 2050 and replaced by a combination of hydrogen-DRI(producing 23% of the total steel in 2050) and EAF-scrap steel production (producing 65% of total steel in 2050). Under this scenario, production emissions are reduced by over 90% (Durga et al., 2024).
- Meanwhile recent studies have shown that the European Commission's recommended 90% emissions reduction benchmark is attainable for the steel sector without CCS abatement. The phasing out of BF-BOFs to be replaced by hydrogen-DRI facilities as well as the scaling up of scrap-based steel production are the primary drivers for reductions under this scenario (The State of the European Steel Transition, 2025).

Certain enabling conditions provide the US and EU with advantages over other countries and regions for reducing steel sector emissions. These enablers are covered further on in this report.

However, the literature also supports a variety of country- and region-specific pathways that can also unlock deep emissions reductions. For example, Brazil could achieve an emissions reduction potential of at least 88% by 2050 without CCS. This scale of reduction is possible in Brazil by capitalising on conditions unique to the country. Namely renewable biomass as a bridging technology to phase out BF-BOF production while hydrogen-based production technology develops and achieves scale in the sector (Hebeda et al., 2023). By incorporating regional and national case studies from the literature into the overall analysis, important nuance for understanding the aggregate global transition is observable.

Overall, the broader literature does not have pathways in which the steel sector reaches real zero by 2050. The reasons for this are multiple and are discussed later. However, the literature still highlights the real possibility for deep reductions in fossil fuel demand from the steel sector. As with the IAM pathways assessed, the primary levers for decarbonising steel are increased secondary steel production via EAFs, and a switch in the primary production route to hydrogen-based steel production.

Enablers of a real zero pathway in steel

Specifically, three key enablers help define a country's transition to a real zero steel sector: scrap steel reserves, renewable potential, and the age of existing CO_2 emitting facilities.

Improvements in scrap collection, sorting, recycling rates and the use of secondary steelmaking processes using EAFs can reduce the emissions from the steel industry. Secondary steelmaking uses a fraction of the energy required to produce virgin iron and can be decarbonised via the use of renewable electricity.

Regions with larger pools of scrap steel can reduce emissions at an accelerated rate by replacing CO_2-intensive basic oxygen furnaces (BOFs) with EAFs (World Steel, 2024). Regions with less scrap steel are more reliant on breakthrough technologies to produce virgin steel, and are forecasted to attain economies of scale closer to the middle of the century (OECD, 2024).

The EU and the US both have large scrap steel resources that factor into their transition pathways. In the US where EAF already composes 68% of production, scrap-based EAF steel production is viewed as a vital bridging method to reduce emissions before hydrogen-based production methods become viable (Durga et al., 2024). Studies covering the EU's steel sector have found similar advantages. Aggressive action to replace aging BOF facilities with EAF technology while increasing scrap steel recycling and material efficiency permits steeper emission reductions in the short term, and could account for 22-26% of total emissions reductions by 2050 (The State of the European Steel Transition, 2025).

However, as noted before, there will be limits to the availability of scrap steel and the use cases for secondary steel, which highlights a crucial role for green primary steel production in the future. In pathways using green hydrogen as a reducing agent, the availability of low-cost renewable electricity will be key to achieving real zero. Solar and wind energy access in India and hydroelectricity in Scandinavia are consistently highlighted as examples of this relationship between renewable energy and accelerated steel emissions reduction pathways (Das & Rodrigues, 2025; Decarbonising the Indian Steel Industry: Roadmap Towards a Green Steel Economy, 2023; Walter, 2021). In the case of India, this can be further substantiated with the results from the recent green ammonia auctions in India, where a lowest bid of 570 USD/ton of green ammonia was discovered. This translates to a green hydrogen price of less than 3 USD/kg hydrogen, which makes the business case for green iron production extremely competitive.

A final indicator for estimating a country's rate of transition is the average age of its existing BF-BOF fleet. The age of existing facilities can distort a country's decarbonisation pathway. Nations with older fleets often elect to begin a phase-in of cleaner production pathways earlier, due to reduced concerns around asset stranding, as is the case in the EU and US. In nations with younger BF-BOF facilities, such as India and China, the transition period observed in the literature is often delayed, with most emissions cuts arriving in the later years of the national pathway (de Villafranca Casas et al., 2022; Decarbonising the Indian Steel Industry: Roadmap Towards a Green Steel Economy, 2023). However, the speed with which nations can transition is ultimately a matter of political resolve. Historical precedents show that rapid change in the steel sector is possible, with China growing steel production more than ten–fold over the period of the late 1990s to now. It remains technologically feasible to achieve real zero, irrespective of economic conditions and incentives, underscoring the crucial role of effective policy in directing a real zero transition in the steel sector.

Summary

Both the reviewed literature and the IAM pathways assessed are in broad agreement on the pathway towards a fossil-free steel sector. Increased use of secondary steel production, coupled with the use of hydrogen-DRI for primary steel production, can rapidly displace fossil fuels from the steel sector in the coming decades. This highlights the critical importance of clean electricity to ensure that Scope 2 emissions from the steel sector are also zero.

However, as seen in the Power section, achieving clean electricity as early as the mid-2030s is possible, and this would act as an enabler for decarbonisation in all rapidly electrifying end-use sectors.

The reviewed models and scenarios do not include all real zero options for steel production, with direct reduction via electricity not captured in the existing literature. Additional technology options to achieve real zero in steel could help accelerate the transition towards a fossil free steel sector.

There is a discrepancy between the IAM pathways and the broader literature on the pace of achieving real zero. The most ambitious IAM scenarios, all of which are from the

REMIND modelling framework, achieve real zero in the 2040s, with other IAMs achieving close to real zero (over 90% reductions and approaching 100%) over the same time frame.

In the literature, the reviewed scenarios approach real zero by 2050 and do not fully achieve real zero. Instead they would achieve a fully fossil free steel sector sometime post-2050. The deepest reductions observed at the global level in the literature (excluding the contributions of CCS) is just over 90% by 2050, in the case of the US (Durga et al., 2024).

This leads to two main questions – why in general do the IAM scenarios evidence deeper reductions in the steel sector pre-2050 than the literature, and what additional effort would be required for the wider literature to achieve real zero pre-2050?

Difference between the IAMs and the broader literature

On the first question, there are a range of possible reasons for this discrepancy. A full analysis of this is out of scope in this report, but we highlight a range of possibilities below.

Option 1: Differences in ambition between modelling frameworks

As highlighted in the methods summary, one of the key features of the IAM scenarios is that they are likely close to or testing the feasibility frontier of decarbonisation within these modelling frameworks, as they are trying to reduce emissions in line with the Paris Agreement's long-term temperature goal. This results in very high carbon prices or similar proxies for regulatory effort, and very rapid transitions away from fossil fuels.

Meanwhile, many of the wider literature studies may not have been set up to explicitly achieve real zero or the highest possible reductions in fossil fuel use in the steel sector but are instead more likely to represent the existing targets and ambitions of the steel sector or major economies. The literature studies may potentially not demonstrate a real zero steel sector pre-2050, not because this is not possible, but because they were not set up to explore this.

Option 2: Differences in technology representation between the modelling frameworks

Secondly, the two frameworks may have differences in the level of technological representation. IAMs likely have a coarser representation of the steel sector than many bottom-up sector-specific modelling efforts. This coarser representation could result in some of the key barriers to the steel transition being omitted, enabling an earlier date of real zero compared to the literature studies.

However, on the other hand, the IAMs also are able to capture inter-sectoral competition for mitigation measures, particularly hard-to-scale technologies such as CCS and geological storage of CO_2. Some IAMs, including REMIND, account for limitations on geological storage – which can lead to the prioritisation of CCS for carbon removal and particularly hard-to-avoid emissions such as process-related emissions from cement/lime (Zhang et al., 2024). Meanwhile where real zero alternatives exist and are scalable, these are prioritised to reduce the competition for a scarce CO2 storage resource. Some of the literature studies may not account for this competition, allowing the steel sector to rely on CCS without considering the wider system impacts of this choice. This would again explain some of the difference.

Option 3: Differences in breakdown of the technology mix into primary versus secondary steel

There is also the potential that the breakdown of steel production into primary versus secondary steel varies between the two modelling frameworks. As highlighted before, in some markets, the IAMs appear to be underestimating the need for, and demand for, primary steel production. This could enable the IAMs to achieve an earlier date of real zero.

For example, when focusing only on the REMIND 3.5 model, as the latest version of the REMIND model, and the model in which there is the greatest role for primary production out of the REMIND frameworks (Figure 11), we see that the model still assumes lower levels of primary production in Europe and India than is observed in the bottom-up literature, driven in part by lower overall steel demand, and also greater assumptions on the scale-up of secondary steel. If IAMs are underestimating the need for primary steel production, this could also potentially enable them to achieve real zero earlier.

However, it is also important to highlight that in other key markets such as China, and the US, the modelling frameworks are more similar in their assumptions around total steel production, and the breakdown into secondary versus primary steel. For example, in China, REMIND 3.5 assumes that primary steel production will reach around 300-320 Mt / year, while the literature reviewed has production volumes of 330–370 Mt / year. While this is slightly higher, it is unlikely to explain the whole difference in the level of ambition between REMIND (which achieves real zero in China around 2040), and the literature (which does not achieve real zero even by 2050).

This highlights that differences in the assumptions around primary steel production alone are not sufficient to explain the differences between the two modelling frameworks. Some of the differences likely arise from other factors, such as the IAMs generally pushing closer to the feasibility frontier of the transition, or accounting for competition over CO_2 storage with other needs such as CDR.

Accelerating real zero in the broader literature scenarios

While the broader literature does not achieve real zero, this does not mean that it is impossible to achieve real zero in these modelling frameworks. As an illustrative example, we consider the IEA's Net Zero scenario (Net Zero Emissions Guide - Steel and Aluminium, 2023), which models the global steel sector within an energy system transition that achieves net zero CO_2 emissions by 2050.

In this scenario, around 430 Mt of steel production in 2050 is still coming from fossil-based approaches, with 380 Mt of this equipped with CCS. If this was entirely replaced with additional primary production, then we estimate that this would require an additional 25 Mt of green hydrogen production to enable this. This would increase global hydrogen demand in 2050 by around 20% in the IEA Net Zero scenario (where it is 120 Mt) – a notable increase, but also potentially within the bounds of plausibility.

It is beyond the scope of this research to conclusively identify which of these factors, and in which regions, drive the differences between the IAMs and the broader literature. There are some structural factors (such as considering competition for a scarce CO_2 storage resource and pushing the ambition frontier), which could explain why the IAMs often achieve earlier dates of real zero than the literature, and should be seen as a strength of these modelling frameworks. On the other hand, IAMs may be limited by their coarser representation of the steel sector and over-optimistic assumptions about the scale to which primary steel production can be replaced by secondary routes.

A more in-depth research project would be needed to fully elucidate the differences and arrive at a comprehensive assessment of feasibility frontier for reaching real zero in the steel sector. On the basis of the existing evidence, and based on our indicative calculations of the additional action required to achieve real zero in the wider literature sources, we would suggest that we have increasing confidence in the ability of the steel sector to achieve real zero in leading regions through the 2040s, with the world as a whole achieving a fossil-free steel sector by 2050 or soon after.

Shipping

International shipping was responsible for around 780 million tonnes (Mt) of CO_2e of emissions in 2023, or approximately 1.5% of the global total (ICCT 2025). Almost all ships are currently powered by fossil fuels, largely heavy fuel oil, and over 40% of all ships transport fossil fuels around the world (Fricaudet *et al*., 2025).

Shipping has historically been seen as a poster child for the “hard-to-abate” label, with the long distances involved meaning that direct electrification via batteries faces major challenges around energy density, as the weight and volume of batteries which would be needed to power ships over very long distances has been seen as prohibitively high.

The main real zero solutions that have so far been envisaged to displace fossil fuels involve scaling up alternative zero-carbon fuels such as methanol and hydrogen, and derivatives such as ammonia or synthetic e-fuels. Meanwhile, the alternative options that have been proposed involve some combination of shifting to lower-carbon, but still fossil-based fuels (such as LNG), fitting CCS on-board ships to capture emissions, and compensating for any remaining emissions via CDR.

Global pathways

For shipping, we only focus on the global sector and do not include regional or national level breakdowns. This is because shipping is inherently an internationally distributed sector, with ship building, key transportation routes, and ports/refuelling hubs spread across the world. Different models take different approaches to disaggregate shipping demand to the regional level[5], making regional comparison invalid. It is also not fully clear what it would mean for any individual region to reach real zero in international shipping.

Figure 13 shows the most ambitious reductions in each modelling framework review for international shipping across the seven different modelling frameworks for which data was provided. Fewer models achieve real zero in shipping compared to other sectors,

[5] For example, one model could distribute future demand based on historical patterns of international shipping demand, while another could look at future GDP/population growth to estimate shipping demand. Demand could also be allocated to the origin or destination of the shipping route, or equally distributed between the two.

and the dates by which they achieve real zero are later than in other sectors. Nevertheless, it is possible to achieve deep reductions in in shipping even by the 2030s, and eliminate fossil fuels by 2050 as indicated by some of the pathways shown here. In 2035, the most ambitious scenarios from WITCH 5.0, IMAGE 3.3 and REMIND 3.5 are approaching a 40% reduction in emissions, and by 2050, GCAM 7.2 achieves a 100% fossil free international shipping sector. Meanwhile two further models, REMIND 3.5 and WITCH 5.0 are very close to achieving real zero, and do so in the early 2050s.

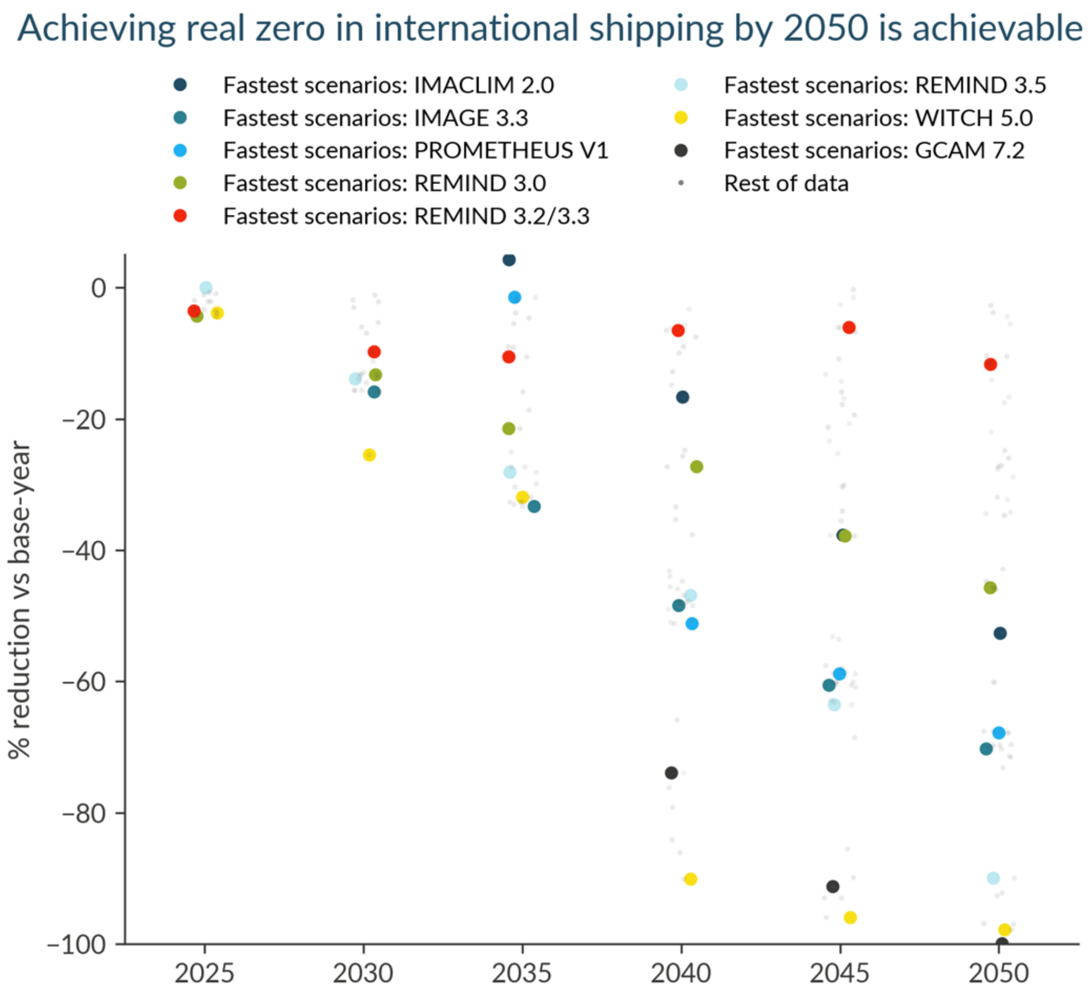


Figure 13: Achieving real zero in shipping: evidence from global pathways.

A real zero shipping sector is possible by 2050. In the pathways produced by GCAM 7.2 (Speizer *et al* 2024), this is achieved by a balanced mix of different mitigation levers. Direct electrification plays a role, providing around 15% of final energy in 2050. The potential for direct electrification of ships by batteries is growing, driven by rapid cost-reductions and improvements in energy density (Kersey *et al* 2022). Recent advances in battery shipping could lead to even greater potential for electrification beyond this level. As pathways have often failed to account for the pace of technological progress in solar PV (Jaxa-Rozen & Trutnevyte, 2021), it may be that pathways are currently failing to keep pace with real-world innovation in the batteries sector.

However, it is perhaps unlikely that shipping will be entirely electrified, and therefore some level of demand for zero-carbon shipping fuel will exist. In GCAM 7.2 almost 50% of final energy is provided by hydrogen, with the remaining 30-40% coming from a mix of synthetic fuels and biofuels. GCAM explicitly does not model ammonia as an option for shipping decarbonisation, and so the lack of ammonia as an energy carrier should not be seen as a statement on the potential for ammonia to help achieve real zero in shipping. Indeed, as seen in the Literature review, ammonia emerges as a critical option for achieving real zero shipping.

A review of the IAM pathways suggest that that real zero in shipping is possible by mid-century. This should become the guiding benchmark for shipping companies looking to lead the energy transition in their industry.

Literature review

The latest IAMs pathways demonstrate that from a top-down energy modelling perspective a real zero transition for the international shipping sector can be achieved by 2050. We complement this analysis with a review of the existing sectoral roadmaps on shipping from the broader literature. We identify several studies that present decarbonisation pathways for international shipping and focus on those pathways which achieve real zero emission by 2050. These come from UMAS (Smith et al., 2025) Mærsk Mc-Kinney Møller for Zero Carbon Shipping (MMMCZCS, 2022), (Transport & Environment, 2025) and the Science Based Targets initiative (SBTi, 2023).

Pathways to real zero from the literature

The results from studies using bottom up and/or top-down emission reduction pathways required for shipping to reach real zero or near zero emissions by 2050 are summarised in Table 3.

The four studies all point towards near-complete decarbonisation of shipping by 2050, but they differ significantly in the pace and ambition of reductions.

- Smith *et al* (2025b) presents a wide range of scenarios, with only modest reductions by 2030 (-41% to +5%), reflecting uncertainty around early action. However, emissions fall steeply thereafter, falling 95–97% by 2050.

- In contrast, Transport & Environment (2025) and MMMCZCS (2022) both envisage much faster cuts, with around 50% reductions by 2030 and a more convex pathway to full decarbonisation by 2050.
- The SBTi (2023) pathway, which employs a logistic emission reduction curve, is less ambitious in the short term (falling 36% by 2030), but then sees a dramatic acceleration in the 2030s and 2040s to reach 96% reductions by 2040 and 100% reductions by 2050, driven by the inherent acceleration of the S-curve.

Taken together, the studies show a common end-point of zero emissions by 2050, but diverge in whether reductions are front-loaded in early action, as with the Transport & Environment and MMMCZCS studies, or back-loaded in the case of SBTi, or spread across multiple possible pathways (UMAS). These differences reflect differences in certainties and the current starting point of the transition which is still in its infancy.

Study	Unit	2020	2030	2035	2040	2050
UMAS (2025)	Emissions (CO_2e)	863	508-903	329-468	138-257	27-48
	% change from 2020	-	*-41 to 5%*	*-46 to -62%*	*-70 to -84%*	*-95 to -97%*
Transport & Environment (2025)	Emissions (CO_2e)	899	429.2	226.9	108.1	0.0
	% change from 2020	-	*-52%*	*-75%*	*-88%*	*-100%*
SBTi (2023)	% change from 2020	-	*-36%*	-	*-96%*	*-100%*
MMMCZCS (2022)	Emissions (CO_2e)	1189	591.8	447.3	298.2	0.0
	% change from 2020	-	*-50%*	*-62%*	*-75%*	*-100%*

Table 3: Emissions reductions comparison from different studies reviewed in the literature.

The UMAS study develops three core scenarios to align international shipping with 1.5°C, which represent ‘Early Action’, ‘Balanced Action’ and ‘Delayed Action’. The early action scenario assumes emissions reductions starting in the 2020s, leading to a gradual and more cost-effective transition driven by steady uptake of scalable zero-emission fuels (SZEFs), retrofits, and fewer prematurely scrapped ships. The Balanced Action scenario represents cuts beginning later in the 2020s, achieving around 10% lower cumulative CO_2 emissions than the other scenarios and delivering costs only marginally higher than the early action scenario while avoiding the turbulence of delayed action. Lastly, the Delayed Action scenario by contrast, delays reductions until around 2030, which compresses the transition into the 2030s, requiring rapid technology shifts, widespread retrofits and scrapping, and significantly higher costs. Overall, earlier action enables smoother and cheaper decarbonisation, while delayed action is more disruptive and costly, with a steadier balanced action offering an intermediate balance. The same can be true for the pathways from the other studies which employ similar pathways albeit at different paces.

Technology pathways to real zero

To make these emission reductions a reality, two key changes need to happen – the sector needs to switch to zero emission fuels and improve operational and efficiency measures. Doing this could contribute to 80% and 15% of the sector's emission reductions, respectively (MMMCZCS, 2022, 2025a). Of the studies analysed, the UMAS (Smith et al., 2025) and (MMMCZCS, 2021) studies provide projections for fuel mixes, while T&E (2025) provide indications on the uptake trends of alternative fuels (Table 4).

Study	Fuels
UMAS (2025)	• **2030**: Ammonia ~15%, hydrogen minor, fossil fuels declining • **2040**: Ammonia >60%, hydrogen limited, biofuels small niche • **2042 onwards**: Ammonia **dominates (>80%)**; fossil fuels near-zero • Hydrogen remains **vital upstream**, not dominant onboard
Transport and Environment (2025)	• European Scope: • **2030**: Start of ammonia uptake • **2040**: ammonia dominant fuel + start of e-fuels growth • **2045 and onwards**: e-fuels grow but ammonia remains dominant
MMMCZCS (2021)	• **2030**: Ammonia ~8%, but blue ammonia, LNG 2% • **2040**: Ammonia >32%, biofuels 18% • **2050**: Ammonia **majority (>55%)**; fossil fuels 5%, biofuels 35%, e-fuels 5%

Table 4: Projected fuel mix for international shipping in selected decarbonisation scenarios.

The UMAS scenarios all point to a future where ammonia becomes the dominant zero-emission fuel for shipping, with differences mainly in the speed of transition. In the Early Action pathway, fossil fuels decline rapidly from 2030 and are almost entirely displaced by ammonia by the mid-2040s, while the Balanced Action pathway shows a steadier, more gradual uptake. The Delayed Action case keeps fossil fuels in the mix longer, but then relies on a sharp late surge in ammonia adoption after 2040. UMAS projects only a 10% share of other fuels, which would be mostly biofuels, noting that the study accounts for the limited scalability of biofuels.

By contrast, the MMMCZCS and T&E studies envision a more diversified mix, where ammonia is important but is complemented by notable shares of biofuels (MMMCZCS) and e-fuels (T&E) by mid-century. Scaling bio-methanol to decarbonise shipping faces multiple sustainability and scalability challenges given the limitations on the availability of feedstocks for biofuels and risk of increasing food security challenges in the future (Energy Transitions Committee, 2021). Keeping bio-methanol deployment down to minimal levels could help.

Another difference between the MMMCZCS and UMAS fuel mix projections is the build-up and phase out of LNG captured by the UMAS study across all its scenarios. This is an artifact of current trends in the rapid growth in LNG as a fuel reflected in the new builds and orderbooks (DNV, 2024).

Projected fuel mix by UMAS and MMMCZCS studies

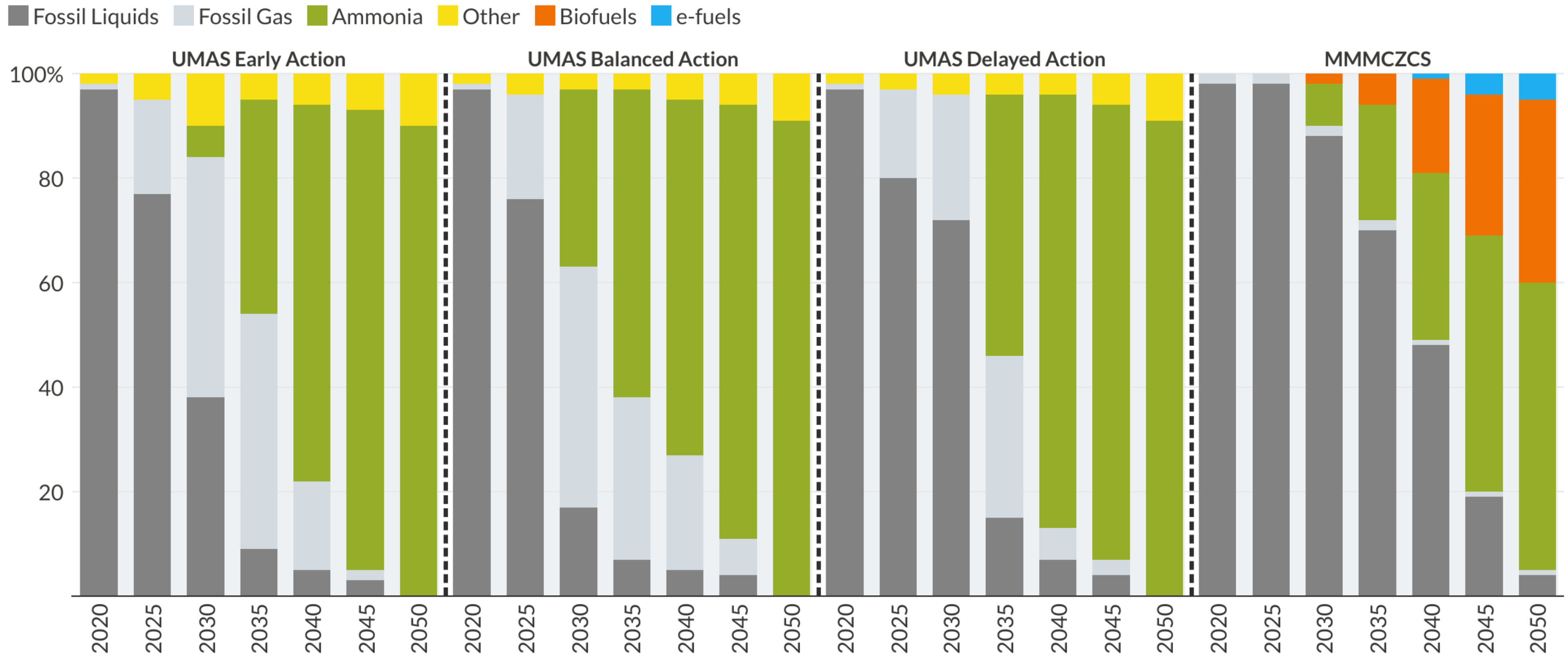


Figure 14: Projected fuel mix by UMAS and MMMCZCS studies. Fossil liquids cover LSFO and MDO fuels. Fossil gas refers to LNG. Other fuels refers to a wide mix of fuels, including hydrogen, synthetic methanol, methanol, electricity, shore power electricity, bio-LSFO, bio-MDO, bio-LNG (bio-methane) and bio-methanol.

Other literature studies, such as from DNV, while offering deep emissions reductions into the future, do not reach real zero by 2050 and still envisage high reliance on fossil fuels, namely LNG as an alternative to heavy fuel oils. To accommodate for these large shares of fossil fuels, the study envisages great increases in on-board CCS to close the emission gap (DNV, 2022, 2024). On-board CCS technology is still yet to be proven commercially viable and effective on-board vessels, acknowledging that it increases weight and reduces available storage space on the vessel. Some estimate that fitting CCS to ships would increase fuel consumption on-board by 40%, in order to capture 90% of the emissions (Lloyd's List, 2025). Given the abysmal track record of CCS in stationary applications, the feasibility of using CCS for decarbonising international shipping should be taken with a great degree of caution.

Why ammonia over hydrogen?
Ammonia emerges as the leading SZEF because of its relative competitiveness compared to other options. This competitiveness is shaped by both fuel production and onboard technology costs. Ammonia's production cost lies between hydrogen (lower) and synthetic methanol (higher). However, hydrogen incurs significantly higher storage and handling costs onboard and onshore compared to ammonia. Ammonia's comparatively lower operational costs therefore offset its higher production costs relative to hydrogen, making it the most attractive long-term option.

The UMAS study assumes that the announced green ammonia capacity far exceeds blue ammonia projections out to 2030, but the overall capacity remains insufficient unless development accelerates sharply in the coming years. If green ammonia growth is delayed to 2030, then a steady balanced action scenario would not be possible and a delayed action scenario becomes inevitable. Green ammonia production would have to jump from existing annual growth rates of about 10% to about 18% CAGR (Compound Annual Growth Rate) (Smith et al., 2025).

The potential for alternative technologies to deliver real zero in shipping

Battery power on vessels has major limitations due to the high energy density of batteries, increasing weight of vessels and limited cargo space. This has not made battery power an attractive option for long distance voyages but has been touted as an option for short distance voyages and uses – such as passenger ferries. Due to this lack of efficiency, battery electric fuels have had limited representation in modelled decarbonisation pathways for shipping.

While pure battery-electric propulsion faces strong technical and economic constraints for long distance shipping, a hybrid power plant approach, where ~80% of energy demand is met with batteries and the remainder with renewable fuels, offers significant potential. Compared with methanol dual-fuel internal combustion engines, hybrid battery vessels could reduce life-cycle renewable energy demand by over 65%, making them far more efficient. This efficiency means that electrifying smaller merchant vessels on short voyages could cut up to 17% of current CO_2 emissions in these segments, while freeing an additional 1.8 EJ of renewable energy for other e-fuel production (MMMCZCS, 2024).

To increase the capacity for battery capacity on-board vessels, supportive enablers must be in place. These include the design and deployment of optimised battery systems (e.g. containerised solutions to minimise cargo loss), widespread shore power and high-capacity charging infrastructure in ports, and access to low-carbon electricity along shipping routes. Battery electric solutions are therefore positioned as a complementary pathway: well-suited for short-sea and hybrid applications, less viable for deep-sea operations.

Wind-assisted propulsion is emerging as a potential technological solution to reduce fuel consumption on vessels. While yet to be deployed commercially, technologies such as rotor sails, kites and suction wings are already being trialled on commercial vessels and have reached a relatively high level of technological readiness, with the most advanced solutions (e.g. rotor sails) at or near full commercial maturity. They can deliver significant fuel savings in the range of 5–20%, thereby directly reducing emissions when combined with other efficiency measures (EMSA, 2023).

Enablers of a real zero pathway in shipping

Reaching real zero in international shipping will require not only technological shifts but also strong institutional and policy enablers. The IMO Net Zero Framework in 2023, which was set to be adopted in October 2025, would set a GHG fuel standard coupled with a carbon pricing mechanism (IMO, 2025). It would not only provide a critical global mandate and reference point for national governments, shipowners, and cargo owners, but also penalise the use of fossil fuels to accelerate the transition of the global fleet to zero emission fuels and technology. There are key concerns on the effectiveness of the Framework due to the weak targets, compliance flexibilities and limited of equitable transition considerations, and insufficient consideration of the limitations of biofuel scale-up in shipping (MMMCZCS, 2025b; Transport & Environment, 2025) (MMMCZCS, 2025b; Transport & Environment, 2025). Nevertheless, it marks a major milestone in the right direction. However, implementation is now further off with the IMO voting in October 2025 to postpone the decision by one year after pressure from the US to vote against the measure.

The transition also depends on finance and international cooperation. Meeting the projected demand for SZEFs could require trillions of dollars in capital investment across fuel production, port infrastructure, and vessel retrofits (Baresic et al., 2024). Public–private partnerships, concessional finance, and blended finance models will be key in de-risking early investments and ensuring an equitable transition, particularly for developing economies that are central to global shipping networks. Meanwhile, cargo owners and charterers can reinforce demand certainty through green procurement and long-term offtake agreements, creating the commercial case for large-scale fuel supply chains.

Summary

Our assessment of both integrated assessment models (IAMs) and literature shows broad alignment which support real zero emissions in international shipping by 2050 is achievable. While IAMs typically reach full decarbonisation slightly later than other sectors, the GCAM and PROMETHEUS models are shown to be the most ambitious demonstrating that fossil fuel use in shipping can be eliminated by mid-century. Similarly, from the literature review, shipping sector pathways developed by UMAS, the Mærsk Mc-Kinney Møller Center, Transport & Environment, and the SBTi all converge on the same outcome, even though they vary in the speed and ambition of reductions before 2050. Comparing the 2035 benchmark as a half-way point between today and 2050, the literature envisages steeper emission cuts (of rough 60% to 75%) than the most ambitious IAMs models which see emissions only half.

Across these studies there is no single consensus on the precise mix of fuels that will replace fossil energy. Instead, scenarios point to a range of possible futures, including varying levels of reliance on direct hydrogen use, synthetic fuels, biofuels, and ammonia. This diversity reflects both uncertainty in fuel technology development and the influence of different modelling approaches, whether global top-down IAMs or sector-specific bottom-up analyses. What is consistent across all perspectives is the recognition that scalable zero-emission fuels (SZEFs) must underpin the transition, supported by operational efficiency improvements and enabling infrastructure in ports.

Based on our comparative analysis, ammonia emerges as the most likely dominant fuel pathway for international shipping. Its competitiveness stems from a balance of production costs, onboard handling advantages over hydrogen, and scalability in comparison to biofuels or synthetic methanol. While other SZEFs will play complementary roles depending on geography, vessel type, and trade routes, ammonia appears best placed to anchor the global fuel transition in the sector. This conclusion is echoed across both IAMs and the most robust sectoral studies, suggesting that green ammonia should be considered the cornerstone of strategies for achieving a real zero shipping sector by 2050.

Other sectors

We further complement our analysis with a review of the dates of real zero and the fuel mix by which real zero is achieved in the sectors of **power** and **light duty vehicles (LDVs**).

Power

Our review identifies a broad set of global integrated-assessment and energy-systems models that provide data on deep decarbonisation of the power sector, including GCAM (6.0 NGFS and 7.2), IMAGE 3.3, MESSAGEix-GLOBIOM 1.1-BMT-R12, PROMETHEUS V1, REMIND (3.0, 3.2/3.3, and 3.5), WITCH 5.0, COFFEE 1.5, and IMACLIM 2.0.

Importantly, we have not yet applied the filtering process to the results in the power sector, to exclude pathways in which pre-2025 emissions reductions significantly exceed historical trends (see Methods Summary for more detail). Including this filtering step could potentially delay the dates of real zero found in the analysis partially, by removing those pathways which are able to achieve real zero rapidly due in part to their assumptions around pre-2025 action.

Figure 15 summarises the power-sector outcomes across these models. The figure shows, for each model, the deepest reductions in power-sector emissions versus the base year across all regions, highlighting the three most ambitious regions per model.

Overall, the analysis finds substantial near-term declines by 2030 in many model-region combinations, accelerating through 2040. The number of models that achieve real zero rises through 2035, and by 2040 four different modelling frameworks have demonstrated the feasibility of a real zero power sector. The frequency with which models achieve real zero becomes increasingly widespread by 2045–2050, with most models and virtually all regions showing at least one pathway that attains real zero. This cross-model and cross-region convergence reinforces that achieving real zero in the power sector is technically achievable in by the 2040s, even though the precise timing varies by model family and regional context.

In addition, many models and regions are able to achieve very deep reductions, either attaining or getting close to real zero in the mid-2030s. This is critical, as providing zero-carbon electricity alongside widespread electrification can ensure that end-use sectors are not only real zero at the point of use, but real zero across their upstream emissions chains.

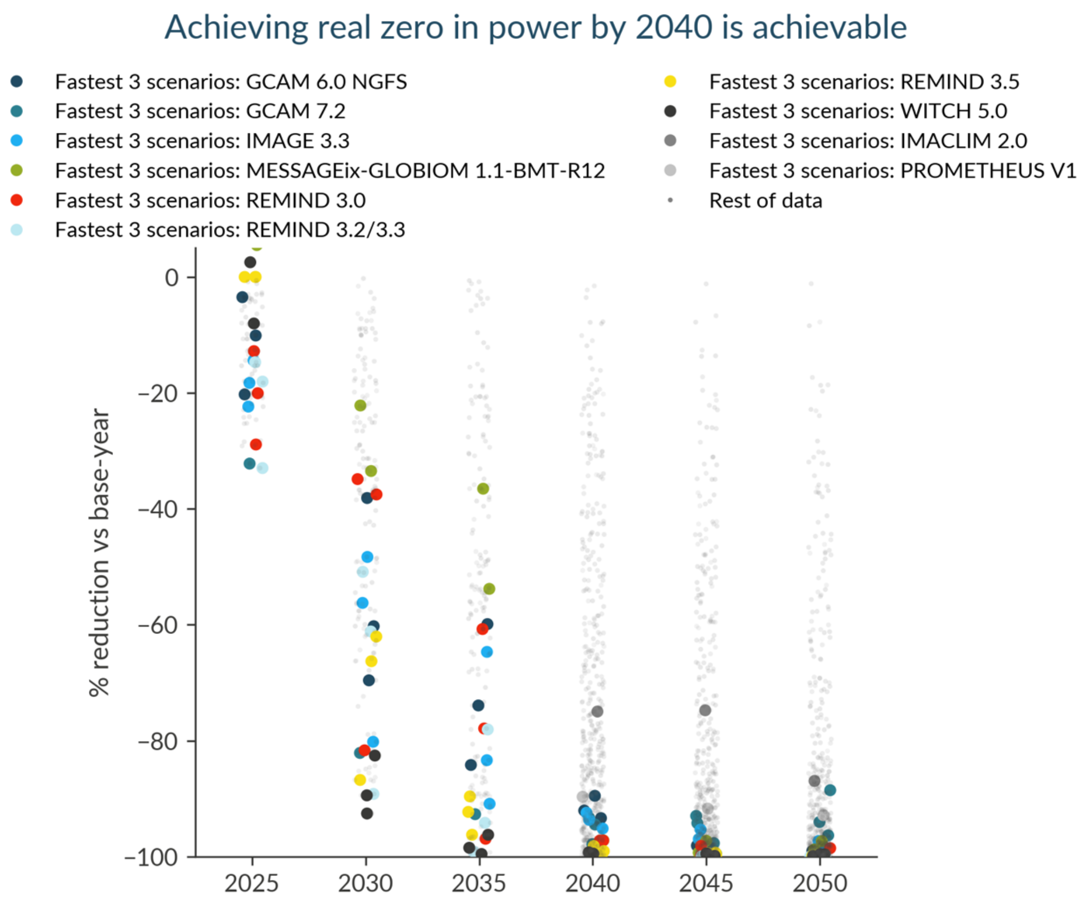


Figure 15: Achieving real zero in the power sector: evidence from global pathways.

Rapid and deep reductions in power-sector emissions are achievable. By 2035, across all regions and all models, the most ambitious reductions reach ~70–90% and are at or near real zero in the leading regions, notably Europe and North America. Meanwhile, by

2040, virtually all models show 90–100% reductions in the power sector, with many regions achieving real zero.

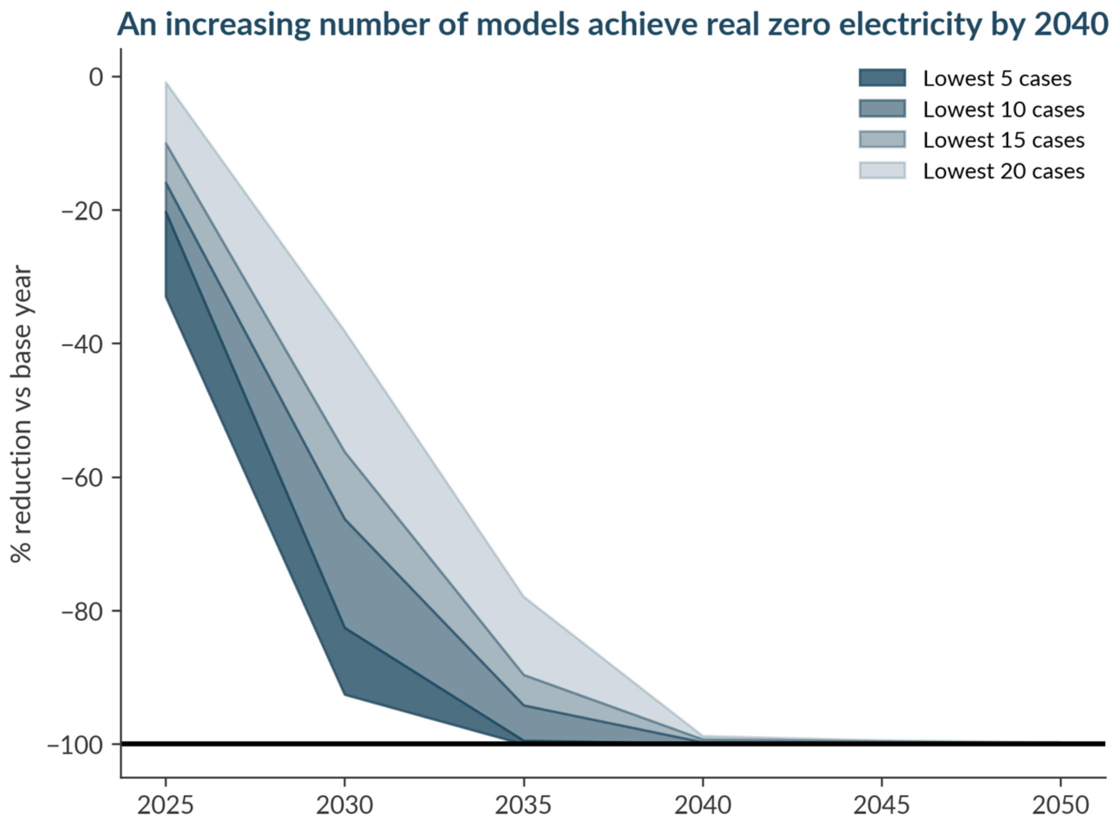


Figure 16: The ambition frontier for achieving real zero power – evidence from the global pathways

Figure 16 highlights how a modelled pathways increasingly achieve real zero in the power sector by 2040 while Figure 17 shows further details on how many models achieve real zero in each region, and how many regions achieve real zero in each model.

By 2050, the broadest regional coverage comes from REMIND 3.2/3.3, which achieves real zero across nearly all regions. WITCH 5.0 also demonstrates widespread regional decarbonisation, reaching real zero in several regions by 2040. In contrast, models such as GCAM 6.0 NGFS, IMAGE 3.3, IMACLIM 2.0, and PROMETHEUS V1 remain more carbon-intensive through mid-century, failing to reach a fossil-free power sector even by 2050. This continued divergence across IAMs underscores that many still depend heavily on fossil generation with carbon capture and storage (CCS), despite increasing evidence that the economic case for fossil CCS in power is being undermined by the rapid cost declines in renewables (Grant *et al*., 2021). As highlighted before – just because a modelled scenario does not reach real zero in a sector, does not mean that real zero is not possible in this sector, or even within this modelling framework – but perhaps simply that existing scenarios have not been set up to explore or achieve real zero in this sector.

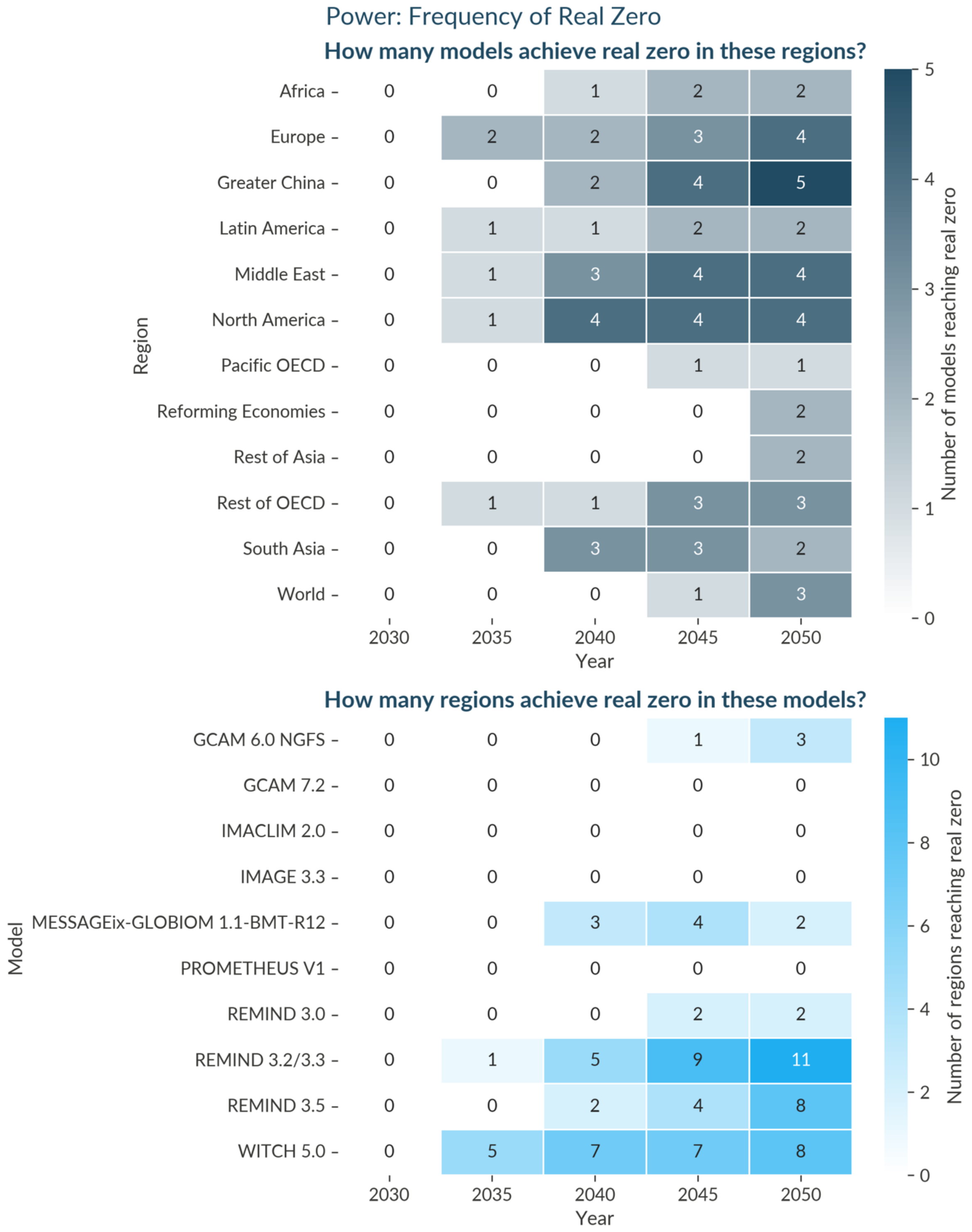


Figure 17: Frequency of real zero in each region and model - power sector.

This suggests that real zero in the power sector is already achieved in several leading regions by the mid-2030s, expands broadly across regions and models through the 2040s, and attains near-global coverage by 2050 in the most ambitious frameworks. We note that we are using a very stringent definition of real zero in this work, which requires fossil fuel demand to fall by more than 99% to count as real zero. Previous work by Climate Analytics has looked at the dates at which clean power is "effectively" reached, using a different threshold of <2.5% share of electricity coming from fossil fuels in the power sector (e.g., Climate Analytics 2022). Using this threshold, the dates at which models approach real zero would be even earlier (see Figure A2 and Figure A3).

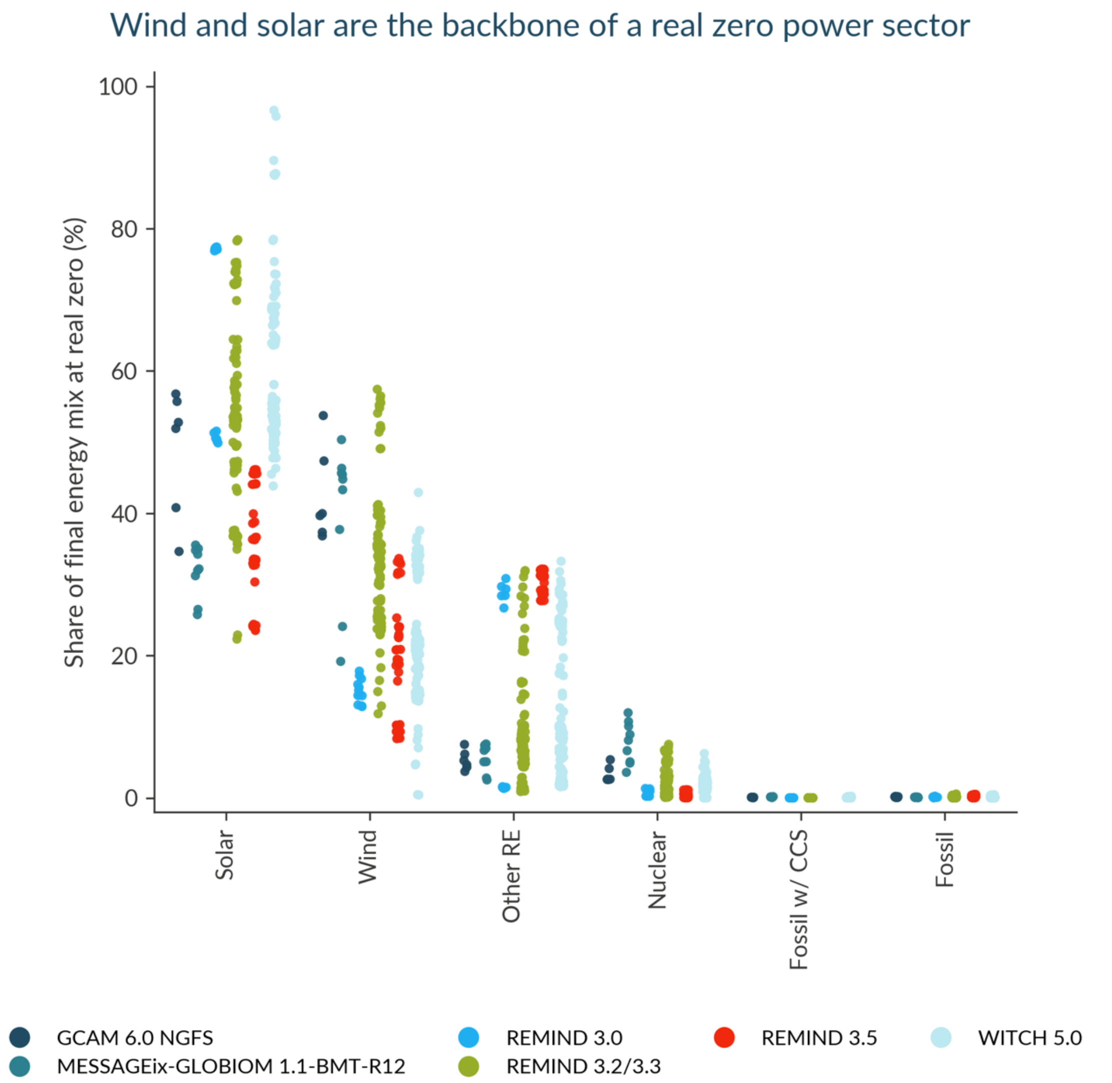


Figure 18: The generation mix that delivers real zero - evidence from global pathways (power)

Figure 18 shows the generation mix that delivers real zero across the reviewed models. While mixes vary by model and region, real-zero systems are consistently dominated by variable renewables. Solar is frequently the single largest contributor – often ~30–70% across models – with a tail up to ~80% in certain regions of the REMIND scenarios. Wind typically supplies a substantial complementary share (~10–55% across REMIND, MESSAGEix-GLOBIOM, and IMAGE). "Other renewables" (e.g., hydro, geothermal, sustainable bioenergy) add smaller but material contributions (generally 0–35%). Firm "other technologies" are limited: nuclear is usually 0–20%, while fossil unabated or with CCS appears is (by definition) 0%. Overall, the models indicate that real-zero power systems are delivered primarily – sometimes almost entirely – by renewables, complemented by firm low-carbon resources, storage, and grid flexibility.

Light duty vehicles

Our review covers a consistent set of global integrated-assessment and energy-systems models with detailed Light Duty Vehicles (LDV) pathways, including GCAM 7.2, IMAGE 3.3, and REMIND (3.0, 3.2/3.3, 3.5).

Figure 19 summarises outcomes across these models. Importantly, we have not yet applied the filtering process to the results in the LDV sector, to exclude pathways in which pre-2025 emissions reductions significantly exceed historical trends (see Methods Summary for more detail). Including this filtering step could potentially delay the dates of real zero found in the analysis partially, by removing those pathways which are able to achieve real zero rapidly due in part to their assumptions around pre-2025 action.

The figure shows, for each model, the deepest reductions in LDV emissions versus the base year across all regions, highlighting the three most ambitious regions per model. Across model–region pairs, LDV decarbonisation is rapid. By 2030, many best-case points already show ~40–90% reductions, reflecting the fast uptake of electrification in ambitious pathways. By 2035, leading instances in every model reach ~85–95% reductions, with several pathways approaching real zero.

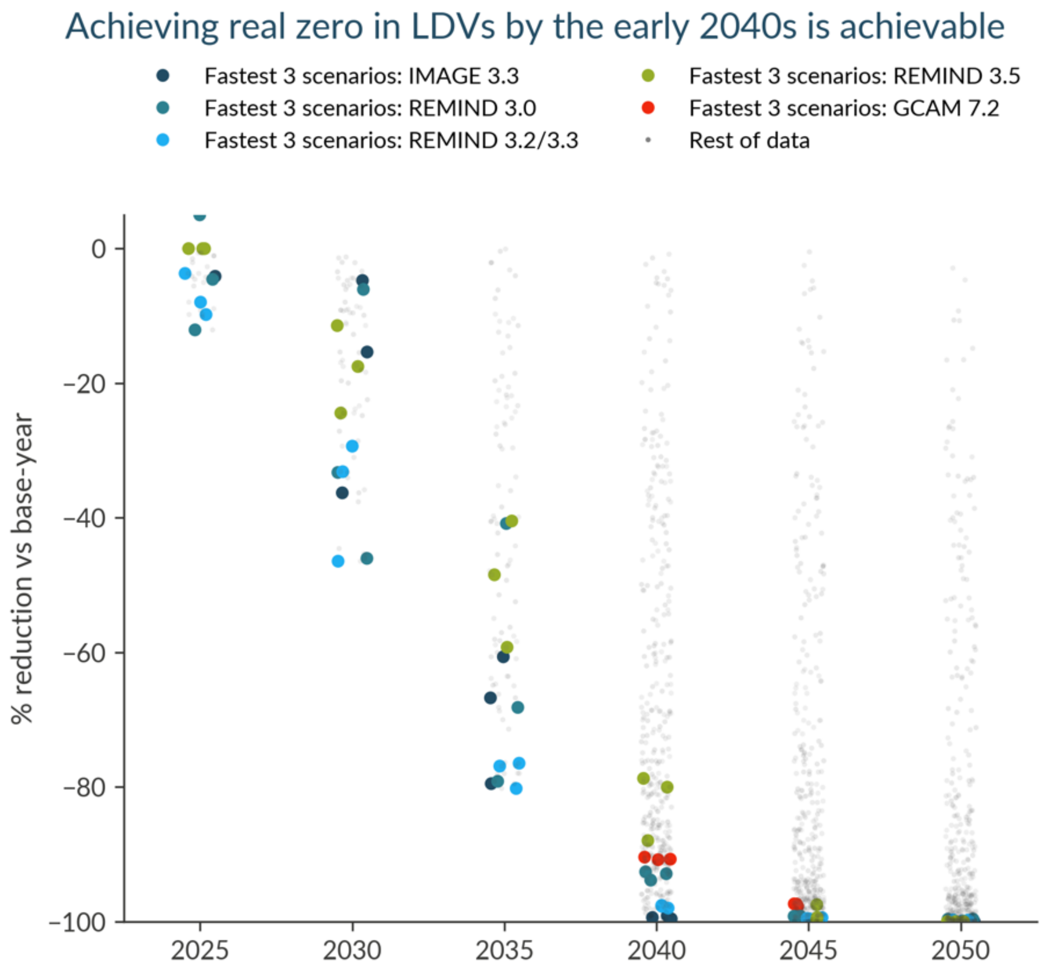


Figure 19: Achieving real zero in the LDV sector – evidence from global pathways

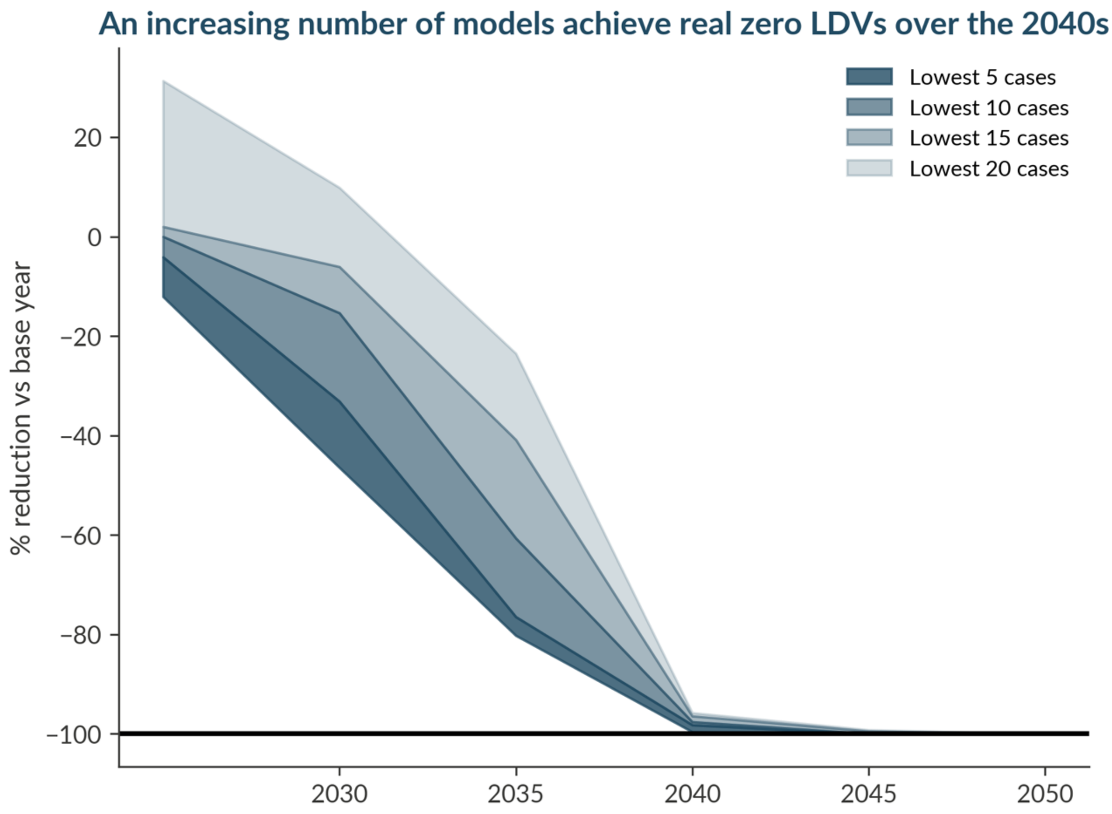
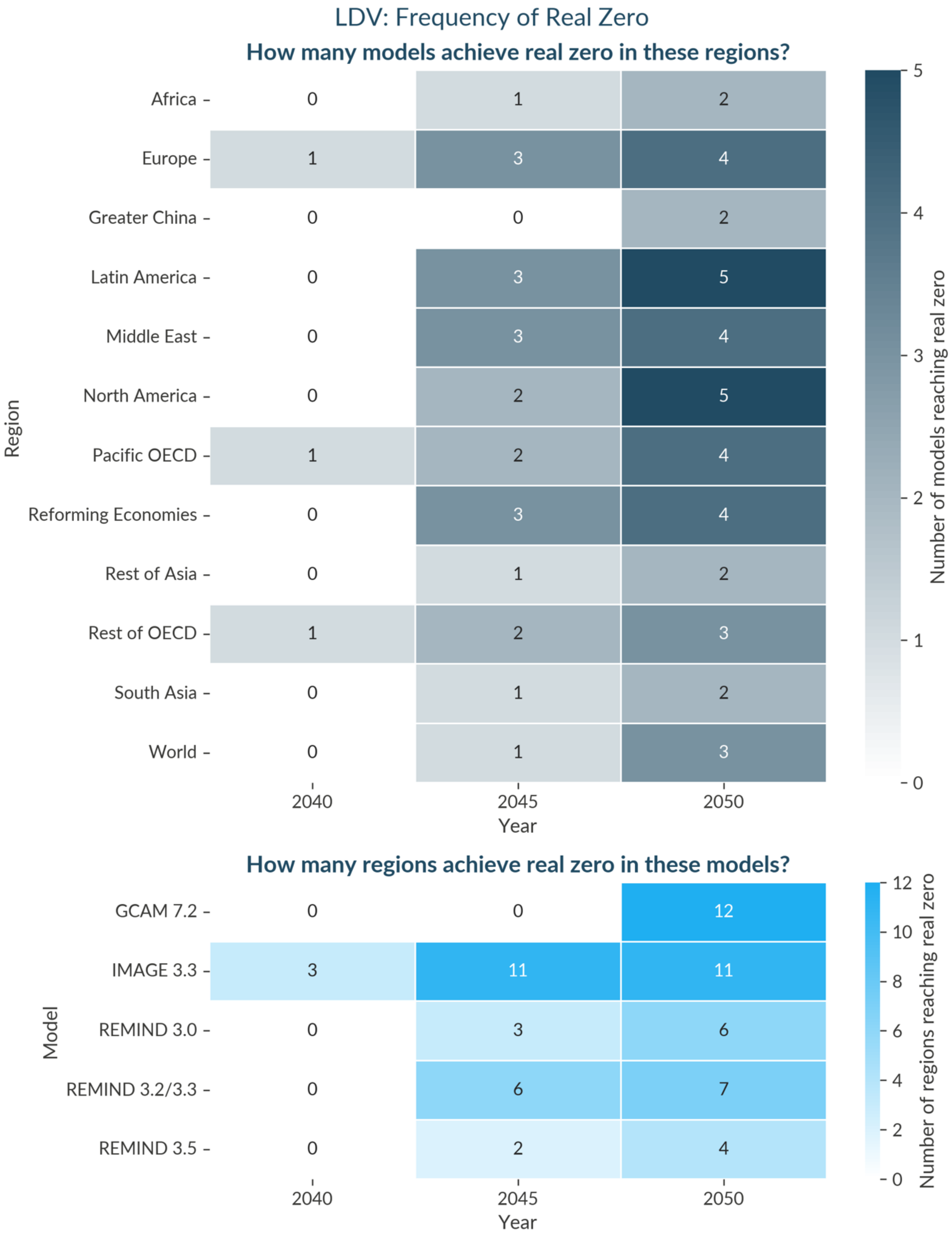


Figure 20: The ambition frontier for achieving real zero in LDVs – evidence from the global pathways

Figure 20 shows how a large fraction of global pathways converge to achieving real-zero in LDVs over the 2040's. Meanwhile Figure 21 highlights how many models achieve real zero (real zero, ≤−99%) in each region (in the top-panel), and how many regions achieve real zero in each model (in the bottom-panel). Two model families deliver (near) global LDV real zero within the time horizon: IMAGE 3.3 reaches 11 regions by 2045 (and remains at 11 in 2050), while GCAM 7.2 reaches all 12 regions by 2050. The REMIND variants broaden progressively: REMIND 3.2/3.3 spans 6 regions by 2045 and 7 by 2050; REMIND 3.0 reaches 3 by 2045 and 6 by 2050; REMIND 3.5 reaches 2 and 4 over the same years. Taken together, by the late 2040s multiple model families offer at least one LDV real zero pathway across most regions, with a subset providing full global coverage.

By region, early real zero entries by 2040 appear in Europe, Pacific OECD, and the Rest of the OECD. By 2045, coverage thickens: Europe, North America, Pacific OECD, Rest of OECD, China, Middle East, and Reforming Economies show 2–3 models at real zero. Latin America reaches 3, and first entries appear in Africa, India, and Rest of Asia. By 2050, the distribution is broad: North America and Latin America each have 5 models at real zero; China, Europe, Middle East, Pacific OECD, and Reforming Economies have 4;

Rest of OECD has 3; and Africa, India, and Rest of Asia each have 2. At the World aggregate, one model reaches real zero by 2045, rising to 3 by 2050.



Region	2040	2045	2050
Africa	0	1	2
Europe	1	3	4
Greater China	0	0	2
Latin America	0	3	5
Middle East	0	3	4
North America	0	2	5
Pacific OECD	1	2	4
Reforming Economies	0	3	4
Rest of Asia	0	1	2
Rest of OECD	1	2	3
South Asia	0	1	2
World	0	1	3

Model	2040	2045	2050
GCAM 7.2	0	0	12
IMAGE 3.3	3	11	11
REMIND 3.0	0	3	6
REMIND 3.2/3.3	0	6	7
REMIND 3.5	0	2	4

Figure 21: Frequency of real zero in each region and model - LDV sector

This pattern suggests LDV real zero emerges first in Europe and other OECD regions around 2040, then extends across North America, China, Reforming Economies, the Middle East, and others through the 2040s, reaching near-global coverage by 2050 in the most ambitious model families.

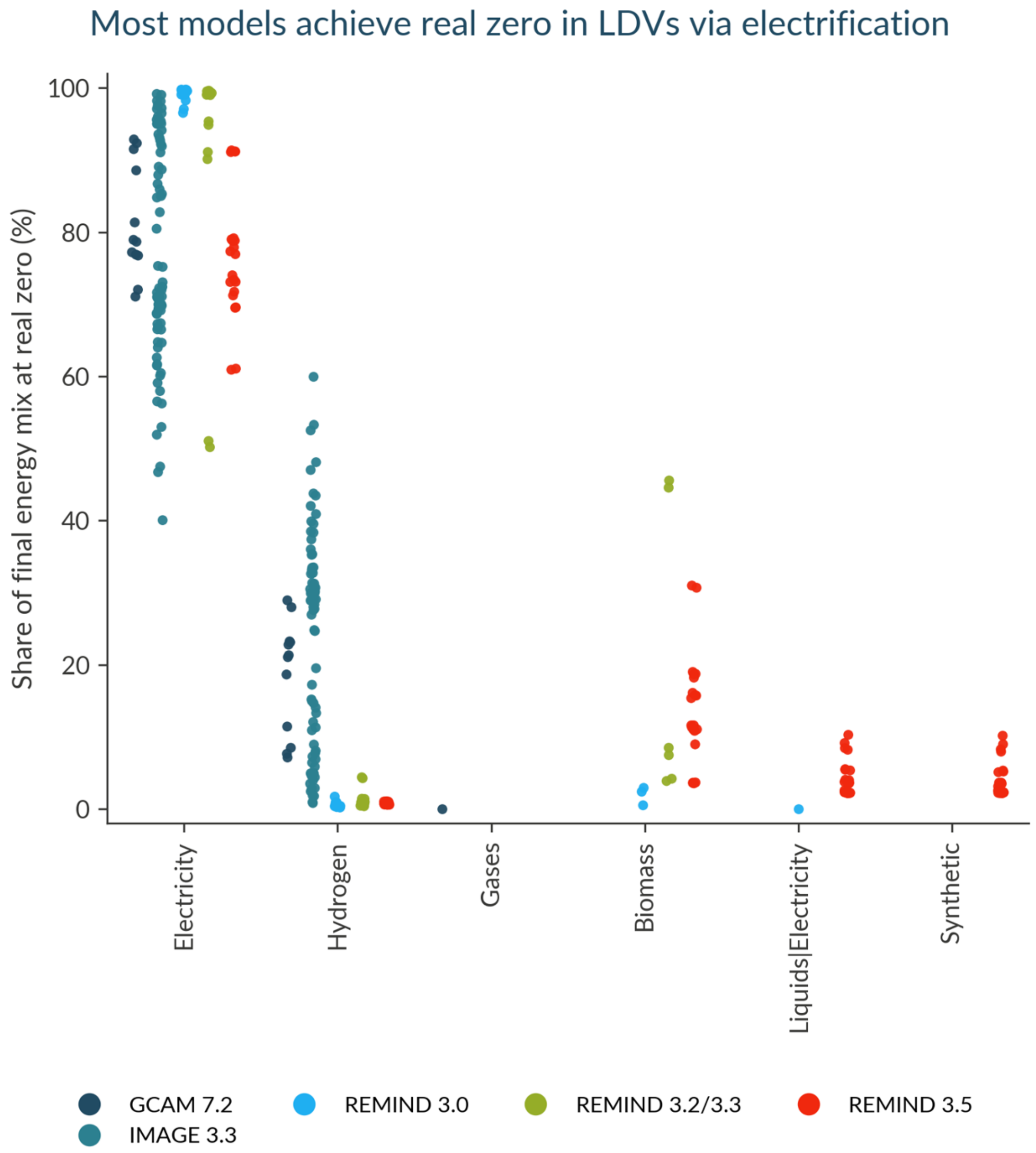


Figure 22: The generation mix that delivers real zero - evidence from global pathways (LDV)

Figure 22 shows that real-zero LDV pathways are overwhelmingly electricity-led. Across models, electricity supplies the dominant share at real zero – typically ~70–100%. REMIND variants cluster at the very high end (often ~95–100%), GCAM 7.2 is mostly ~70–90%, and IMAGE 3.3 ranges more widely (~40–90%) but still centres on electrification.

Hydrogen appears mostly as a minor component (0–10%) in most frameworks, with a few IMAGE 3.3 trajectories showing larger shares (up to ~60%) and occasional GCAM 7.2 cases around ~10–30%. Such high hydrogen shares are difficult to justify based on real-world evidence, which overwhelmingly supports direct electrification as the most efficient and cost-effective route for LDVs. These results likely reflect gaps in how the models represent transport technologies and behaviour, rather than realistic expectations. Future model improvements should address these issues to better align with current knowledge and observed trends.

Biomass contributes in a subset of REMIND 3.5 cases (roughly ~5–30%, with isolated higher points), while synthetic liquids are near-zero in almost all runs.

Taken together, the picture at real zero is a battery-electric LDV system with small, model-dependent roles for hydrogen and biofuels; the few high-hydrogen outcomes reflect specific pathway assumptions rather than a cross-model consensus.

Conclusion

As global temperatures continue to rise and climate impacts continue to escalate, the world needs robust guidelines and benchmarks to inform climate action and set out a pathway to bring warming back below 1.5°C prior to the end of the century.

We know that, at the global level, reaching net zero CO_2 at or around mid-century, and net zero GHGs soon after, are critical to stopping global warming and then bringing temperatures back down to below 1.5°C before 2100.

But, while critical at the global level, the concept of net zero is being undermined by the proliferation of net zero targets and approaches at the national and corporate level. These net zero targets often set up a very loose "net" – enabling large-scale continued consumption of fossil fuels that is compensated for by CDR. They also often rely on large-scale use of fossil CCS to enable continued consumption of fossil fuels.

While such an approach might find a more positive reception with board members and shareholders averse to change, the overreliance on CCS and CDR is ultimately taking companies down a risky and unreliable pathway that relies on fixes rather than innovation, and clings to the energy system of the past rather than embracing technological change. The robust alternative is to commit to real zero – fully eliminating fossil fuels, and with it, reliance on fossil CCS and CDR for managing continued fossil fuel emissions.

This report investigates the techno-economic feasibility of reaching real zero emissions in five key sectors of the economy – trucks, steel, shipping, power and light-duty vehicles. It assesses the existing evidence base produced by global IAMs and bottom-up studies, and identifies when (and how) real zero can be reached across these sectors, looking across a range of geographical scales.

It is important to highlight that this report reviews the existing evidence base, much of which was not produced to explicitly investigate the feasibility of reaching real zero emissions. Therefore, when scenarios and/or models do not achieve real zero in a given sector / region, that does not necessarily mean that real zero is not possible in that given modelling framework. It only means that the specific scenarios generated to-date by the model do not reach real zero. Developing scenarios that explicitly test the feasibility frontier of achieving real zero emissions would be a valuable next step in developing this research.

However, the research to-date suggests that real zero is not a pipedream, but a technically feasible goal that companies can orient themselves around in the energy transition, and that it is possible in many cases to achieve real zero before 2050.

In **trucks**, leading regions such as the EU27 could potentially achieve real zero as early as 2040, and increasingly so by 2050. In **steel**, the earliest dates of real zero found are in the IAM studies which achieve this milestone by 2040. It may be the case that these studies are underestimating the need for primary steel production – which could delay the achievement of real zero by a few years. However, achieving real zero through the 2040s, or around 2050 in the steel sector should be achievable. In **shipping,** both global IAM studies and more detailed shipping-specific analyses suggest that real zero could be reached by 2050. Meanwhile in the case of **power** and **light-duty vehicles**, the most ambitious models achieve real zero in the 2030s and by 2040 respectively.

While the dates of real zero vary across sector and region, in all cases the feasibility of reaching real zero by 2050, if not by 2040, is demonstrated in the leading regions. Leading companies can and should aim to achieve real zero ahead of these regional averages – with the first real zero companies achieving this goal in the 2030s and with a growing consortium of real zero companies by 2040. By committing to real zero targets, companies can avoid the risks and hazards associated with CCS/CDR reliance and help ensure that any CDR that is successfully scaled is used where it is needed most – to get temperatures back below 1.5°C.

The accompanying report – *Real zero: an opportunity, not a cost* – explores in more depth the economic opportunities of real zero in three key sectors, and demonstrates how, and under what conditions, real zero can unlock tangible economic benefits (Climate Analytics, 2025). Further work will build on this initial scoping analysis, to further demonstrate both the feasibility and desirability of real zero as a guiding star for corporate action.

Despite the cacophony of contrarian voices, we can bring an end to the fossil fuel era. Doing so represents one of the great industrial revolutions of human history, in which the innovators and leaders will reap the benefits, while the laggards will be consigned to the history books. Only time will tell which corporations are ready to lead the charge to a fossil-free economy, and which will face the consequences of inaction.

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Annex

Methods Annex

Definition of “real zero”

In this report, real zero is defined as the point at which fossil fuel demand in a given sector falls by more than 99% compared to its baseline level. This baseline is often set as 2020, as most reviewed pathways see coordinated action to reduce fossil fuel demand start in 2020. However, where the scenario baseline differs from 2020 (for example, starting in 2025), we use this alternative base-year, to ensure we are comparing scenarios against their correct baseline.

This represents a stringent threshold that goes beyond net-zero accounting to identify when fossil energy use is effectively eliminated from a sector. A secondary threshold of 95% reduction is also tracked for diagnostic purposes, capturing earlier decarbonisation milestones that do not yet constitute full fossil phase-out, but demonstrate that a scenario is approaching real zero.

A model–scenario–region combination is considered to have reached real zero when any year’s fossil energy demand—or, where that data is unavailable, an equivalent emissions or energy proxy—falls to ≤1% of its baseline level (i.e. a ≥99% reduction).

Because not all models report fossil energy demand in a consistent manner, the next section outlines the variable prioritisation tree used to determine which indicator is applied in each case to evaluate progress toward real zero.

Variable Prioritisation Tree

To ensure comparability across models that report different variables or levels of detail, the analysis applies a hierarchical variable prioritisation tree when assessing progress toward real zero. This structure identifies, for each sector and pathway, the highest-quality variable available to measure reductions against the 2020 baseline.

The prioritisation follows this order:

- Direct fossil fuel demand — used wherever possible as the primary indicator of progress toward real zero.

- Sectoral CO_2 emissions — applied where fossil demand data are unavailable, assuming proportionality between fossil energy use and emissions.
- Proxy energy carriers — if neither fossil demand nor emissions data are reported, secondary variables such as solids, liquids, or gases demand are used to approximate fossil fuel use.

Each selected variable is then assessed against the real zero threshold defined above (≥99% reduction relative to 2020). This approach ensures a consistent and transparent methodology across all integrated assessment model (IAM) pathways, even when the level of sectoral detail varies.

Filtering Steps

Before evaluating progress toward real zero, multiple filters are applied to ensure that only physically and economically plausible pathways are considered.

- **Early-decline and data quality filters:** Some IAMs exhibit abrupt early declines in fossil fuel demand immediately after 2020 that are inconsistent with observed data (for example, scenarios that unrealistically reduce fossil use by more than 5% between 2020 and 2025). To address this, all pathways in which **fossil demand/emissions over 2020–2025 fall more than 5% faster than the current trends** are excluded. We use IEA data to estimate current trends in fossil fuel consumption and emissions. This ensures that model trajectories start from realistic near-term conditions before projecting rapid transitions.
- **Electricity demand consistency filter:** In the power sector, we exclude any model–scenario–region where total electricity generation ever falls below its 2020 level at any point from 2025–2050. This maintains consistency between fossil phase-out and total power supply, avoiding cases where a model achieves "real zero" simply by eliminating demand.
- **Early real-zero removal:** In addition, we exclude "early achievers" — model–scenario–region combinations that reach a 95% reduction in fossil generation by 2030. These outlier cases are typically the result of unrealistic or incomplete power sector representations (e.g. instantaneous fuel switching or missing demand data). The filter is implemented programmatically by scanning the power sector time series and removing any combination where fossil emissions or demand reach ≤–95% by 2030.

Additional Results

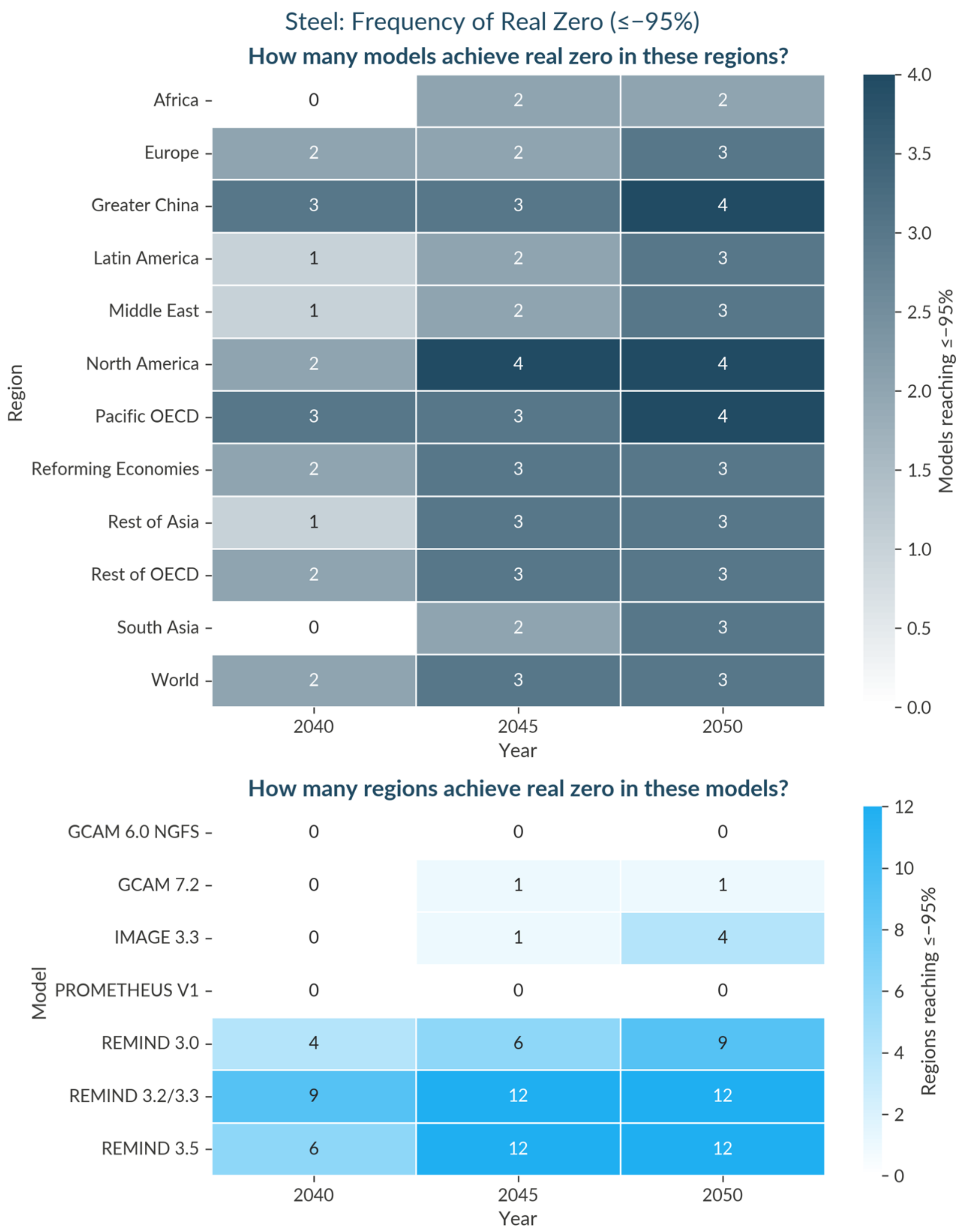
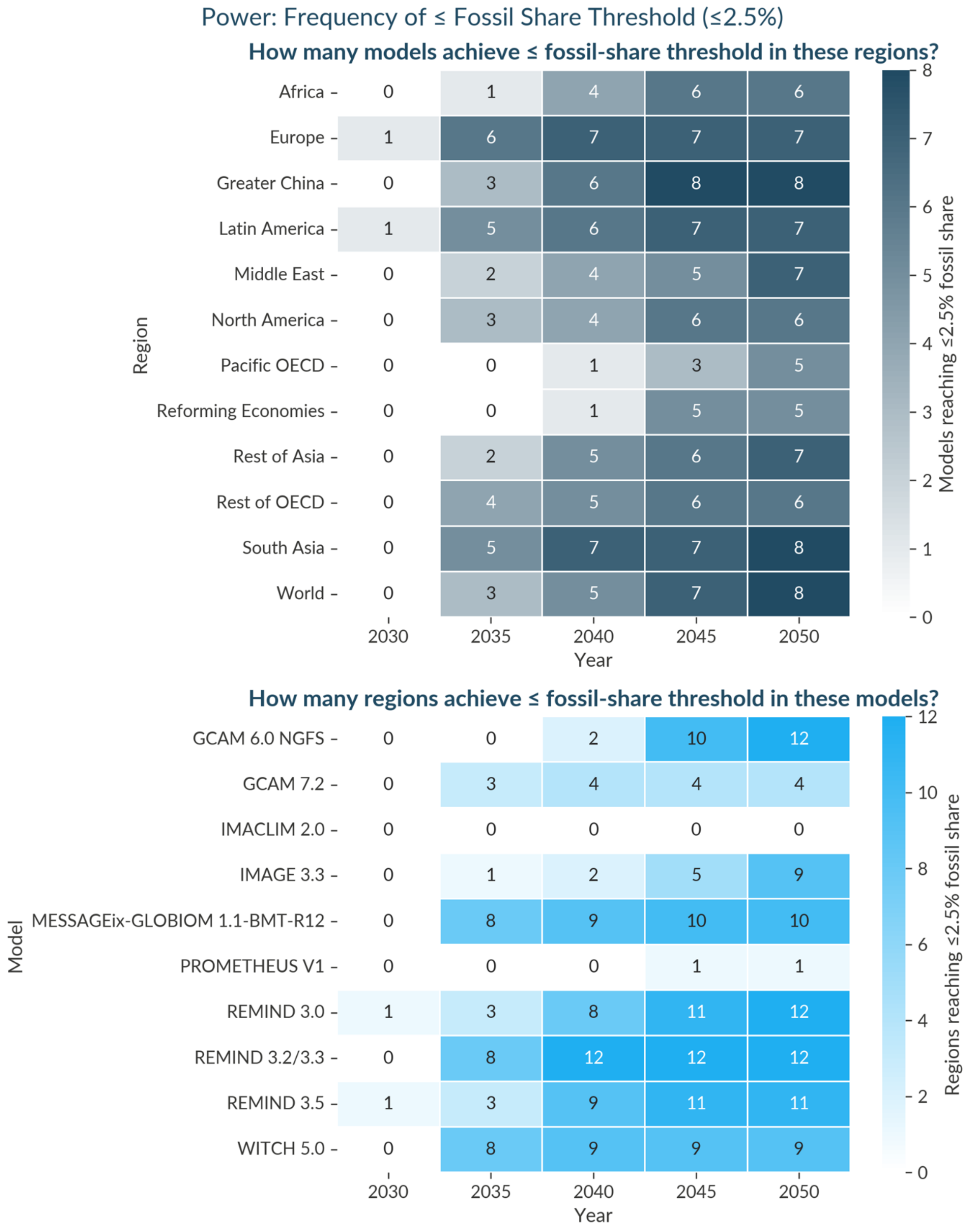


Figure A1: The number of models and regions that achieve >95% reductions in fossil fuel use in the steel sector



Region	2030	2035	2040	2045	2050
Africa	0	1	4	6	6
Europe	1	6	7	7	7
Greater China	0	3	6	8	8
Latin America	1	5	6	7	7
Middle East	0	2	4	5	7
North America	0	3	4	6	6
Pacific OECD	0	0	1	3	5
Reforming Economies	0	0	1	5	5
Rest of Asia	0	2	5	6	7
Rest of OECD	0	4	5	6	6
South Asia	0	5	7	7	8
World	0	3	5	7	8

Model	2030	2035	2040	2045	2050
GCAM 6.0 NGFS	0	0	2	10	12
GCAM 7.2	0	3	4	4	4
IMACLIM 2.0	0	0	0	0	0
IMAGE 3.3	0	1	2	5	9
MESSAGEix-GLOBIOM 1.1-BMT-R12	0	8	9	10	10
PROMETHEUS V1	0	0	0	1	1
REMIND 3.0	1	3	8	11	12
REMIND 3.2/3.3	0	8	12	12	12
REMIND 3.5	1	3	9	11	11
WITCH 5.0	0	8	9	9	9

Figure A2: The number of models and regions that achieve <2.5% electricity generation from fossil fuels

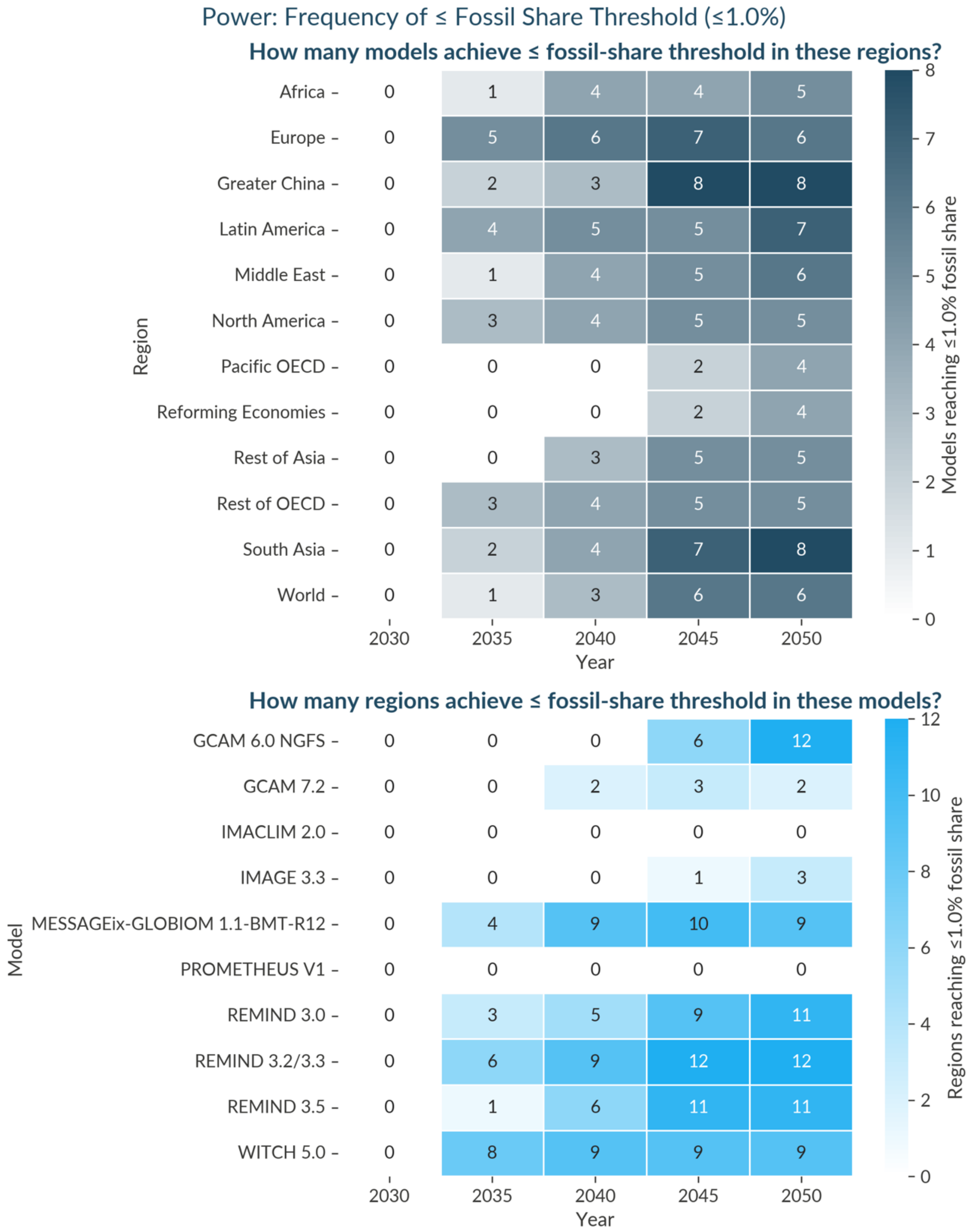


Figure A3: The number of models and regions that achieve <1% electricity generation from fossil fuels

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