VISION 2050

A strategy to decarbonize the global transport sector by mid-century

icct
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

PREFACE

This document has its origins in an internal strategic planning analysis that ICCT staff undertook in 2018 and 2019. Its purpose was to systematically test and refine a vision for decarbonizing the global transport sector that could help ICCT allocate its resources to the best practical effect. A preliminary version was presented at an all-staff conference held in May 2019. The work was continued and revised and elaborated throughout the remainder of that year, and presented to ICCT's Board of Directors in October 2019. It constitutes the analytical framework of ICCT's organizational planning for the near future.

Vision 2050 summarizes the outcomes of that internal exercise in a way that we hope may prove useful to the wider external community of organizations and individuals working, like us, to avert a global climate crisis. For road, air, and maritime transportation it articulates a set of targets for greenhouse gas emissions that we collectively must reach if we are to keep global warming below 1.5°C, and a series of steps that we collectively can take to reach them.

That is, it attempts to look into an uncertain future. But it is not immune to the turbulent present. As we prepared this summary, the COVID-19 pandemic delivered a harsh reminder that human society is contingent. The International Energy Agency projects an 8% drop in global energy sector CO_2 emissions in 2020. While this is a significant reduction in carbon emissions, it is also expected to be temporary. The powerful momentum behind the technological systems on which the global transportation sector depends may be seen in how rapidly China's carbon emissions rebounded once that country reopened its economy after radical measures to halt the spread of the novel coronavirus began to take effect. The climate crisis remains with us, and it remains urgent. This our strategy for meeting it, one that we will continue to update and refine on an annual basis to take account for changes to our baseline projections and to mark progress.

INTRODUCTION

Global demand for passenger and freight transportation is trending strongly upward, driven by population and economic growth, and in particular by a rapidly expanding cohort of new middle-class consumers in countries like China and India. As transportation demand has grown so too, inexorably, have carbon emissions from the global transportation sector. That is a trend that we know cannot be permitted to continue. The destructive effects of the warming that has already occurred as a consequence of anthropogenic emissions of carbon dioxide and other greenhouse gases are dire enough: deadly heat waves from Montreal to Karachi, and Tokyo; extreme rains from North Carolina to Kerala; drought in the Horn of Africa; intense wildfires from Australia to California and Sweden; and more. Scientists warn that we must steeply reduce greenhouse gas emissions by mid-century to avoid additional warming that will have genuinely catastrophic effects. In that light, the task of transforming the technologies and systems that move people and goods around the world seems imperative, however daunting.

And greenhouse gas emissions do not even fully describe the environmental challenges posed by rising demand for transportation in a system that remains dependent entirely, or even primarily, on burning fossil fuel. The public health toll from air pollution, especially in many large cities, remains unacceptably high. Beijing "airpocalypse" of 2015 and Delhi's air pollution emergency of 2019 exemplify the problem, but it is not confined to only a few regions. More than 90% of the world's population lives in areas that do not meet the air quality guidelines set by the World Health Organization—including places, like parts of the United States and Europe, that do not habitually think of themselves as suffering from air pollution. Climate and health impacts are inherently coupled. For example, particulate matter in diesel engine exhaust has significant and direct adverse impacts on both health and climate, and electric vehicles with zero tailpipe emissions bring significant co-benefits in improved air quality.[1]

THE BOTTOM LINE IS THAT A SECTOR THAT IS ALMOST EXCLUSIVELY DEPENDENT ON A SINGLE ENERGY SOURCE, PETROLEUM, OPERATING ON INFRASTRUCTURE THAT REPRESENTS TRILLIONS OF DOLLARS OF INVESTMENT OVER MANY DECADES, MUST CHANGE SUBSTANTIALLY IN LITTLE MORE THAN A GENERATION.

The bottom line is that a sector that is almost exclusively dependent on a single energy source, petroleum, operating on infrastructure that represents trillions of dollars of investment over many decades, must change substantially in little more than a generation. Efforts to limit pollution and climate impacts of existing technologies must be continued and strengthened. Yet that will not be enough. Ambitious policies, incentives, and investments to bring forth new, clean transportation technologies and systems must be put in place without delay.

Many people have already engaged these problems. Policymakers at all levels of government are working to implement new environmental protections and other

1 Black carbon, one of the main components of diesel particulate matter, has a global warming potential of nearly 900 times that of CO_2 (over a 100-year time frame) and 3200 times that of CO_2 over a 20-year time frame.

measures. The automotive industry is investing in the development and deployment of new technologies. Philanthropies are directing large sums to support climate action. Advocacy and consumer groups are launching campaigns to raise awareness and put pressure on decisionmakers. Scientists and academic institutions are conducting research and analyses to support decision-making. The ICCT works with all these stakeholders, and we find ourselves in need of our own vision for decarbonizing the transport sector in order to effectively allocate our own resources and activities for maximum effect over these critical next five years.

In this paper, we address four questions that are central to the ICCT's vision for decarbonizing the global transportation sector.

1. What is the baseline trajectory of global transportation emissions from 2020 to 2050 by country and by vehicle segment?

2. What is the magnitude of reductions needed if the global transport sector is to contribute to keeping global temperature rise below 1.5°C?

3. What is an ambitious yet feasible set of policies and technologies for decarbonizing the transportation sector by mid-century?

4. What are the highest priority focus areas over the next five years?

About the ICCT

The ICCT was established in 2001 as an independent source of technical and policy expertise on clean transportation with the core mission of *improving the environmental performance and energy efficiency of road, marine, and air transportation, in order to benefit public health and mitigate climate change*. In the last five years alone, we have worked successfully with regulators and lawmakers around the world and have played a significant role in 48 distinct regulations and policies, which are together projected to result in billions of tons of carbon dioxide reductions and prevent thousands of premature deaths over the next decade and beyond.

Today, the ICCT has an annual operating budget of $13 million, a staff of more than 60, offices in Washington, San Francisco, Berlin, and Beijing, with new offices planned in Brazil and India. Our core work focuses on the key transportation segments—passenger vehicles, heavy-duty vehicles, marine, aviation—as well as the fuels that power them. Our geographic focus is on the major automotive markets—China, US/Canada/Mexico, Europe, India, and Brazil—as well as other growing markets in the Middle East, Latin America, Southeast Asia, and Africa. In addition, we work at the sub-national level with major provinces, states, and cities. More information can be found on our website at www.theicct.org.

TRANSPORTATION SECTOR EMISSIONS 2020–2050

What is the baseline?

The transportation sector accounts for approximately one-quarter of global anthropogenic CO_2 emissions. In 2015, greenhouse gas emissions in the global transportation sector were equivalent to 10.9 billion metric tons (Gt) of carbon dioxide-equivalent emissions (CO_2-e).[2] We project that present-day (roughly, 2019–2022) CO_2-e emissions from transportation globally will rise to 11.9 Gt .[3] The four largest vehicle markets, in terms of new vehicle sales—United States, China, the European Union, and India—account for 46% of global CO_2 emissions from transportation. If treated as individual vehicle markets, maritime shipping (11%) and aviation (10%) would be the third and fourth largest emitters, after China. Put differently, two-thirds of transportation CO_2 emissions in 2020 are from the four largest vehicle markets and the marine and aviation sectors.

Looking at the contribution of different modes of transportation (Figure 1), on-road vehicles dominate, accounting for roughly 77% of global transportation CO_2 emissions in 2020 (43% from light-duty vehicles including 2 and 3 wheelers and 34% from heavy-duty vehicles including buses). Heavy-duty vehicles make a disproportionate contribution to climate and air pollution relative to their numbers in the global vehicle fleet, in part because of their substantial emissions of particulate matter, including black carbon (not included in Figure 1), which has high short-term warming potential.

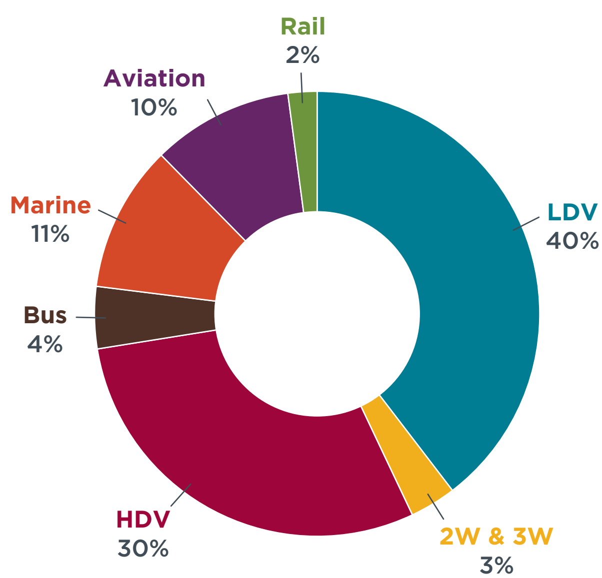

Figure 1. Share of 2020 well-to-wheel CO_2 emissions from transportation, by mode.

Public health impacts from transportation emissions have continued to rise despite progress on reducing emissions per vehicle-kilometer-traveled (VKT). Between 2010

2 GHG and short-lived climate pollutant emissions from transportation include gases and other climate forcers besides CO_2, such as methane and black carbon, whose effects in the atmosphere vary. CO_2 equivalency summarizes those effects in terms of the amount of CO_2 emissions that would produce them, to simplify comparisons.

3 Our estimate of 10.9 Gt CO_2-e in 2015 is 12% higher than the International Energy Agency's (IEA) and 3% higher than that of the OECD International Transport Forum (ITF). Compared with IEA, we estimate higher fuel life-cycle emissions from biofuels due to indirect land use change.

and 2015, the number of deaths attributable to transportation-related fine particle and ozone pollution worldwide increased from 361,000 to 385,000, with most of premature deaths (86%) attributable to ambient fine particulate matter ($PM_{2.5}$), and the remainder attributable to ozone.[4] Based on these estimates, the transportation sector accounted for approximately 11% of total global mortality attributable to these pollutants from all sources in 2015. Overall, we estimate that exposure to transportation emissions resulted in 7.8 million years of life lost and approximately $1 trillion in health damages globally in 2015. Among transportation sources, on-road diesel vehicles were the largest contributor to both $PM_{2.5}$ and ozone premature deaths worldwide. In short, despite the adoption of more stringent vehicle regulations in many countries, the transportation sector remains a significant contributor to the global burden of air pollution-related morbidity and mortality.

This burden is concentrated in certain countries and regions. In 2015, more than three-quarters of transportation-related health impacts occurred within four countries and trade blocs: China, with 117,000 premature deaths or 30% of the global total; the South Asian Association for Regional Cooperation (SAARC), which includes India, with 86,000 premature deaths or 22% of the global total; the European Union and the European Free Trade Association (EFTA), with 58,000 premature deaths or 15% of the global total; and the North American Free Trade Area, with 31,000 premature deaths or 8% of the global total (Figure 2).

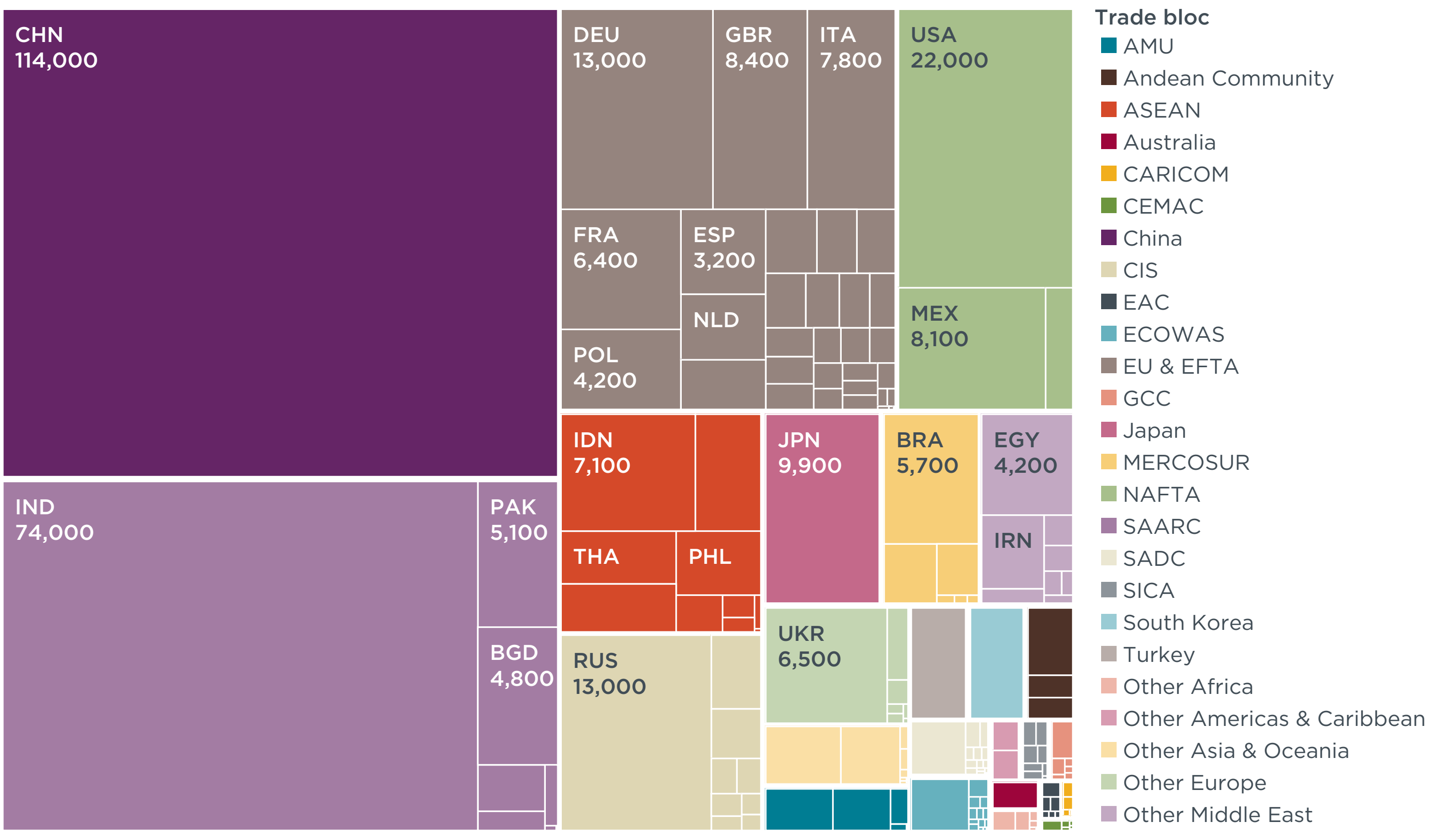

Figure 2. Mortality attributable to on-road transportation emissions in 2015 (by trade bloc).

4 The assessment on which this section is based used the GEOS-Chem global chemical transport model to simulate the fractions of ambient $PM_{2.5}$ and ozone concentrations that are attributable to transportation emissions, combined with epidemiological health impact assessment methods consistent with the 2017 Global Burden of Disease study. The term $PM_{2.5}$ refers to particles that are 2.5 microns or less in diameter.

Scenario Modeling: Methodology

Throughout this paper we refer to two different transportation emissions scenarios that we modeled using ICCT's Global Inventory Modeling tool, called "Roadmap." For details on the model, see www.theicct.org/transportation-roadmap. The assumptions underlying each scenario are summarized in Appendix A to this paper.

A fundamental assumption behind the emissions scenario results presented here is that emissions reductions and technology improvements in the transportation sector are driven first and foremost by government regulations. Correspondingly, the baseline scenario assumes no further vehicle technology improvements after the end date of currently adopted policies.

Scenario 1: "Baseline trajectory" assumes no further policies are put in place other than those already adopted as of 2019.

Scenario 2: "Ambitious yet feasible" utilizes assumptions based on ICCT's judgment of technology potential, estimated costs, policy opportunities, and regulatory compliance.

Table 1 Transportation Sector Emissions 2020–2050: Key numbers

Current situation	
~25%	Share of global anthropogenic CO_2 emissions from the transportation sector in 2016
12 billion metric tons	Annual GHG emissions from the transportation sector in 2020
385,000	Annual premature deaths attributable to transportation exhaust emissions in 2015
$1 trillion	Annual cost of health damages from transportation emissions in 2015
Baseline scenario	
21 billion metric tons	Annual GHG emissions from the transportation sector in 2050 without further policy action
90%	Approximate proportion of transportation emissions growth from 2020 to 2050 that will occur in China, Asia-Pacific, India, Africa, and the maritime shipping and aviation sectors
Target	
2.6 billion metric tons	Annual GHG emissions from the transportation sector in 2050 to limit global warming to 1.5°C
9.4 billion metric tons	Annual GHG emission reductions from the global transportation sector 2020 baseline required to limit global warming to 1.5 degrees.
Estimated reductions	
8 billion metric tons	Annual GHG emissions reduction in 2050 from 2020 baseline that could be achieved under ICCT's "ambitious yet feasible" scenario from the new-vehicle fleet and fuels.
85%	Fraction of GHG emissions reduction from baseline 2020 levels to 2050 target that can be obtained under ICCT's "ambitious yet feasible" scenario from the new-vehicle fleet and fuels.[5]

5 Estimated potential reductions from 2020 baseline from existing and emerging technologies in 2050 (8 Gt) divided by reductions from 2020 baseline required to achieve 1.5 degree trajectory in 2050 (9.4 Gt) = 85%

What is the baseline scenario?

Under the baseline scenario, the ICCT projects that global CO_2-e emissions[6] from transportation will grow significantly over the next 30 years, from approximately 12 Gt in 2020 to 21 Gt annually in 2050 (Figure 3). But within that overall trend, as illustrated in Figure 4, the regional distribution of global transport emissions will shift substantially. Whereas the benefits of currently adopted policies are projected to offset growth in travel demand in the United States and Europe,[7] we expect rapid growth in travel demand in China, the Asia-Pacific region, India, and Africa to outpace the effects of adopted policies and lead to substantial emissions growth in those regions. Substantial emissions growth is also projected for the global aviation and marine sectors. All told, without further policy action we expect nearly 90% of projected growth in transportation CO_2 emissions to take place in China, Asia-Pacific, India, Africa, and in the global aviation and marine sectors.

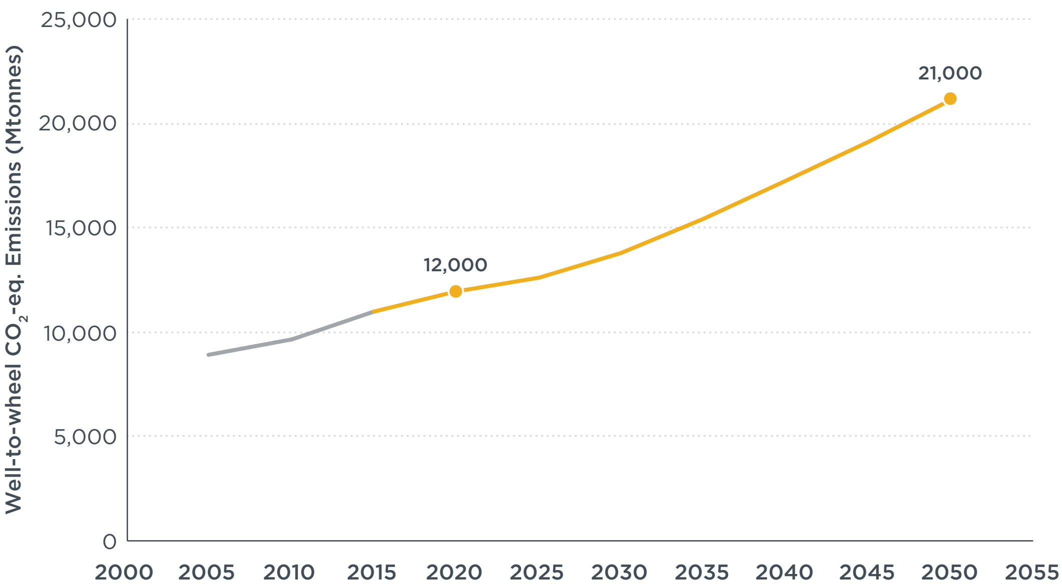

Figure 3. Projected growth in annual CO_2-equivalent emissions from the global transportation sector in the absence of further policy action.

6 This number reflects CO_2 emissions plus CO_2-equivalent emissions of black carbon, methane, and hydroflourocarbons (HFCs).

7 If the adopted policies underlying these projections are not implemented effectively, or are relaxed, then these projections would need to be revised.

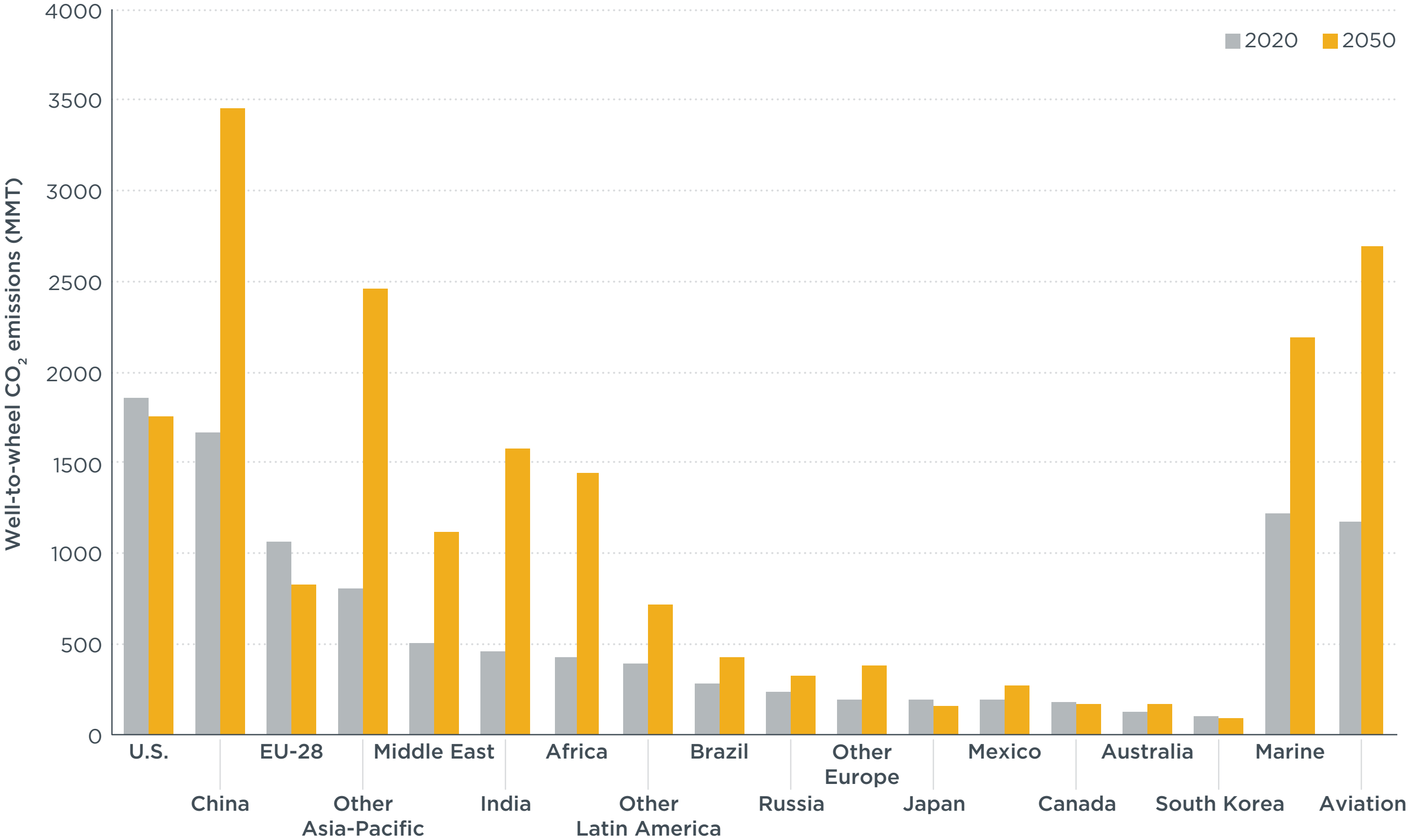

Figure 4. Transportation CO_2 emissions by region, with global aviation and marine sectors, in 2020 and 2050.

What is the target?

Achieving the Paris Agreement objectives to limit the global temperature increase to "well below" 2°C this century and "pursue efforts to limit the temperature increase even further to 1.5°C",[8] will require steep reductions in carbon emissions from all sectors. In 2018, the Intergovernmental Panel on Climate Change (IPCC) released a special report on "Global Warming of 1.5°C."[9] That report analyzed the results of dozens of models and hundreds of scenarios to evaluate the emissions pathways and sectoral transformations that are consistent with limiting temperature change this century to 1.5°C.

To establish a range of transport sector emissions in 2050 that can be considered plausibly consistent with limiting temperature change to 1.5°C, we analyzed the mitigation pathways developed through the Integrated Assessment Modeling Consortium (IAMC) for the IPCC report 1.5°C Scenario Explorer.[10] We extracted the 50 scenarios from 8 models that reported sector-specific emissions for transport. We then excluded those scenarios that allow for "high overshoot," since under such scenarios the global temperature increase can approach up to 2°C before relying heavily on negative-emission technologies (such as carbon sequestration) to reduce temperature change back down to 1.5°C by the end of the century. Such scenarios

8 "What is the Paris Agreement?" United Nations Framework Convention on Climate Change, accessed 29 February 2020, https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement.

9 Intergovernmental Panel on Climate Change, "Global Warming of 1.5°C" (2018), https://www.ipcc.ch/sr15/

10 "IAMC 1.5°C Scenario Explorer and Data hosted by IIASA," Integrated Assessment Modeling Consortium and International Institute for Applied Systems Analysis, accessed 29 February 2020, https://data.ene.iiasa.ac.at/iamc-1.5c-explorer.

carry substantial risks of triggering irreversible effects such as climate feedbacks (also called "tipping points"), rapid sea level rise, and biodiversity loss. To mitigate these risks, the transport emissions target defined in this analysis is based on the results of 1.5°C scenarios with either no or limited ("low") overshoot.

Emissions of non-CO_2 pollutants were then converted to CO_2-equivalent using global warming potential values over a 100-year time horizon. Among the scenarios that we considered, the median estimate for global transportation emissions in 2050 is 2.6 Gt of CO_2-equivalent,[11] and half of the scenarios fall between 1.8 and 3.3 Gt (Figure 5). The median estimate for 2050 represents a 9.4 Gt reduction from 2020 levels and an 18.4 Gt reduction from projected 2050 levels for the global transportation sector. We calculate the amount of reductions required by subtracting the 2050 target level of 2.6 Gt from the 2020 baseline of 12 Gt for a reduction target of 9.4 Gt annual reductions in 2050. As we describe in greater detail later in this document, we estimate that existing and emerging policies and technologies can generate about 8 Gt of reductions, which comes close but does not fully achieve the magnitude of reductions required to enable the transport sector to fully contribute to keeping global warming below 1.5°C. We find that our "ambitious yet feasible" projections can achieve an 85% reduction from the 2020 baseline which is the central finding of this scenario analysis. The remaining 15% will require additional reductions from policies that reduce vehicle miles traveled (e.g., increases in public transit ridership, increased rates of walking and biking, compact development, and so on) to achieve our 2050 target of 2.6 Gt of CO_2-e.

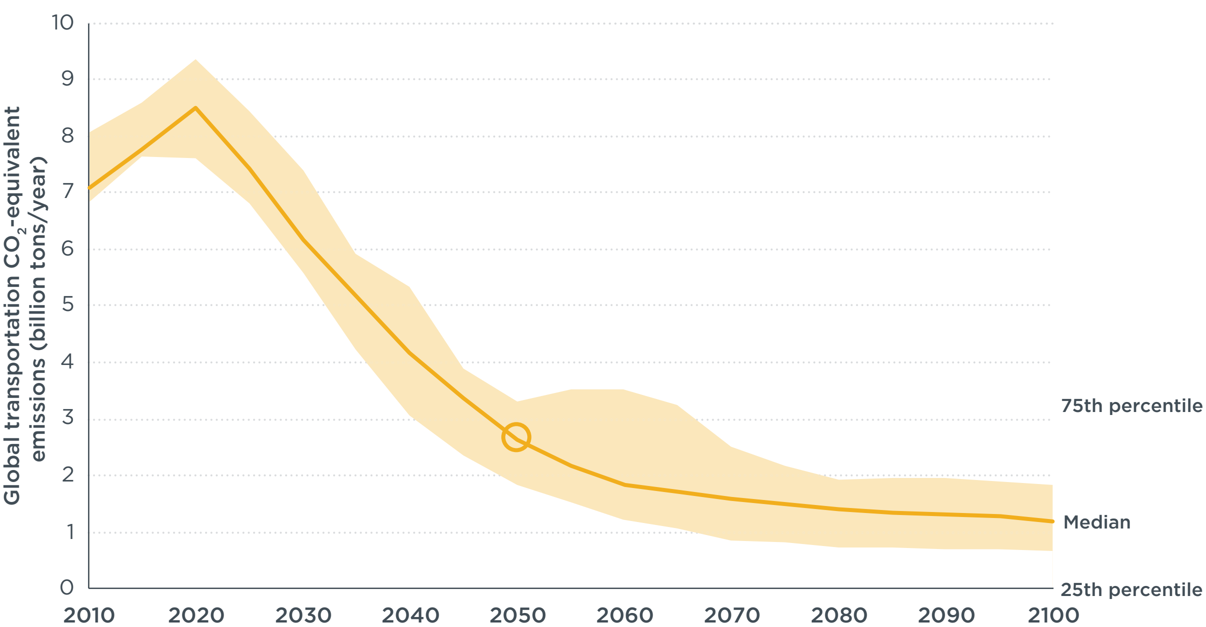

Figure 5. Summary of global transport sector CO_2-equivalent emissions pathways, based on an analysis of 1.5°C scenarios with no or low overshoot. 2050 target is 2.6 Gt.[12]

11 This number reflects CO_2-equivalent emissions of black carbon, methane, and HFCs.

12 Note that in this chart the peak, in 2020, is lower than the 2020 emissions level represented in figures 3 and 7, 12Gt. Those charts, reflecting ICCT methodology, show well-to-wheel CO_2-equivalent emissions, which include upstream emissions as well as vehicle emissions. This chart, reflecting IPCC methodology, does not include upstream emissions. ICCT expects future electric vehicles to be powered by near-zero or zero-carbon electricity. This is in contrast to IPCC estimates of future negative emissions from energy supply (i.e., negative upstream emissions). Combining ICCT's expectations that upstream emissions of transportation fuels in 2050 will be greater than zero with the analysis of IPCC scenarios (which generally assume these emissions are negative by 2050 under "<1.75 degrees at any point" scenarios), our target for fuel lifecycle transport emissions in 2050 should be either equal to or less than the 2.6 Gt target. The exact target depends heavily on the assumptions made for other sectors, so to meet the Paris agreement goals, global fuel lifecycle transport CO_2 emissions in 2050 should be reduced to less than 2.6 Gt CO_2, in combination with emission reductions in other sectors.

What is an ambitious yet feasible scenario?

Achieving the global CO_2 target for the transportation sector will mean the accelerated deployment of existing and emerging low-emission and zero-emissions technologies across all transportation segments. One of the key focus areas of ICCT research is to track technology developments across transportation segments: light-duty vehicles, heavy-duty vehicles, marine, aviation. We have produced numerous studies and reports looking at the potential for CO_2 reduction from a wide range of vehicle and fuel technologies. In addition, we track the likely timeframe for commercialization and adoption, as well as the projected costs of technologies. Furthermore, we are acutely aware of the known gaps between emissions reductions demonstrated in laboratory settings and those achieved in the real world. With this baseline knowledge, we are well placed to propose an "ambitious yet feasible" decarbonization scenario: technologically feasible while also taking into account such practical considerations as cost, time required to achieve large-scale production and deployment, and differences in advertised versus real-world emissions.

Our analysis here was also informed by a parallel modeling exercise we conducted for the Global Fuel Economy Initiative that incorporated inputs and review from the International Energy Agency, the United Nations Environment Program, the University of California Davis, and the International Transport Forum.[13]

As we developed our conclusions for what is possible, we kept in mind the crucial balance between improving efficiency of "conventional" vehicles and ramping up market penetration of zero-emissions vehicles. Even under the most optimistic decarbonization scenarios, more than two billion new internal combustion engine (ICE) vehicles will be sold over the next 30 years. It is critical that these vehicles be as efficient as possible. Notwithstanding that fact, if the transportation sector is to be decarbonized, ultimately the vast majority of vehicles must produce zero tailpipe emissions and be fueled by carbon-neutral and renewable energy sources.

EVEN UNDER THE MOST OPTIMISTIC DECARBONIZATION SCENARIOS, MORE THAN TWO BILLION NEW INTERNAL COMBUSTION ENGINE (ICE) VEHICLES WILL BE SOLD OVER THE NEXT 30 YEARS. IT IS CRITICAL THAT THESE VEHICLES BE AS EFFICIENT AS POSSIBLE.

Below we detail the assumptions that went into our "ambitious yet feasible" scenario for technological improvements across transportation segments as well as upstream fuel and electricity production.

LOW-CARBON FUEL AND ELECTRICITY PRODUCTION

To decarbonize the transportation sector it is crucial that the energy sources—electricity and liquid or gaseous fuels—powering vehicles be produced in a very low-carbon or carbon-neutral way. Low-carbon energy sources should be implemented in parallel to the deployment of zero-emissions and advanced technologies on the vehicle side. In our analysis we include the potential for CO_2 reductions from the use

13 Global Fuel Economy Initiative, "Prospects for fuel efficiency, electrification and fleet decarbonisation," GFEI Working Paper 20 (May 2019) https://www.globalfueleconomy.org/data-and-research/publications/gfei-working-paper-20.

of biofuels separately from the vehicle-side technologies, while grid decarbonization is embedded within the vehicle-side analysis.

For electric and fuel cell vehicles, decarbonizing the electricity grid becomes increasingly important. In our "ambitious yet feasible" scenario we assume that by 2050 the grid will be close to fully decarbonized—specifically, that 99% of the electricity needed to charge EV batteries and provide the main energy source for generating hydrogen (or ammonia) to use in fuel cells will be produced through carbon-neutral pathways. While this is an ambitious assumption, the International Energy Association considers it feasible based on its own analyses.[14]

Sustainable biofuels are another key to meeting the 2050 target. We assume a ceiling on sustainable bioenergy production by 2050 (after accounting for biomass conversion efficiency) equivalent to approximately 23 million barrels per day (mbd) of crude oil.[15] We project that 67% of this bioenergy production (about 15.5 mbd) could be directed to the transportation sector. This represents about 25% of current global transportation energy demand (approximately 35 exajoules [EJ] per year out of 128 EJ per year total demand). Most of the potential for producing low-carbon biofuels comes from cellulosic energy crops grown on available grassland, with the remainder from agricultural and forestry residues and wastes. Our assessment does not include biofuel potential from traditional food and feed crops, because of the significant indirect land-use change (ILUC) emissions associated with these feedstocks. Since nearly all conventional modes of transport today operate on petroleum-derived fuels, the climate benefit of using the available sustainable biomass resource in one transport segment versus another is very similar. Our analysis assumes that of the 15.5 mbd equivalent of sustainable biofuel projected to be used in transportation in 2050, 79% will be used in on-road, 7% in marine, and 14% in aviation applications. In this analysis, we prioritize on-road biofuels because they are less costly to produce compared to biofuels to replace aviation fuel (kerosene).

We conducted a separate analysis of the potential to use electricity to generate liquid or gaseous fuels for use in the transport sector (also known as "power-to-liquids" and "power-to-gas" or "eFuels"). An earlier ICCT analysis for the European Union estimated the maximum potential to produce synthetic diesel fuel using electricity (also known as "power-to-X") at approximately 1.2 EJ per year in 2050, or about 0.5 mbd of oil equivalent. We scaled that estimate globally by comparing current global electricity consumption with current EU electricity consumption to reach a very rough estimate of 8.4 EJ per year globally in 2050, or nearly 3.5 mbd of oil equivalent. Based on our EU assessment, synthetic diesel fuel produced using renewably generated electricity is very expensive, and the potential for ramping up this technology is limited even with strong policy support through 2050. While this fuel pathway can theoretically deliver very high greenhouse gas reductions (70%–80% compared to petroleum), it delivers much lower benefits than simply using electricity directly to power electric vehicles. Therefore, the sector that would most benefit from this technology would be aviation. For reference, aviation currently uses 7 mbd of oil equivalent fuel, and we project a tripling of jet fuel consumption in 2050 under a business as usual trajectory. We added our global estimate of power-to-X potential at 8.4 EJ per year, or 4 mbd, to our estimate of 5 EJ per year for global

14 "Energy Technology Perspectives 2017," International Energy Association, report and associated data, accessed 29 February 2020, https://www.iea.org/etp/etp2017/restrictedaccessarea/.

15 Stephanie Searle, "Bioenergy can solve some of our climate problems, but not all of them at once," 15 October 2018, https://theicct.org/blog/staff/bioenergy-solve-some-climate-problems-not-all-once.

low-carbon biofuel potential allocated to aviation, with the assumption that 100% of the eFuels would be used to help decarbonize the aviation sector.

LIGHT-DUTY VEHICLES

Significant benefits can be obtained from improving the efficiency of light-duty vehicles, improving compliance with vehicle-efficiency standards, and promoting zero-tailpipe-emissions vehicles.

In our "ambitious yet feasible" scenario, we assume that the real-world CO_2 emissions of new ICE light-duty vehicles improve at an average annual rate of 2% over the next 30 years. Adopted regulations targeting LDV efficiency in major markets call for 4% to 5% reductions, and numerous technical studies have shown that reductions of this magnitude appear to be feasible. We believe 2% annual improvement is a more realistic projection in view of changes in fleet composition (increased number of SUVs and larger vehicles); the gap between test-cycle and on-road efficiency; increased use of off-cycle credits and other flexibility mechanisms in existing regulations; and a slowing rate of technological advance in internal-combustion engine efficiency, as automakers increasingly direct their R&D efforts toward electric vehicles. Key technologies driving improvement in LDV efficiency are hybridization, high-efficiency engine designs, engine downsizing with turbocharging, and improved aerodynamics.

We estimate that better compliance with LDV efficiency standards—which implies improved enforcement of regulations—could boost efficiency gains for new ICE (including non plug-in hybrids) by an additional 0.5% per year in 2020–2030, and by an additional 0.25% per year in 2030–2050. In the context of 2% baseline projection of annual improvement, differences of this magnitude are significant. Our estimate reflects current trends in major markets, which have recently seen changes in certification test cycles intended to bring official evaluations of vehicle efficiency into a closer relationship to actual, real-world, on-road performance.

Electric vehicles are likely to become an increasingly important part of automakers' compliance paths for vehicle fuel-efficiency and CO_2-emission standards. In our analysis, we assume 95% electrification of the total stock of two-wheel and three-wheel vehicles worldwide by 2050, and nearly 90% penetration of zero-emission vehicles in the EU and China passenger vehicle fleets. For the rest of the global market, including the United States, we assume a lower but still significant 66% electric share of the total vehicle stock by 2050. These reflect a further assumption that EVs will make up 22% of total global LDV sales by 2025 and 35% by 2030. As of today, in the aggregate automakers have announced or committed to the manufacture and sale of 22 million EVs globally by 2025, which would represent 19% of total projected LDV sales. Government commitments and policies in the aggregate, meanwhile, call for 15 million annual sales of EVs by 2030, which would represent a 14% sales share on a global basis. Thus, both automakers and regulators would have to build on their commitments to meet the EV trajectory envisioned in this analysis. In our estimation, rapidly approaching cost parity between EVs and ICEs makes our more aggressive trajectory ambitious yet feasible.[16]

16 Nic Lutsey and Michael Nicholas, "Update on Electric Vehicle Costs in the United States through 2030" (International Council on Clean Transportation, April 2019), https://theicct.org/publications/update-US-2030-electric-vehicle-cost.

HEAVY-DUTY VEHICLES

As with light-duty vehicles, significant benefits can be obtained from improving the efficiency of heavy-duty vehicles, improving compliance with efficiency standards, and increasing the proportion of zero-tailpipe-emissions vehicles in the global fleet.

As with light-duty vehicles, in our "ambitious yet feasible" scenario we assume that the real-world CO_2 emissions of new ICE heavy-duty vehicles decline at an annual rate of 2%. This represents a global average. Markets with the most advanced efficiency regulations (the United States, the European Union, and Japan, for example) will likely come close to reaching the cost-effective limits of ICE efficiency under current technology forecasts. Technological keys are improvements in engine efficiency, reductions in aerodynamic drag, reductions in tire rolling resistance, and hybridization. As with light-duty vehicles, the rate of advance in ICE technology may slow as manufacturers increasingly direct R&D efforts to electric technologies in order to meet increasingly stringent efficiency targets.

As with LDVs, we assume that improved compliance with HDV efficiency standards, brought about by improved enforcement as needed, could boost efficiency gains for new ICE (including non plug-in hybrid vehicles) by an additional 0.5% per year in 2020–2030 and 0.25% per year in 2030–2050.

In the HDV segment, we assume that EV market uptake will move from the easiest vehicle segments to electrify to larger, more challenging segments. Specifically, we estimate that by 2050 electric buses will be 81% of the global bus stock (93% of new bus sales); electric light heavy-duty trucks (such as those used for local delivery) will make up 69% of the global stock (87% of new LHDT sales); electric medium heavy-duty trucks (such as those used for regional delivery) will be 42% of the global stock (60% of new MHDT sales); and electric heavy heavy-duty trucks (such as those used for long haul trucking) will be 29% of the global stock (44% of new HHDT sales). Our modeling does not differentiate between battery electric vehicles, which are more likely to play an outsized role in the smaller truck segments, and fuel cell vehicles, which will likely be more important in decarbonizing large-truck segments.

MARINE

There are significant benefits to be obtained from improving the operational and technical efficiency of maritime vessels and from adopting new zero-emissions technologies in the marine sector. In this study, the global shipping sector includes international and domestic maritime vessels as well as fishing vessels.

Three classes of ships account for 55% of CO_2 emissions in the global shipping sector: container ships (23% of global shipping CO_2), bulk carriers (19%); and oil tankers (13%). Carbon reductions can be achieved through improved operational efficiencies, such as slow steaming, and technology-based efficiency improvements, such as hull air lubrication and wind-assisted propulsion. The International Maritime Organization's Energy Efficiency Design Index requires steady improvements in energy efficiency of new marine vessels.

Our evaluation of recent positive developments in zero-emissions—batteries and hydrogen fuel cells being used in passenger vessels and short-sea shipping applications as well as planned pilot projects for transoceanic low- and zero-emission vessels that use electofuels in internal combustion engines, hydrogen fuel cells, batteries, wind-assisted propulsion, or some combination of these—leads us to forecast a significant potential for reducing CO_2 emissions in the maritime shipping sector from their adoption.

Combined, operational changes, technology-based efficiency improvements, and zero-emissions technologies have the potential to cut marine emissions 67% from the current projection for 2050 (Figure 4). Factoring in use of low-life-cycle-emissions biofuels in the marine sector can increase that estimated reduction to 71% from business-as-usual. These gains are in line with the International Maritime Organization's 2050 target under its initial GHG strategy to reduce emissions at least 50% below 2008 levels.

AVIATION

As in the marine sector, significant benefits can be obtained from operational and technology-based efficiency improvements in aviation as well as from new zero-emissions technologies.

We incorporate assumptions that aviation emissions can be mitigated through demand management, halting the deployment of supersonic aircraft, and accelerating advances in efficiency technologies. We do not consider emission offsets because these assume credit for mitigation measures undertaken elsewhere in the economy and in that sense do not represent additional reduction potential. Demand management tools such as carbon pricing and consumer information can reduce baseline passenger-kilometer growth by 0.7% to 4% per year. Halting the development of supersonic aircraft could avoid a potential increase of 116 million metric tons per year by 2035 (including upstream impacts).[17] Improving new-aircraft efficiency through engineering and design innovations such as advanced wing tube technologies and alternative airframes can further reduce aircraft fuel burn by 30% by 2050.

We further estimate that 50% of emissions from regional flights could be reduced through electrification by mid-century, with net-zero lifecycle emissions.

In total, we estimate that the aviation sector's emissions can be reduced by about 77% from 2050 projections and 47% from our 2020 baseline (Figure 4), 85% if including biofuels devoted to aviation. Additional reductions (not considered here) would require larger reductions in demand growth via economic instruments, constraining airport capacity, and/or enforcing personal limits on flying.

BLACK CARBON EMISSIONS

Reductions in diesel black carbon emissions confer significant health and climate benefits. Globally, the two largest sources of transportation-related black carbon are diesel engines found in heavy-duty vehicles and marine vessels. While both black carbon and CO_2 contribute to global warming, the mechanisms by which they do so are different, and it is therefore not straightforward to compare the climate impacts of reducing them. Black carbon is one of a category of pollutants known as short-lived climate pollutants because they remain in the atmosphere for less time than CO_2. Others in this category include methane and hydrofluorocarbons (HFCs). While they are shorter-lived than CO_2 they have much higher global warming potentials, and controlling these pollutants is crucial to keeping global temperatures below 1.5°C. The climate benefits of reducing black carbon include slowing the rate of near-term

17 Dan Rutherford, Brandon Graver, and Chen Chen, "Noise and climate impacts of an unconstrained commercial supersonic network" (International Council on Clean Transportation, January 2019) https://theicct.org/publications/noise-climate-impacts-unconstrained-supersonics. IEA, "Energy Technology Perspectives 2017."

temperature increases, and increasing the probability of staying below a given temperature threshold.[18]

Diesel particulate filters (DPFs), a well known and commercially available technology, nearly eliminate diesel black carbon emissions. To give a perspective on potential benefits, if every country in the world adopted and implemented DPF-forcing Euro 6/VI-equivalent standards by 2025, these policies would reduce global black carbon emissions from on-road diesel vehicles by 740,000 metric tons per year in 2050.[19] Those reductions would be equivalent to between 1 Gt and 2 Gt of CO_2 in 2050.

Next to heavy-duty vehicles, the marine segment is the largest source of black carbon emissions, which are particularly harmful in the Arctic. Strategies to mitigate black carbon emissions from ships include numerous emissions control technologies, limiting access to the Arctic, using shore power at ports, and banning heavy fuel oil (HFO).[20] For our modeling we assumed that black carbon emissions from ships decrease proportionally as CO_2 emissions decrease.[21] We further assume that the majority of black carbon reductions over the next 30 years will be from the HDV (70%) and the marine (15%) segments.

SUMMARY OF THE AMBITIOUS YET FEASIBLE SCENARIO

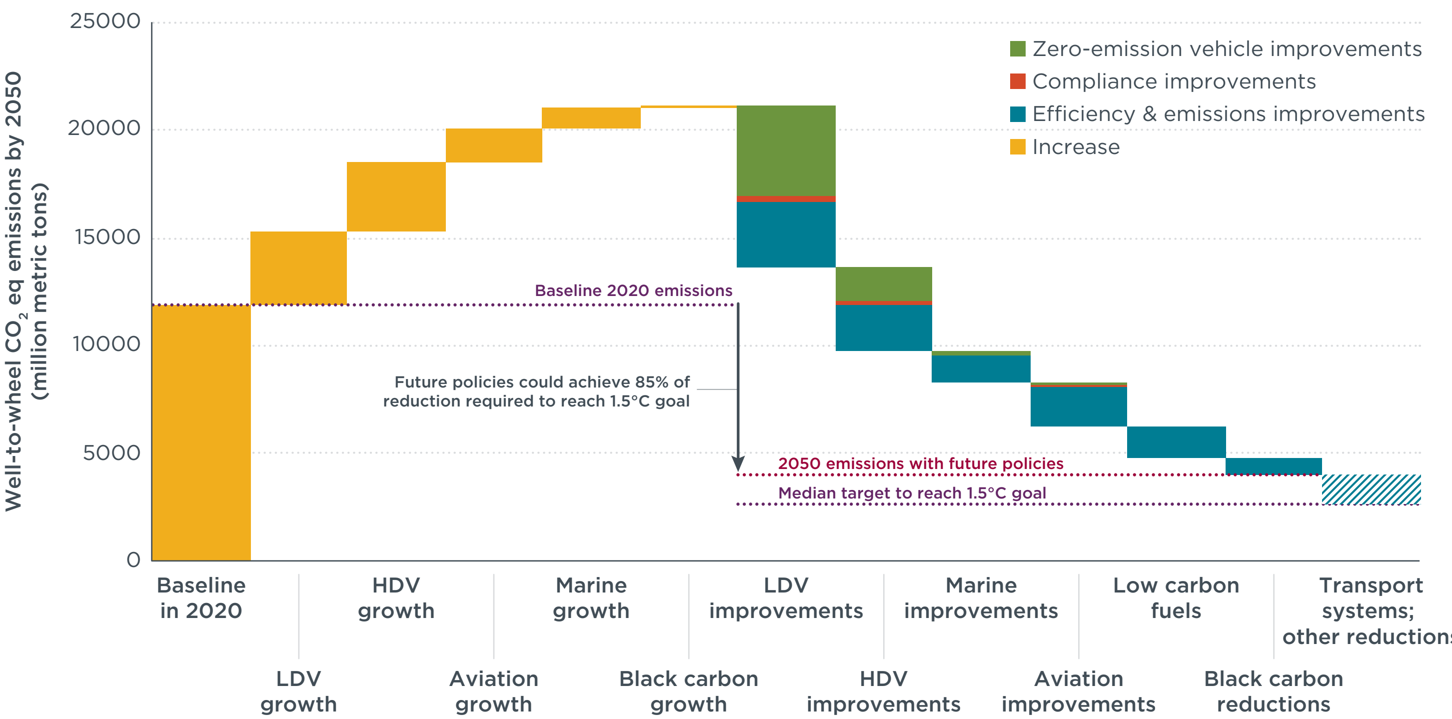

Figure 6. Baseline CO_2-equivalent emissions and mitigation potential in 2050 by major transportation segment.

18 D. Shindell et al., "A climate policy pathway for near- and long-term benefits," *Science* 05 Vol. 356, Issue 6337 (May 2017): 493-494. DOI: 10.1126/science.aak9521 http://science.sciencemag.org/content/356/6337/493.

19 Joshua Miller and Lingzhi Jin, "Global progress toward soot-free diesel vehicles in 2019" (International Council on Clean Transportation, September 2019) https://theicct.org/publications/global-progress-toward-soot-free-diesel-vehicles-2019.

20 International Council on Clean Transportation, 6th workshop on marine black carbon emissions, Helsinki, September 18–19, 2019. https://theicct.org/events/6th-workshop-marine-black-carbon-emissions

21 Naya Olmer et al., "Greenhouse gas emissions from global shipping, 2013–2015" (International Council on Clean Transportation, October 2017), tables 6 and 7, https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015.

Figure 6 illustrates the potential for emissions reductions from LDVs, HDVs, marine, aviation, and biofuels (further detailed in appendix A). The yellow bars on the left-hand side of the chart quantify the impact of factors that are expected to drive up GHG emissions (including CO_2, N_2O, methane, and black carbon) by 2050. These reflect policies adopted as of February 2019, and assume no further policy action. Added to baseline emissions for 2020 they result in a 77% increase of current emissions by 2050 . The blue, green, and red bars on the right side of the figure show the estimated potential impact of efficiency improvements, zero-emission vehicle growth, and improved compliance from each segment of the transport sector. These estimates attempt to account for technology constraints, limits on policy ambition, and realistic assumptions about policy effectiveness, based on past experience. The hatched bar at the right of the figure shows the gap that remains, after accounting for these constraints, between the sum total of the mitigation potential we have identified and the 2.6 Gt transport-sector emissions target consistent with the goal of limiting global warming to 1.5°C.

As Figure 6 shows, the largest single mitigation opportunity in our assessment is energy-efficiency improvements across all modes. Next is electrification of light-duty and heavy-duty vehicles. This finding underscores the importance of continuing support for efficiency measures while simultaneously targeting measures to accelerate electric vehicle adoption.

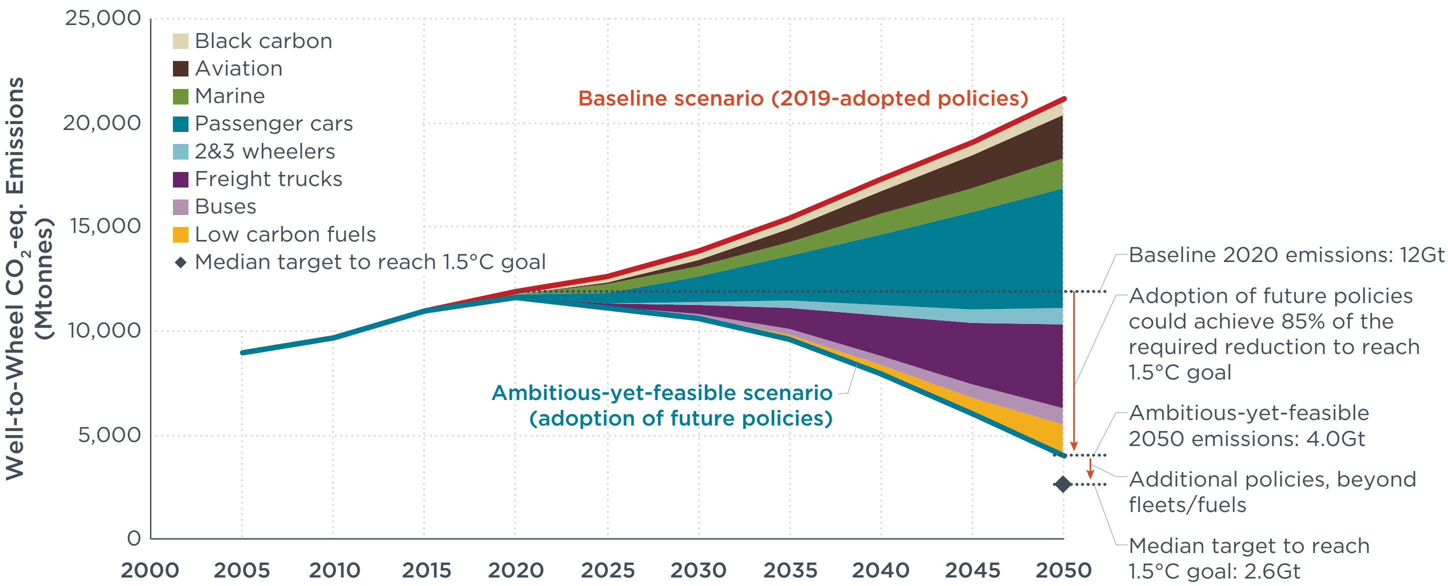

Figure 7. Global well-to-wheel CO_2 reductions from transportation segments, based on ICCT's "ambitious yet feasible" scenario.

The results of our modeling can be presented in another way, shown in Figure 7. This wedge chart presents the emission-reduction benefits between 2020 and 2050 of ICCT's ambitious-yet-feasible scenario. As in Figure 6, the calculation for each set of reductions accounts for fuel lifecycle ("well-to-wheel") emissions—that is, including upstream emissions from fuels[22] (or electricity) production—and includes emissions of the non-CO_2 greenhouse gases nitrous oxide and methane (adjusted to CO_2

22 With the previously noted exception that we include a separate wedge from reductions resulting from sustainable biofuels.

equivalents using 100-year global warming potential). The top (red) line traces the modeled emissions trajectory assuming no further mitigation action beyond current policies; as noted previously, it indicates that overall transportation sector emissions can be expected to increase by almost 80% between 2020 and 2050 without further policy interventions beyond those already adopted or committed to by governments around the world. As in figure 6, we identify the sector-wide emissions target we determined as consistent with achieving the goals of the Paris Agreement.

Our "ambitious yet feasible" scenario primarily relies on the successful deployment of four key types of policy:

1. Efficiency standards mandating that manufacturers achieve a certain CO_2 emission or fuel efficiency target in new vehicles

2. Zero-emission vehicle mandates that require manufacturers to achieve a certain fraction of zero emissions vehicles in their total annual sales volume

3. Emissions standards mandating that manufacturers meet certain emissions limits for specific pollutants, such as particulate matter or nitrogen oxides, in new vehicles

4. Renewable fuels standards requiring fuel suppliers to include a certain content of renewable fuels in the fuel mix they sell

Our scenario analysis does not account for any policies or measures that may slow or decrease the current trajectory for transportation demand. Any measures that are successful in slowing demand, beyond those that fill in the gap shown in Figure 7, will effectively lower the requirements in terms of the quantity of technology adoption necessary to meet our targets.

The chart shows that fully realizing the emissions reduction potential associated with our ambitious yet feasible scenario results in projected sectoral emissions of approximately 4 Gt in 2050. This represents an 8 Gt reduction from baseline 2020 emissions. As our target in 2050 is 9.4 Gt lower than the 2020 baseline, our "ambitious yet feasible" scenario achieves 85% of the total required reduction. It leaves a gap of approximately 1.4 Gt to achieve our target in 2050, which must be filled by implementing additional policies outside of those that address the new-vehicle fleet and fuels, such as fiscal incentives, city-level vehicle restrictions, carbon pricing, infrastructure investments, road-toll differentiation, vehicle scrappage schemes, and more.

What is the highest priority work over the next five years?

ICCT will use the results of the analysis presented in this document to guide its strategic approach to electric and conventional vehicles over the next five years. The most important elements we envision are summarized below. Our hope is that the analysis proves useful to other stakeholders as well.

Electric vehicles are the single most important technology for decarbonizing the transport sector. Our vision is to support an increase in sales fraction of electric

OUR VISION IS TO SUPPORT AN INCREASE IN SALES FRACTION OF ELECTRIC VEHICLES, STARTING WITH THE MOST ATTRACTIVE AND IMPORTANT APPLICATIONS: PASSENGER VEHICLES, 2- AND 3-WHEELERS, AND URBAN BUSES.

vehicles, starting with the most attractive and important applications: passenger vehicles, 2- and 3-wheelers, and urban buses. In each of these vehicle segments, we project that sales of electric vehicles will need to reach between 35% and 75% of the global market in 2030, and exceed 75% between 2040 and 2050. Long-haul straight and tractor-trailer trucks, maritime vessels, and aircraft are more difficult to electrify, and we expect a slower rate of uptake across a range of technologies, from batteries to hydrogen fuel cells to low-carbon or zero-carbon fuels (biofuels, power-to-liquids). Our forecasts are based on announced automaker sales targets; continued policy support, including sales targets, fiscal incentives, infrastructure investments, and energy efficiency standards; and projections of cost parity in the mid-2020s (depending on battery size).

Continued progress on energy efficiency is critical to achieving our climate goals and supporting the transition to electrification. Our modeling suggests that even if we meet our ambitious EV sales targets, more that two billion new internal combustion engine-based passenger vehicles will still be sold in global markets from 2020 to 2050. Ensuring that these vehicles are maximized for efficiency, through effective performance standards, achieves more than half of our projected reductions by 2050 for passenger cars, commercial trucks and buses, and marine vessels (Figure 6). In addition, efficiency standards that increase the cost of conventional vehicles will help accelerate EV cost parity.

Reduction of black carbon through the introduction of world-class standards for vehicles and fuels in as many markets as possible by 2025 is a synergistic strategy pursuing both health and climate benefits. As an interim milestone, we are working to support such standards for vehicles and fuels for on-road vehicles in the G20 countries and in Southeast Asia, Sub-Saharan Africa, and Latin America. A second milestone will be similar standards for non-road engines (e.g., construction and agriculture equipment) and equipment within an additional three to five years. These activities will contribute to a reduction in anthropogenic black carbon emissions to 75% below 2010 levels by 2030. Achieving this target, in combination with reductions in methane and hydrofluorocarbon emissions, could avoid 0.5°C of warming over the next 25 years.[23]

Research and development targeted at zero-emission technologies are needed for the most challenging segments, such as international marine and aviation. For oceangoing vessels, our goal is to achieve the International Maritime Organization's minimum 2050 greenhouse gas reduction target of 50% below 2008 levels. For aviation, our goal is to stabilize greenhouse gas emissions from 2020 to 2035 and to then reduce emissions to 50% below 2005 levels by 2050. In addition to doubling the energy efficiency of these segments and ensuring that future supersonic aircraft meet all existing carbon and noise standards, we support a targeted fee on marine bunker fuels to raise substantial funding for a newly established technology innovation project dedicated to investing in research, development, and deployment

23 Shindell et al., "A climate policy pathway for near- and long-term benefits."

of zero-emission technologies (e.g., hydrogen fuel cells, advanced biofuels, power-to-liquids). Maritime and aviation work will, over the long term, require far greater focus on zero-emission technologies. We have taken only initial steps toward developing the ideal funding mechanism to finance sustainable and near-zero carbon liquid biofuels, encouraging demonstrations to validate the new alternative fuels, and then developing the policies to require their greater deployment. Our analysis indicates that as many as 15 million barrels per day of sustainable biofuels could be achievable. Production on this scale will be needed to support decarbonization of maritime, aviation, and long-haul heavy-duty applications, where large-scale deployment and fleet turnover will be slowest.

A sharper focus must be placed on China, India, and emerging markets. In addition to continued engagement in the United States, California, and Europe, we are already moving to provide greater technical and policy support in China and India. Our analysis indicates that China will generate the largest share of global transportation CO_2 emissions in 2050 by a large margin (Figure 4). Outside of India and China, needs and opportunities are present in Indonesia and Vietnam (ASEAN), Latin America, and Africa. Black carbon emissions, for example, are just as high in ASEAN and Africa as they are in China. This trend is mainly due to poor fuel quality and a very old legacy fleet. We further anticipate that Asia-Pacific and African countries will contribute larger shares of global emissions in 2050 than in 2020 (Figure 4).

THE SCALE OF THE CRISIS WE ARE FACING NECESSITATES INCREASED COLLABORATION AND COMMUNICATION.

Targeted work in cities can have an outsized impact. Cities are severely affected by the air pollution and climate change caused by the transportation sector. From bans on diesel cars to low-emission zones to soot-free electric buses, cities have reacted with policies intended to drive the transition to a decarbonized transport sector, and collectively they have emerged as major players in this policy area. In recent years the ICCT has partnered with city governments through the Real Urban Emissions initiative (TRUE), on zero-emission buses, and in our EV capitals of the world publications. These three programs form the core of our city-based strategy: highlighting elevated emissions from the existing fleet, helping cities procure clean buses, and creating a race to the top for policies to drive electric vehicles. A central element of our strategy is for cities to play a critical role in accelerating progress that is both effective by itself and operates to substantially increase the level of ambition for national policies.

The scale of the crisis we are facing necessitates increased collaboration and communication. The ICCT has established strong partnerships with like-minded organizations in the markets where we work. As we move to implement our strategic plan we realize we must make these partnerships even stronger. Technology solutions alone will not be sufficient to meet transport-related climate targets. To offer policymakers support on the full portfolio of measures that will be required to achieve our vision, we must leverage strong relationships with partners and engage even more extensively with city, state, and national governments. Realizing these goals will depend in part on developing new outputs designed to meet the more complex outreach needs of cities, grow our communications activities in China and India, and ensure that our work reaches its needed audience.

CONCLUDING THOUGHTS

Our aim is to support the achievement of the Paris Climate Agreement targets to limit the global temperature increase this century to well below 2°C and to pursue efforts to limit the temperature increase to 1.5°C by reducing annual global transportation CO_2 emissions to an estimated 2.6 billion metric tons, as a median target, in 2050. We believe that the key to achieving this target is through the deployment of stringent regulations that promote the rapid adoption of new low- and zero-emissions technologies in the transportation sector and the electricity grid. Moving forward it is important to develop and implement more detailed and targeted strategies for each region or market in order to ensure that relevant policymaking is well supported. There are key metrics that can be tracked in the short term in order to show progress. These metrics include: adoption and implementation of relevant policies; conventional and electric vehicle sales; global sales of transportation fuel; real-world emissions to measure compliance with regulations; and investment in development and production of new technologies. Tracking metrics such as these on an annual basis will not only give us insight into the progress being made towards the longer-term target, but will inform any necessary strategy adjustments.

APPENDIX A

Table 1. Key assumptions for the "ambitious yet feasible" scenario model

Segment	Assumptions	Technology	References
	Vehicle		

Light Duty Vehicles	Efficiency
	• Real-world emissions of new ICEs improve annually at 2% from 2020 to 2050
	  • Faster rates of improvement occur between 2020 and 2035
	  • Slower rates of improvement after 2035
	• New vehicle average efficiency improvement of 47% between 2020 and 2050.
	
	Electrification
	• 95% electrification of global stock of two- and three-wheelers by 2050
	• 66% electrification of global stock of passenger vehicles by 2050
	  • 89% in China and EU by 2050
	  • 71% in India by 2050
	  • 66% in US
	  • 39% in Asia-Pacific and Africa
	• Global EV sales of 22% by 2025, 35% by 2030
	
	Compliance
	• Improved compliance and enforcement of efficiency standards boosts efficiency by 0.5% per year from 2020 to 2030 and by 0.25% per year from 2030 to 2050
		• Turbocharging and downsizing
		• Atkinson and Miller cycle
		• Mild hybridization
		• Full hybridization
		• Improved aerodynamics and lightweighting
		• Electric vehicle batteries
			Lutsey, N., et al. (2017). *Efficiency technology and cost assessment for U.S. 2025–2030 light-duty vehicles*. https://theicct.org/publications/US-2030-technology-cost-assessment
			
			Lutsey, N., & and Nicholas, M. (2019). *Update on Electric Vehicle Costs in the United States through 2030*. https://theicct.org/publications/update-US-2030-electric-vehicle-cost.
			
			Global Fuel Economy Initiative. (2019). *Prospects for fuel efficiency, electrification and fleet decarbonization*. https://www.globalfueleconomy.org/media/708302/gfei-working-paper-20.pdf
			
			International Council on Clean Transportation. *Transportation Roadmap*. https://www.theicct.org/transportation-roadmap
			
			Compliance gains based on current trends in major markets, which have recently focused on test cycle improvements to better reflect real-world emissions performance.

Heavy Duty Vehicles	Efficiency
	• Real-world emissions of new ICEs improve annually at 2% from 2020 to 2050
	  • Faster rates of improvement 2020–2035
	  • Slower rates of improvement after 2035
	• New vehicle total average efficiency improvement of 41%–43% between 2020 and 2050.
	
	Electrification
	• 69%, 42%, 29% electrification of global stock of light commercial vehicles, rigid trucks, and tractor trailers, respectively.
	• Global EV truck sales of 0%–17% by 2025, 5%–33% by 2030
	• 81% electrification of global stock of buses by 2050 (93% of new bus sales).
	
	Compliance
	• Improved compliance and enforcement of efficiency standards boosts efficiency by 0.5% per year from 2020 to 2030 and by 0.25% per year from 2030 to 2050
		• Engine efficiency improvements (especially in markets where heavy duty standards lag)
		• Aerodynamic drag reduction
		• Tire rolling resistance reduction
		• Hybridization
		• Battery electric and fuel cell electric
			Global Fuel Economy Initiative. (2019). *Prospects for fuel efficiency, electrification and fleet decarbonization*. https://www.globalfueleconomy.org/media/708302/gfei-working-paper-20.pdf
			
			Mezler, D., et al. (2018). *EU HDVs: Cost effectiveness of fuel efficiency technologies for long-haul tractor-trailers in the 2025-2030 timeframe*. https://theicct.org/publications/cost-effectiveness-of-fuel-efficiency-tech-tractor-trailers

Segment	Assumptions	Technology	References
Marine	Efficiency • Ship energy efficiency improved by 70% by 2040 Electrification • Targeted fees on marine bunker fuels can raise funding for developing/incentivizing ship electrification • 17% of energy demand can be met by zero-emission vessels by 2050	• Operational efficiency improvements (e.g., slow steaming) • Engine, propeller, hull improvements • Batteries, wind-assist, and fuel cells	Emissions reductions from operational efficiency, technical efficiency, and ZEV penetration are calculated according to follow-on analysis using the model developed for ICCT's policy update on the IMO's initial GHG strategy. Rutherford., D., & Comer, B. (2018). *The International Maritime Organization's initial greenhouse gas strategy*. https://www.theicct.org/publications/IMO-initial-GHG-strategy. Comer, B., Chen, C., & Rutherford, D. (2018). *Relating short-term measures to IMO's minimum 2050 emissions reduction target*. https://www.theicct.org/publications/short-term-measures-IMO-emissions
Aviation	Efficiency • 40% reduction in operational emissions from 2020 to 2050 Electrification • 10% of fuel use replaced by electric aircraft by 2050 • Corresponds to half of fuel used by regional flights Compliance • Halting the development of supersonic flights could save 96 million metric tons of CO_2 (121 MMT including upstream).	• Aircraft design improvements • Demand mitigation	Rutherford, D., et al. (2019). *Noise and climate impacts of an unconstrained commercial supersonic network*. https://www.theicct.org/publications/noise-climate-impacts-unconstrained-supersonics Kharina, A., Rutherford, D., & Zeinali, M. (2016). *Cost assessment of near- and mid-term technologies to improve new aircraft fuel efficiency*. https://www.theicct.org/publications/cost-assessment-near-and-mid-term-technologies-improve-new-aircraft-fuel-efficiency Tecolote Research. (2016) Aviation fuel efficiency technology assessment (AFETA). https://www.theicct.org/publications/aviation-fuel-efficiency-technology-assessment-afeta Searle, S., & Christensen, A. (2018). *Decarbonization potential of electrofuels in the European Union*. https://theicct.org/publications/decarbonization-potential-electrofuels-eu
Black Carbon	On-road diesel • 95% reduction in annual on-road BC emissions by 2050 after implementing Euro 6/VI-equivalent standards in all countries by 2025 Marine • Near 50% reduction in annual marine BC emissions by 2050 through strong policies and technology implementation • BC emissions proportional to net CO_2 emissions	• Particulate filters • Marine emission control technologies • Limited Arctic access • Shore power required at ports • Ban on heavy fuel oil	Miller, J., & Jin, L. (2019). *Global progress toward soot-free diesel vehicles in 2019*. https://www.theicct.org/publications/global-progress-toward-soot-free-diesel-vehicles-2019 International Council on Clean Transportation. *6th workshop on marine black carbon emissions*. https://theicct.org/events/6th-workshop-marine-black-carbon-emissions Olmer, N., et al. (2017). *Greenhouse gas emissions from global shipping, 2013–2015*, tables 6, 7. https://theicct.org/publications/GHG-emissions-global-shipping-2013-2015

Segment	Assumptions	Technology	References
	Upstream		
Electricity Grid	• 99% reduction in global-average grid carbon intensity (gCO_2/kWh) from 2020 to 2050 • Hydrogen (and, possibly, ammonia in marine) used in fuel cells is assumed to be generated using grid electricity.	• Renewable energy • Carbon capture and sequestration	International Energy Association, (2017). *Energy Technology Perspectives 2017, Catalysing Energy Technology Transformations*. https://www.iea.org/reports/energy-technology-perspectives-2017. Associated data available at https://www.iea.org/etp/etp2017/restrictedaccessarea/

Low Carbon Fuels	Sustainable Biofuels
	• 35 EJ (15 million barrels per day) of bioenergy available annually by 2050
	  • 79% for on-road
	  • 7% for marine
	  • 14% for aviation
	• Low-carbon biofuels sources include
	  • Cellulosic energy crops grown on available grassland
	  • Agricultural/forestry residues and wastes
	• Excludes food and feed crops due to the associated indirect land-use change emissions
	E-fuels
	• 1.2 EJ available annually in EU by 2050
	• Scaled up to 8.4 EJ available globally by share of EU electricity out of total global electricity consumption
			Searle, S., & Malins, C. (2014). A reassessment of global bioenergy potential in 2050. https://onlinelibrary.wiley.com/doi/full/10.1111/gcbb.12141
			
			Malins, C., Searle, S., & Baral, A. (2014). A Guide for the Perplexed to the Indirect Effects of Biofuels Production. https://theicct.org/publications/guide-perplexed-indirect-effects-biofuels-production
			
			Smeets, E., et al. (2007). A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, 33(1), 56–106. https://doi.org/10.1016/j.pecs.2006.08.001
			
			Searle, S. (2018). *Bioenergy can solve some of our climate problems, but not all of them at once*. https://theicct.org/blog/staff/bioenergy-solve-some-climate-problems-not-all-once
			
			El Takriti, S., Pavlenko, N., & Searle, S. (2017). Mitigating international aviation emissions: Risks and opportunities for alternative jet fuels. https://theicct.org/publications/mitigating-international-aviation-emissions-risks-and-opportunities-alternative-jet
			
			Searle, S., & Christensen, A. (2018). *Decarbonization potential of electrofuels in the European Union*. https://theicct.org/publications/decarbonization-potential-electrofuels-eu

Table 2. Fraction of total 2050 vehicle kilometers traveled by electric vehicles

	LDV			HDV		
Region	2W & 3W	Passenger cars	Light commercial vehicles*	Buses	Rigid trucks	Tractor trailers
U.S.	100%	70%	65%	80%	55%	35%
EU-28	100%	90%	85%	90%	65%	50%
China	100%	90%	85%	95%	65%	40%
India	100%	75%	70%	75%	45%	25%
Other Regions	100%	49%	47%	76%	27%	16%
Global Total	**100%**	**69%**	**66%**	**79%**	**40%**	**28%**

* U.S. assumptions also apply to certain medium-duty trucks weighing under 14,000 pounds gross vehicle weight

Table 3. 2030 electric vehicles sales targets

	LDV			HDV		
Region	2W & 3W	Passenger cars	Light commercial vehicles[24]	Buses	Rigid trucks	Tractor trailers
U.S.	72%	34%	34%	37%	21%	10%
EU-28	75%	41%	43%	59%	21%	10%
China	95%	53%	49%	71%	21%	10%
India	72%	28%	24%	26%	11%	0%
Other Regions	68%	23%	22%	29%	4%	1%
Global Total	**74%**	**35%**	**33%**	**37%**	**10%**	**5%**

Table 4. Cumulative fuel consumption reduction (2020 vs 2050)

	LDV			HDV		
Region	2W & 3W	Passenger cars	Light commercial vehicles	Buses	Rigid trucks	Tractor trailers
U.S.	37%	44%	47%	35%	37%	34%
EU-28	36%	45%	49%	38%	38%	56%
China	41%	34%	37%	43%	42%	44%
India	24%	41%	56%	47%	46%	44%
Other Regions	36%	56%	52%	40%	41%	49%
Global Total	**33%**	**47%**	**48%**	**45%**	**41%**	**43%**

Table 5. Effective annual fuel consumption reduction (2020-2050)

	LDV			HDV		
Region	2W & 3W	Passenger cars	Light commercial vehicles	Buses	Rigid trucks	Tractor trailers
U.S.	1.5%	1.9%	2.1%	1.4%	1.5%	1.4%
EU-28	1.5%	2.0%	2.2%	1.6%	1.6%	2.7%
China	1.8%	1.4%	1.5%	1.9%	1.8%	1.9%
India	0.9%	1.8%	2.7%	2.1%	2.0%	1.9%
Other Regions	1.5%	2.7%	2.4%	1.7%	1.8%	2.2%
Global Total	**1.3%**	**2.1%**	**2.2%**	**2.0%**	**1.8%**	**1.9%**

24 U.S. assumptions also apply to certain medium-duty trucks weighing under 14,000 pounds gross vehicle weight

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