Rhodium Climate Outlook:
Probabilistic Projections of Energy, Emissions and Global Temperature Rise

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Executive Summary

Eight years after the adoption of the Paris Agreement, the international community will gather at COP28 in Dubai and conclude the first Global Stocktake to gauge progress in limiting global temperature increases to well below 2°C above pre-industrial levels. The need to understand what kind of climate future the world is on track for has become increasingly important not just for diplomats and policymakers, but to almost every actor of the global economy. These policy-*takers* need access to an outlook that incorporates uncertainty in factors over which they have no control—variables like policy, fuel prices, and economic growth. The newly launched Rhodium Climate Outlook strives to provide this kind of information, with detailed data on how the global energy transition, greenhouse gas (GHG) emissions, and temperatures are likely to evolve given current policy and technology trends, but absent a major acceleration in climate policy and clean technology innovation.

The Rhodium Climate Outlook (RCO) seeks to address some of the shortcomings of existing modeling with probabilistic energy, emissions, and temperature projections of use to a wide range of global stakeholders, including policy-*takers*. We've done this by incorporating the following innovations, which to our knowledge have never been combined in a single modeling platform:

- Probabilistic global emissions projections that capture uncertainty in economic and population growth, oil and gas prices, and clean energy technology costs.
- An econometrically-based policy projection module that uses evidence of the determinants of climate policy around the world over the past two decades to provide probabilistic projections for how policy is likely to evolve going forward.
- Projections for all GHG emissions, not just CO_2.
- Probabilistic temperature projections derived directly from our emissions projections but including climate system uncertainty as well.

In this inaugural RCO, we find that:

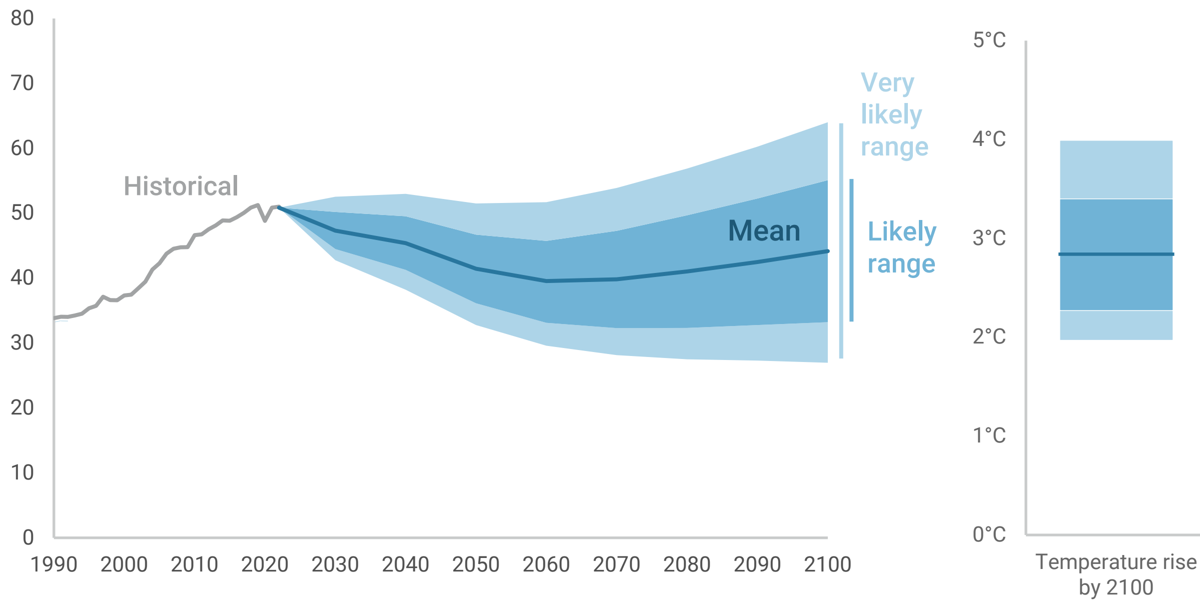
1. The world is very likely on track to exceed 2°C above pre-industrial levels, but we've avoided the most catastrophic projections.

Shortly before the Paris Agreement was adopted in 2015, the Intergovernmental Panel on Climate Change (IPCC) estimated that without additional efforts to reduce emissions, global temperatures would increase between 2.5 and 7.8°C (*very likely* range, i.e. 90% confidence interval) by the end of the century. Policy and technological progress over the past eight years has significantly reduced the global temperature outlook. We now project *very likely* temperature increases of 2.0 to 4.0°C by century's end, with a 2.3 to 3.4°C *likely* range and a mean of 2.8°C. While this is progress from just eight years ago, it still represents a dire climate future—falling significantly short of the Paris Agreement goal of limiting warming to well below 2°C.

2. The world has made progress in decarbonizing electricity and vehicles, but current technology has its limits.

Thanks to several decades of policy and innovation, the world has made considerable progress in decarbonizing power generation and transitioning from internal combustion to electric vehicles. As a result, emissions from power and transportation *likely* fall and peak in the coming decade, respectively, with both declining through mid-century. But momentum in power and transport bottoms out after mid-century as variable renewable energy (like wind and solar) and electric vehicle deployment plateau, and as demand for more power and transportation continues to increase. Without ongoing support for variable renewable technologies, along with significant policy acceleration and innovation in zero-emission dispatchable

FIGURE 1
Global greenhouse gas emissions and temperature rise
Net emissions including removals (billion metric tons of CO_2-equivalent)



Source: Rhodium Climate Outlook, AR5 100-year GWP values. Following IPCC conventions, this report uses *very likely* to indicate a 90% probability of occurring and *likely* to indicate a 67% probability.

generation (e.g., storage, advanced geothermal and advanced nuclear), fossil generation hangs on and even expands in the second half of the century. In transportation, as policy and innovation drive decarbonization for passenger and freight vehicles, emissions from air and marine transport remain stubbornly high and increase (with more than 50% probability) absent an acceleration of policy and innovation in zero-emission fuels and technologies for aviation and shipping.

3. As electricity and transport decarbonize, industry becomes the largest challenge.

We see a greater than 50% chance that emissions from the industrial sector—including production of iron, steel, cement, oil and gas, and chemicals—rise over the coming decades as demand for industrial products grows without widely available, cheap decarbonization solutions, offsetting the progress achieved in power and road transportation. By 2050, industry consumes more fossil fuel than power generation, and emits more GHGs than power, transport, and buildings combined in our projection mean. By century's end, industrial emissions grow to three times the level of emissions from either electricity generation or transportation (projection mean). It took decades of policy and investment in innovation to scale decarbonization technologies in power and transport. Solutions for decarbonizing industry are still in their very early stages of development and will require a significant acceleration in both innovation and policy to achieve the same liftoff velocity as renewables and EVs.

4. Fossil fuel use likely peaks this decade, but not for long.

Global fossil fuel consumption—including coal, natural gas, and oil—is *likely* to peak this decade thanks to progress in decarbonizing power and passenger vehicles. We find a greater than 83% chance that this decline in fossil fuel consumption plateaus after 2060, remaining stubbornly high at more than 60% of today's levels. Without a significant acceleration in policy and clean energy innovation, there is a greater than 50% chance that fossil fuel consumption begins to rise again after mid-century, driven largely by a rise in natural gas demand, a slowing reduction of coal use in industry, and a rebound in oil consumption to meet global aviation, shipping, and plastic demand.

5. Getting below 2°C will require making clean energy cheap beyond the OECD and China.

Emissions from OECD countries and China—today's highest emitters—are *very likely* to decline significantly through mid-century, thanks in part to decades of policy and investments that have brought down the costs of renewable electricity and electric vehicle batteries, positioning these technologies to scale rapidly in the years ahead. The bulk of emissions growth in the future, however, will come from other emerging markets—particularly India and other non-OECD countries in Asia, the Middle East, and Africa—driven by economic growth and rising industrial production. Keeping the increase in global temperatures below 2°C will require investing in the deployment of mature clean energy technologies in these regions, and a significant acceleration of policy and innovation to drive down the cost of emerging clean technologies required to decarbonize hard-to-abate sectors—like industry, shipping, and aviation—to make those solutions affordable for all regions to adopt at scale.

In the first chapter of our inaugural Rhodium Climate Outlook report, we introduce the RCO approach and how it addresses gaps left by other existing global emissions and energy outlooks. In the following chapters, we present our results, first globally, then by sector, and last by region. We end with an overview of key drivers of global emissions and sources of uncertainty in possible climate futures.

CHAPTER 1

What Are We on Track for?

Shortly before the Paris Agreement was adopted in 2015, the IPCC released its Fifth Assessment Report summarizing the state of climate science and the outlook for global emissions at that time. In this report, the IPCC found with "high confidence" that absent additional action to control GHG emissions, global temperatures would continue to rise, reaching 2.5 to 7.8°C by the end of the century (*very likely* range).[1] Against this backdrop, signatories to the Paris Agreement pledged to work together to limit global temperature increases to "well below 2°C" relative to pre-industrial levels, with an aspiration of limiting temperature increases to 1.5°C.

The Paris Agreement called for a five-year cycle to take stock of progress toward meeting these goals and inform decision-makers of where additional action is required. This first Global Stocktake cycle will conclude this year at the UN Climate Change Conference (COP28) in Dubai, where policymakers and stakeholders will try to answer the question "what are we on track for?" This will happen at a critical juncture, providing input to the next round of enhanced nationally-determined contributions (NDCs) that lock in global emissions targets through 2035.

Before the Paris Agreement, most climate and energy modeling was aimed at informing policy-*makers*—those responsible for charting the course for climate and energy policy like the government officials gathering at COP28 in Dubai. Today a much wider range of stakeholders are tracking decarbonization efforts and their impact worldwide—from investors, energy companies, and technology innovators, to farmers, city planners, and healthcare providers.

The need to understand what the world is on track for has become important not just for diplomats and government officials, but to almost every segment of the global economy. These policy-*takers* need access to different types of information about what track the world is on because they ultimately do not control global or national target-setting and domestic implementation of those policies. Decision-makers trying to navigate in a decarbonizing world—including investors, energy companies, manufacturers, and other industry players—need to make investment decisions today that will have implications for the next few decades. They need to understand how a wide range of uncertainties—public policy, fuel prices, technology costs, and economic growth—are likely to impact the demand for, and supply of, clean fuels, technologies, and products so they can invest accordingly. Similarly, decision-makers trying to build resilience in public infrastructure, for example, need information about the temperature rise and associated climate impacts they are likely to experience in the coming decades.

To answer this question of what we are on track for, there has been a proliferation of global GHG emissions and energy outlooks in recent years. Most outlooks, however, are geared toward policy-*makers* as the primary audience, forcing policy-*takers* to make their own judgments about whether or not they believe policy-*makers* will follow through with their promises. As a result, the existing set of global GHG projections have the following limitations for use by real-world actors:

Single, deterministic scenarios: Most outlooks report outcomes under a single scenario (or set of scenarios) that are based on deterministic input assumptions for key variables that are, in reality, highly uncertain. The pace of economic growth, for example, is one of the most important drivers of emissions growth, yet most

[1] Following IPCC conventions, this report uses *very likely* to indicate a 90% probability of occurring and *likely* to indicate a 67% probability.

outlooks rely on a single deterministic GDP projection. Other important uncertainties that drive emissions include population growth, fuel prices, clean technology costs, and the pace of learning for emerging decarbonization technologies.

Policy bifurcation: Because of the inherent uncertainty in how policy will evolve over time, modelers are left to construct stylized emission projections that follow one of two possible policy stories: 1) countries keep policies in place today, but there is no further evolution of policy beyond that; or 2) countries fully implement the pledges they have announced, whether their near-term NDCs, mid-century net zero targets, or global 1.5 degree-consistent emissions scenarios. This provides useful information to policy-*makers* as they set new targets and develop implementation plans, but is much less useful to a policy-*taker* audience that has no direct influence over policy outcomes. And the reality is likely somewhere in between those two extreme policy stories.

Partial emissions picture: The majority of outlooks have focused to date on the energy transition, reporting emissions of carbon dioxide (CO_2) from energy combustion. But energy CO_2 contributes only two-thirds of global greenhouse gas emissions. The rest is emitted as methane (CH_4) from oil and gas production, agriculture and waste; nitrous oxides (N_2O) from agricultural production; hydrofluorocarbons (HFCs) and other fluorinated gases used in refrigeration, cooling, and industrial uses; and CO_2 from industrial processes, forests, and other land uses. Without an integrated understanding of the potential trajectory of emissions of the other third of GHGs, we are left with only a partial picture of what we are on track for.

No integrated temperature rise outcomes: Other available emissions scenarios project out to 2030 or 2050—the edge of known or announced policy pledges. This makes it impossible to provide an integrated set of global temperature rise projections, which require annual data through at least the end of the century. As a result, other modeling efforts do their best to align their 2030 (or 2050) projections with aggregate, global long-term emissions scenarios developed by other groups. This provides limited information about what geographic, sectoral, or technological developments are most important in shaping global temperature outcomes.

Rhodium Climate Outlook

The Rhodium Climate Outlook (RCO) seeks to address these shortcomings with probabilistic energy, emissions, and temperature projections of use to a wide range of global stakeholders, including policy-*takers*. We've done this by incorporating the following innovations, which to our knowledge have never been combined in a single modeling platform:

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- Projections for all GHG emissions, not just CO_2.
- Probabilistic temperature projections derived directly from our emissions projections but including climate system uncertainty as well.

In the following chapters, we provide an overview of our 2023 Rhodium Climate Outlook results, first globally, then by sector, then by region.

CHAPTER 2

Global Climate Outlook

Greenhouse gas (GHG) emissions are produced from every single facet of the global economy, which makes projecting changes in global emissions over the coming decades highly uncertain. We don't have a crystal ball to know what will happen to the drivers of emissions over time—economic growth, demand for energy and materials, fossil fuel prices, deployment of new clean energy technologies, and the evolution of climate policies. While this makes it hard to pinpoint exactly what emissions *will be* in 2050 (or 2100) with any certainty, characterizing these uncertainties in an integrated modeling platform can yield probabilistic energy, emissions, and temperature projections, providing valuable insight into where decarbonization is going well, and where efforts need more focus.

The Rhodium Climate Outlook (RCO) is produced using such an integrated modeling platform: Rhodium's Global Energy Model (RHG-GEM). RHG-GEM captures uncertainty in economic and population growth, oil and natural gas prices, and clean energy technology costs under likely policy evolution to provide probabilistic energy, emissions, and temperature projections through the end of the century (see the Technical Appendix for more detail).

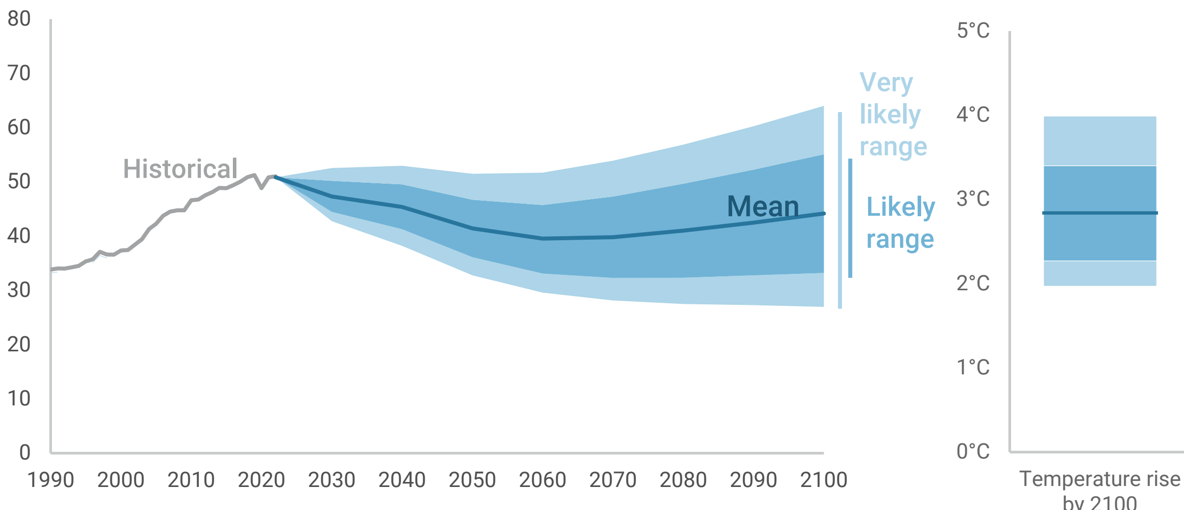
Global greenhouse gas emissions

In this inaugural RCO, we find that global GHG emissions are *likely* to decline gradually through 2050[2], but then plateau through the 2060-2070 period before reversing and gradually increasing through the end of the century (Figure 1). In the mean of our full uncertainty range, emissions decline to around 41.4 gigatons of CO_2e by 2050 (19% below today's levels), reach their lowest point of around 39.6 gigatons by 2060 (22% below today's levels), then rise gradually again, reaching 44.2 gigatons (13% below current levels) by century's end.

FIGURE 1

Global greenhouse gas emissions and temperature rise

Net emissions including removals (billion metric tons of CO_2-equivalent)



Source: Rhodium Climate Outlook, AR5 100-year GWP values.

[2] Projections are decadal, with 2030 as the first projected year. We model existing policies through 2030 only apply our uncertainty framework from 2030 onward.

Taking into account uncertainty in the key drivers of emissions, it is *likely* (67% probability) that global GHG emissions decline by 4-15 gigatons CO_2e by 2050—a drop of 8-29% from today's levels. It is *very likely* (90% probability) that emissions land between 33-51 gigatons in 2050, representing anywhere from an increase of 1% to a decrease of 36%. By 2100, uncertainty in key emission drivers increases, leading to a wider range of emissions outcomes, with global GHG emissions *very likely* somewhere between 27 to 64 gigatons of CO_2e, and *likely* between 33 to 55 gigatons.

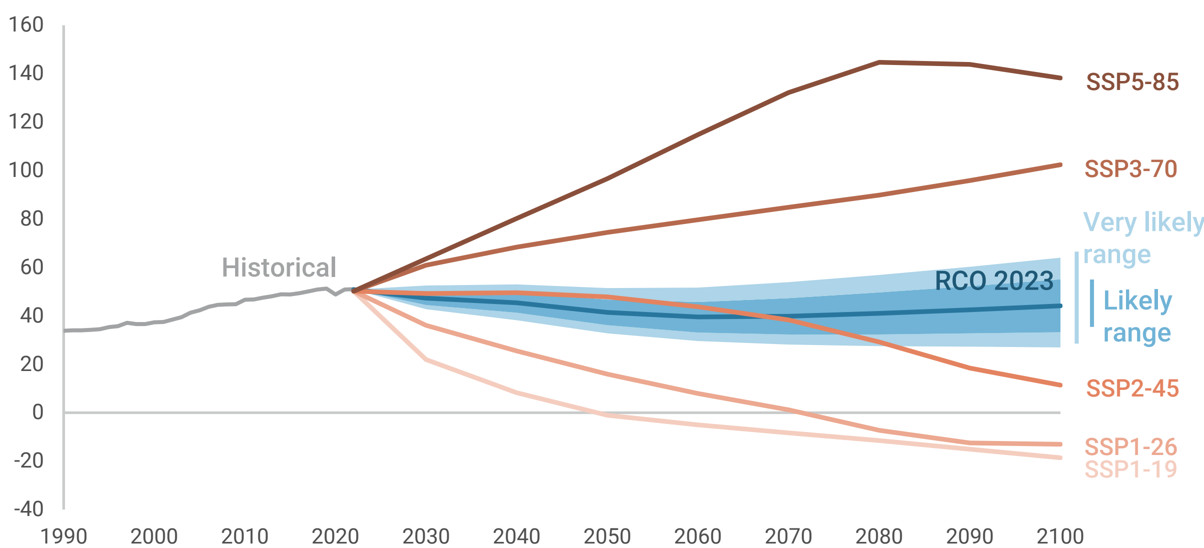
The higher end of the *likely* emission range is characterized by a world with very high economic growth powered by cheap and plentiful fossil fuels and stubbornly high clean energy technology costs. At the lower ends, emissions decline is driven by lower economic growth, and increasingly cheap and plentiful clean energy like renewables and electric vehicle (EV) batteries that out-compete fossil in an environment of high oil and gas prices, paired with more ambitious climate policies.

Even incorporating a wide range of potential socioeconomic, fossil fuel price, clean energy technology cost and climate policy futures, the RCO-projected GHG emissions range is much narrower than the range of emission projections used by global climate modelers to simulate future changes in temperature, precipitation and other climate variables. These emissions projections, known as 'Shared Socioeconomic Pathways", each map out a stylized potential global future.[3] In the highest, SSP5-85, global GHG emissions grow from 51 gigatons CO_2e today to a peak of 145 gigatons in 2080, nearly three times higher than the highest emissions point in our *very likely* range that year (Figure 2). At the lower end, SSP1-19, global net GHG emissions fall to -18.6 gigatons by the end of the century, 46 gigatons lower than the bottom of our *very likely* range that year.

FIGURE 2

Global GHG emissions scenario comparison

Billion metric tons of CO_2e, 100-year GWP, national inventory basis



Source: Rhodium Climate Outlook, IIASA SSP Database. SSP emissions are adjusted to match national inventory reported emissions, for comparability with Rhodium Group historical and projected emissions.

[3] For the sixth round of the Coupled Model Intercomparison Project (CMIP6) used to inform the IPCC's Sixth Assessment Report, global climate modelers were provided with "marker" emissions scenarios developed by the Integrated Assessment Modeling Consortium (IAMC). These emissions scenarios are shown in Figure 2.

Global temperature rise

We translate these emissions projections into global temperature change using the Finite-amplitude Impulse Response (FaIR) model (see the Technical Appendix for more detail). We find that across our range of emission outcomes, we are *very likely* on track for an increase in global mean surface temperature of 2.0 to 4.0°C and *likely* on track for 2.3 to 3.4°C by century's end (Figure 1). The mean projection across our uncertainty range is 2.8°C above pre-industrial levels. Given the current outlook for the key drivers of emissions, we find there is a less than 5% chance of keeping global temperature increases below 2°C, the Paris Agreement goal, absent an acceleration in the pace of climate policy ambition.

This range of projected temperatures is considerably less dire than the 2.5 to 7.8°C *very likely* range included in the IPCC's Fifth Assessment report in 2014 (the year before the Paris Agreement was adopted). Under the SSP5-85 emissions scenario above, global mean surface temperatures increase by 3.2 to 6.4°C on average between 2081 and 2100 (*very likely range*) relative to pre-industrial levels. Under SSP3-70, temperatures increase by 2.8 to 5.2°C during the same time period. In contrast, in the RCO, global mean surface temperatures *very likely* increase by 1.9 to 3.7°C on average between 2081 and 2100.

While the RCO temperature outlook marks a considerable improvement relative to projections from the IPCC Fifth Assessment Report or the higher emissions scenarios used by global climate modelers, it is also clear the world is not on track to meet the Paris Agreement's global temperature targets. The remainder of this report digs into global emissions trends and identifies areas where more policy and innovation are required.

CHAPTER 3

Sectoral Emissions Trends

Digging deeper into the sources of emissions provides helpful insights into where the world is making meaningful progress and where more focus is needed. Over the past few decades, two of the largest sources of emissions—electric power and industry—have accelerated sharply, nearly doubling between 1990 and today. Emissions from transportation—including from cars, trucks, aviation, and shipping—have also risen sharply over that period, growing 65% since 1990.

Looking ahead, however, we see a very different likely path for these sectors (Figure 3). In good news for global emissions, thanks to progress in decarbonizing power generation and transitioning from internal combustion to electric vehicles, it is *likely* that emissions from power and transportation fall and peak in the coming decade, respectively, with both declining through mid-century (Figure 4). Similarly, emissions from buildings *likely* decline through mid-century—thanks in large part to a steep reduction in HFCs driven by implementation of the Kigali Amendment to the Montreal Protocol, as well as electrification of heating and modest efficiency improvements.

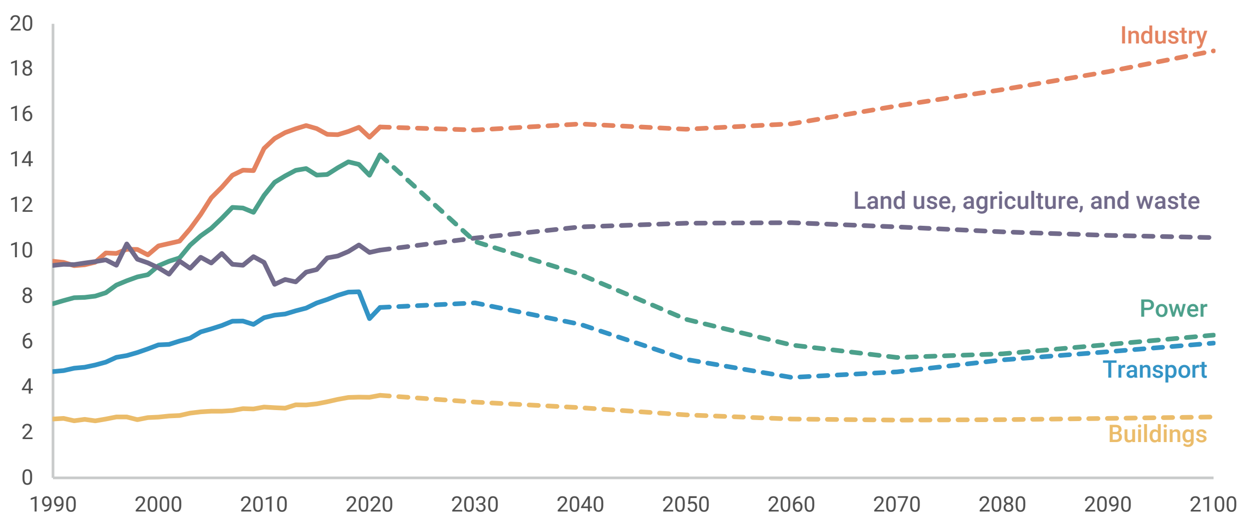
The bad news, however, is that there's a 50% chance that emissions from the industrial sector—including production of iron, steel, cement, oil and gas, and chemicals—rise over the coming decades as demand for industrial products grows without widely available and affordable decarbonization solutions, offsetting somewhat the progress achieved in power and transportation. The outlook for this sector is also extremely uncertain, with demand for industrial products tied to the overall outlook for economic growth, population, and energy prices. Similarly, emissions from agriculture and waste are expected to rise gradually over the next few decades, where they *likely* slow or gradually decline.

In the rest of this chapter, we dive deeper into the dynamics playing out in these key sectors.

FIGURE 3

Global GHG emissions by sector

Net emissions including removals (billion metric tons of CO_2), projection mean

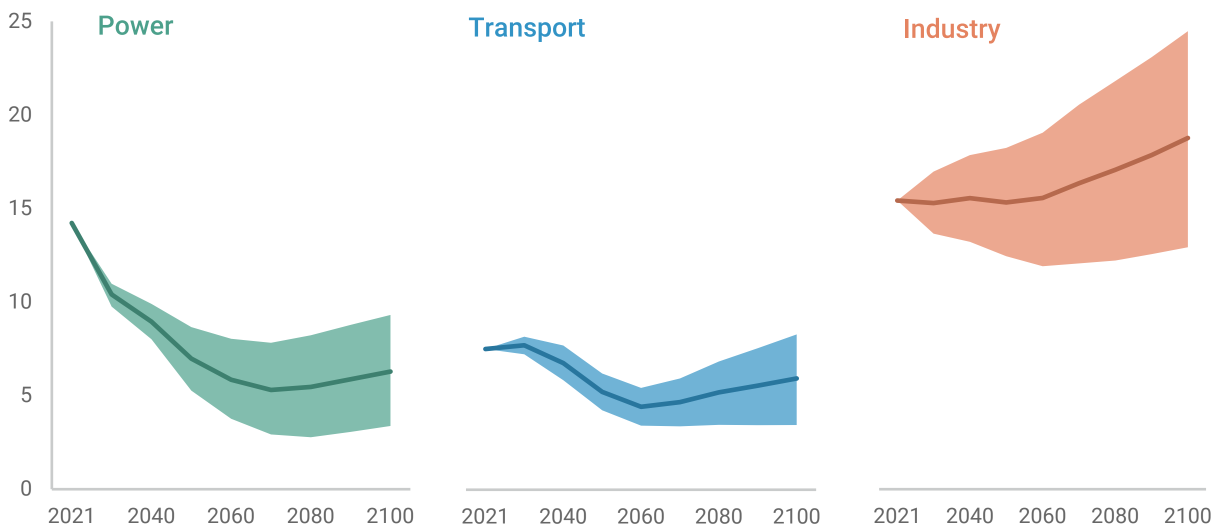


Source: Rhodium Climate Outlook

FIGURE 4

Range of *likely* global emissions for key sectors

Billion tons of CO_2e, *likely* range (67% probability of occurring)



Source: Rhodium Climate Outlook

Electric power

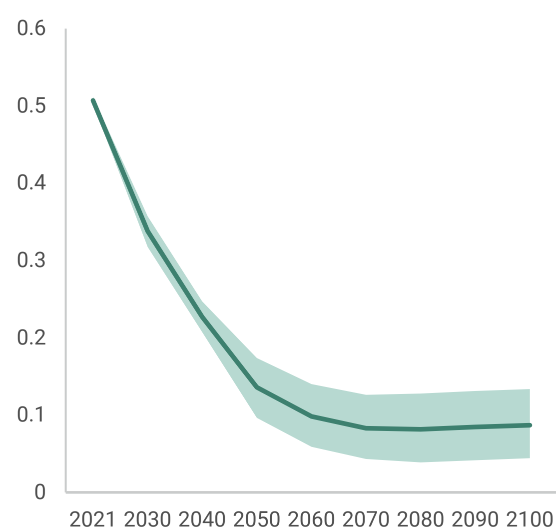
To date, the world has made the most progress in scaling decarbonization solutions for electric power. Due to a combination of the rise in policies targeting power sector emissions and a parallel decline in the cost of solar and wind technologies, renewable deployment has seen exponential growth over the past decade. These trends are expected to continue, helping renewables reach escape velocity, essentially ensuring that the world sees the emissions benefits of a steady reduction in the emissions-intensity of electric power over the coming decades. Indeed, we find that continued improvements in the emissions intensity of power is *very likely* (a greater than 90% probability) through 2070, assuming climate policy ambition does not accelerate beyond its historical pace (Figure 5).

The massive scale-up of renewable energy that fuels this rapid decline in emissions intensity is eye-popping. We find renewable energy generation from solar and wind *likely* reaches 7 to 13 times today's levels by 2050 and 10 to 23 times by 2100 (Figure 6). Driving this growth is an increase in electricity demand across the entire economy, as well as a rise in new demand sources like charging for electric vehicles and hydrogen production (Figure 7). By century's end, new sources of power consumption are responsible for about 75% of the increase in demand on average.

FIGURE 5

Emissions intensity of global electric power

Million metric tons of CO_2e per Terawatt hour (TWh), *very likely* range (90% probability)

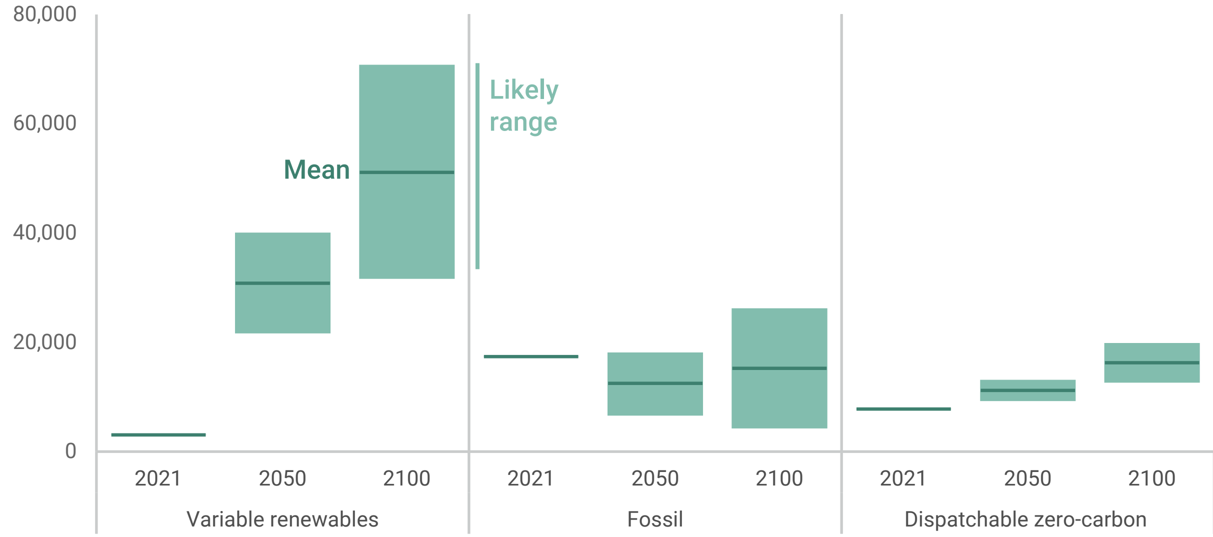


Source: Rhodium Climate Outlook

FIGURE 6

Global electric power generation by source

Terawatt hours (TWh), *likely* range (67% chance)



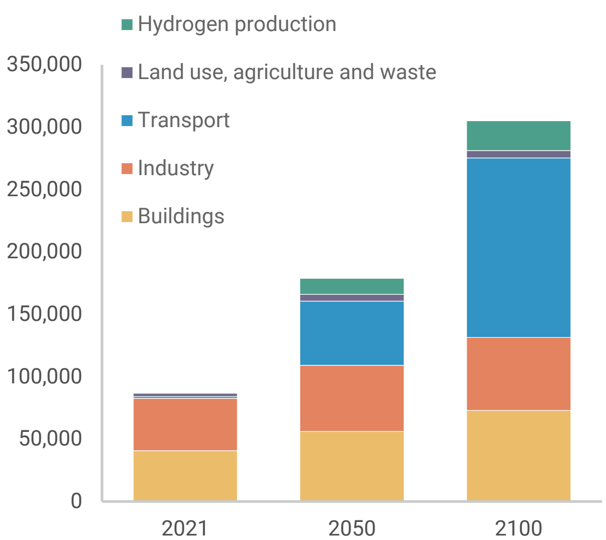
Source: Rhodium Climate Outlook. Bars indicate *likely* range, line indicates projected mean.

Because of their relatively low cost, renewables are the most cost-effective way to scale up electric power capacity to meet the surge in demand we see across all potential futures of the world. We find that total electricity demand *likely* grows 75-140% above today's levels by 2050 (with an average of 100%), and by 150 to 250% by 2100 (with an average of 250%).

FIGURE 7

Global electricity demand by source

Projection mean, TBtu



Source: Rhodium Climate Outlook

In regions where variable renewable energy reaches very high levels of penetration, we see fossil fuels remaining online to provide flexibility. Short-duration battery storage also plays a meaningful role in supporting renewable energy integration, *likely* growing from around 45 GW today to 500 to 3000 GW by 2050 and 3100 to 8800 GW by 2100. Only a relatively small portion of dispatchable generation is met from low- or zero-emission sources like batteries and fossils with carbon capture in many regions, however. As of today, there are very few dispatchable low-carbon power technologies at a level of maturity and cost-effectiveness to compete with fossil fuels for flexibility and deployment at scale. We anticipate that innovation in large-scale batteries, advanced geothermal, and advanced nuclear has the potential to mature these technologies to a point that they can compete, but they all will need significant technological advancement before they can be projected to make significant contributions in the future power system.

Variable renewable resources also require additional support to help fully decarbonize the power system, despite cost reductions for wind and solar across our projected range. While we see substantial renewable expansion in every part of the world, fossil generation sticks around and even expands to help meet demand in regions with limited policy ambition and/or cheap fossil fuels. The low cost of renewables to date might lend a false sense that power sector decarbonization is a "done deal"; however, we find that wind and solar require continued policy support, particularly in markets where affordable, low-cost electricity will be critical to decarbonizing quickly-growing demand in the rest of the economy.

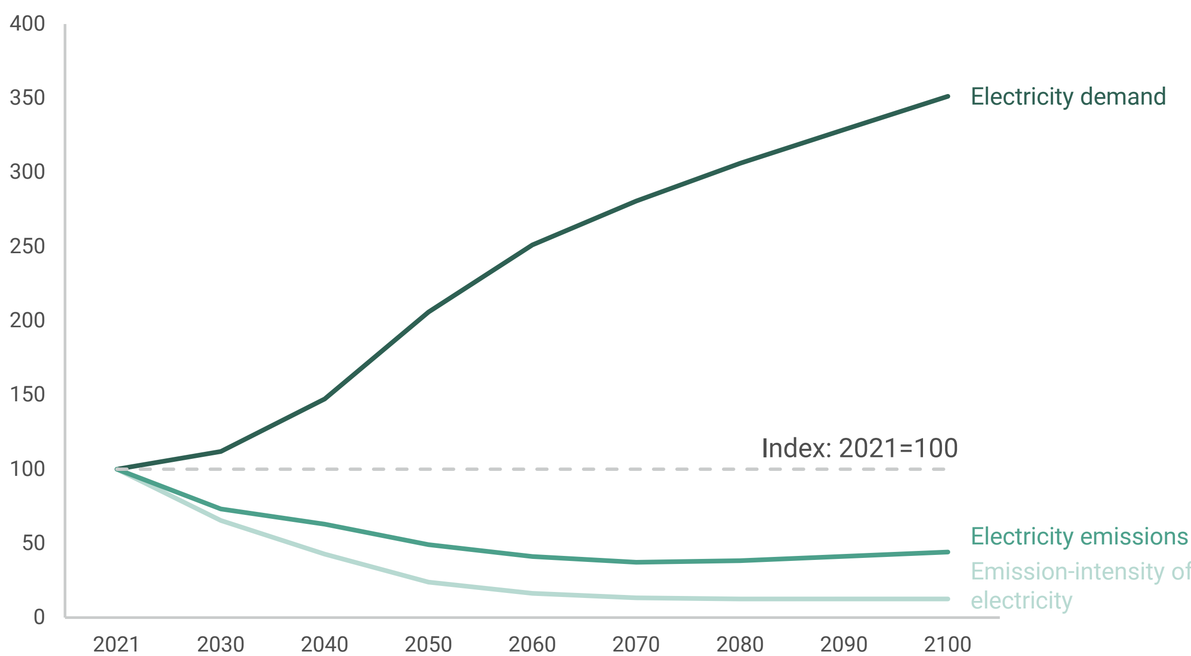
Across our *likely* range, we see the momentum in power sector emission reductions bottoming out after 2060. Without significant innovation in dispatchable zero-carbon generation resources and ongoing policy support for variable renewable energy, fossil power falls from 60% of total electricity generation today to 7 to 32% in 2070 in our *likely* range (with an average of 18%), but then it plateaus at similar shares through 2100. As electric power demand grows, this could translate into far more terawatt-hours of fossil on the grid (Figure 6).

Indeed, we find that after significant progress in reducing the emissions-intensity of electric power and overall power sector emissions through mid-century, decarbonization begins to plateau and even reverse slowly near century's end as global electric power demand continues to grow (Figure 8). To reach net zero emissions across the global economy, emissions from electric power will need to zero out completely, and likely before mid-century to give room for other harder-to-abate sectors. Unless we accelerate policy ambition and innovation in zero-emission flexible technologies, power sector emissions will stubbornly persist, *likely* remaining between 3 and 9 gigatons of CO_2e through century's end.

FIGURE 8

Power sector decarbonization plateaus as demand growth offsets reductions in emissions intensity

Mean projections, index 2021=100



Source: Rhodium Climate Outlook

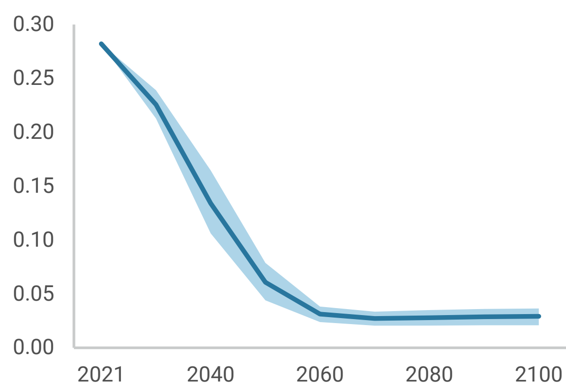
Transportation

The rapid scale up of electric vehicles over the past few years is another good news story demonstrating that with concerted policy action and significant investment in innovation, deploying zero-emission technologies at scale is possible. Over the past 20 years, several countries (as well as critical sub-national actors like California) have put in place a combination of vehicle emissions or efficiency standards, EV mandates, and incentives to help bring the relative costs of EVs down sufficiently to compete with internal combustion engines. As a result, EVs are expected to reach 18% of total global vehicle sales this year, up from only 5% in 2020. EV battery prices are expected to continue to come down over the coming decades, which means it is safe to say that EVs have officially reached escape velocity. The same cost declines in battery technologies that have allowed passenger EVs to take off will also eventually help scale the EV market for medium- and heavy-duty trucks.

FIGURE 9

Emissions intensity of global passenger vehicles

GHGs (tons CO_2e) per mile, *very likely* range (90% chance)



Source: Rhodium Climate Outlook

In fact, our modeling shows that regardless of uncertainty in oil prices or future policy ambition (among the other drivers of uncertainty we model), there is significant confidence (greater than 90%) that the emissions intensity of passenger vehicles (i.e., total GHGs emitted per mile of travel) will drop at least 70% below today's levels by mid-century and 85% below today's levels by around 2070 (Figure 9). We expect a similar outcome for improvements in the emissions intensity of medium- and heavy-duty vehicles.

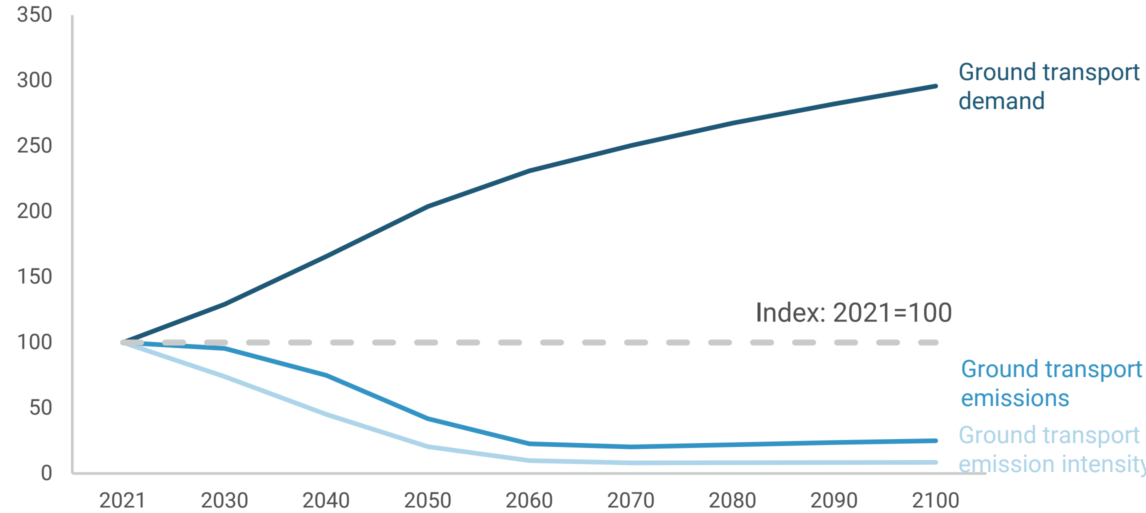
Mirroring what we see in the power sector, however, there is also bad news. While the rapid deployment of existing technologies helps decarbonize the majority of road transport, it doesn't decarbonize the last quarter of emissions. This is due in large part to an increase in global demand for transportation—including both passenger and freight—which rise significantly over the coming decades. By mid-century that demand growth starts to outpace the gains from decarbonization of road vehicles. As a result, the emissions intensity of road vehicles plateaus through century's end (Figure 10). Even with nearly full electrification of road transport, deployment barriers, including infrastructure challenges, remain through century's end, making it difficult to decarbonize the last remaining share of road transport.

The other part of the bad news story for transportation is that, while we have increasingly mature decarbonization technologies for road transport, those don't exist today for aviation and shipping, two modes of transportation where the potential exists for rapid growth in demand (and emissions) across developed and developing economies alike. Marine and aviation emissions are currently only 20% of total transportation emissions, nearly four times smaller than emissions from road transport.

FIGURE 10

On-road vehicle decarbonization plateaus as growth in travel demand soars

Mean projections, index 2018=100

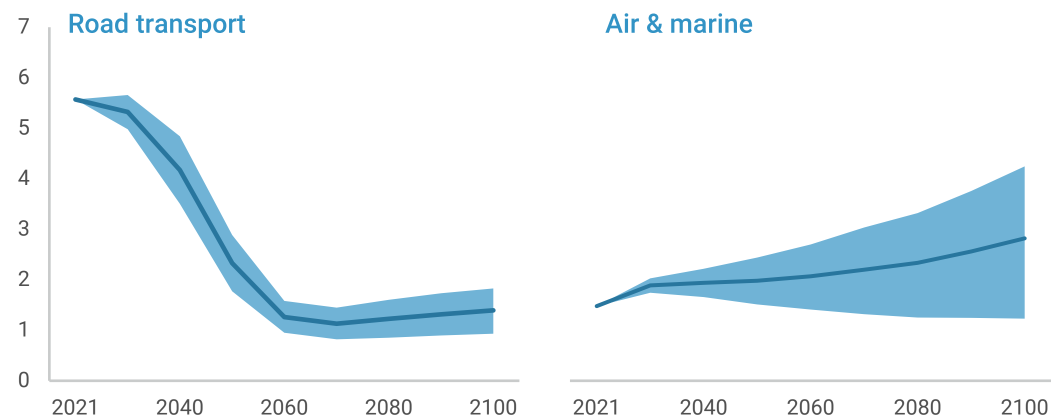


Source: Rhodium Climate Outlook

FIGURE 11

Global GHG emissions by transport mode

Million metric tons of CO_2e, *likely* range (67% chance)



Source: Rhodium Climate Outlook

But as policy and innovation drives decarbonization for passenger and freight vehicles, emissions from air and marine transport remain stubbornly high, despite a significant rise in deployment of low-emission sustainable aviation fuel (SAF) in the aviation sector (Figure 11). Absent an acceleration of climate policy and/or innovation in the marine and aviation sectors, those emissions are likely to exceed road transport emissions by mid-century, rising to double road transport levels by century's end on average as population and economic growth in many emerging markets drive transportation demand.

Industry

When accounting for manufacturing, refining, and oil and gas processing, the industrial sector is already the single largest source of emissions globally. With limited technology and policy progress to date, the emissions outlook for the sector is primarily driven by economic and population trends. As a result, our projection includes a wide range of likely outcomes, with emissions *likely* reaching 12 to 18 gigatons of CO_2e by 2050 and 13 to 25 gigatons by 2100 from 15 gigatons today. But as other sectors decarbonize, industry *very likely* remains the biggest source of emissions by a wide margin. In fact, by 2050, industrial emissions exceed all emissions from power, transportation, and buildings combined in our projection mean. Without meaningful solutions to decarbonize industry, global emissions will remain stubbornly high for the foreseeable future.

Industry is a diverse sector, posing unique challenges for decarbonization. Today, industrial emissions are spread across a wide range of activities, including oil and gas production (25% of emissions), cement and non-metallic minerals (20%), iron and steel (15%), chemicals (8%), refining (6%), among many others. Below we highlight how emissions from this diverse sector are likely to evolve over the coming decades.

Emissions from oil and gas production are the largest single source of industrial emissions. The good news is that cost-effective mitigation solutions exist today to control fugitive methane emissions and CO_2 from flaring. We find that absent additional policy beyond today's levels, however, emissions from oil and gas production rise about 7% through 2040 in our projection mean, and 19% through century's end. Uncertainty in future oil and gas demand contributes to significant uncertainty in the outlook for oil and gas emissions, with the *very likely* range of outcomes (90% probability) for oil and gas emissions in 2050 anywhere from a rise of 40% to a fall of 30%, depending on the overall outlook for oil and gas demand and prices. Recent pledges to significantly reduce the methane emissions-intensity of oil and gas, if implemented, will go a long way to reduce the overall uncertainty in emissions from this sub-sector.

Emissions from chemicals[4] are *very likely* to rise as demand for plastics and industrial chemicals grow. Plastic demand has taken off in recent decades, particularly in China, India and other non-OECD countries in Asia. With few cost-effective decarbonization options, plastics production and emissions continue to rise as economies grow.

For cement, iron and steel (which together make up a third of industrial emissions today), the story is largely a regional one. Cement *very likely* remains a significant source of emissions, emitting twice as much as all passenger vehicles cumulatively between today and 2100. As cement production falls in China after 2035 as a result of expected structural decline (*very likely*), future emissions depend on the pace of demand growth in emerging markets. Similar regional dynamics play out in our steel projections, although unlike cement, global production *very likely* eclipses China's decline and steel production grows after 2030 through the mid-2070s. Despite this growth, iron and steel emissions *likely* fall 4 to 30% by 2050, and 26 to 51% from today's levels by 2100. This happens as the global availability of scrap metal grows, allowing recycled steel to displace an increasing share of iron ore.

Underpinning the fate of cement, iron and steel are major demographic shifts that shape the future of the sector as a whole. Today, China accounts for more than a third of the world's industrial emissions. By 2100, this share plummets to 11% on average due to overall structural decline, slowing urbanization and shrinking population (Figure 13). OECD countries' share also meaningfully shrinks while fast-growing regions—including Africa, the Middle East, and other non-OECD countries—fill in the gap.

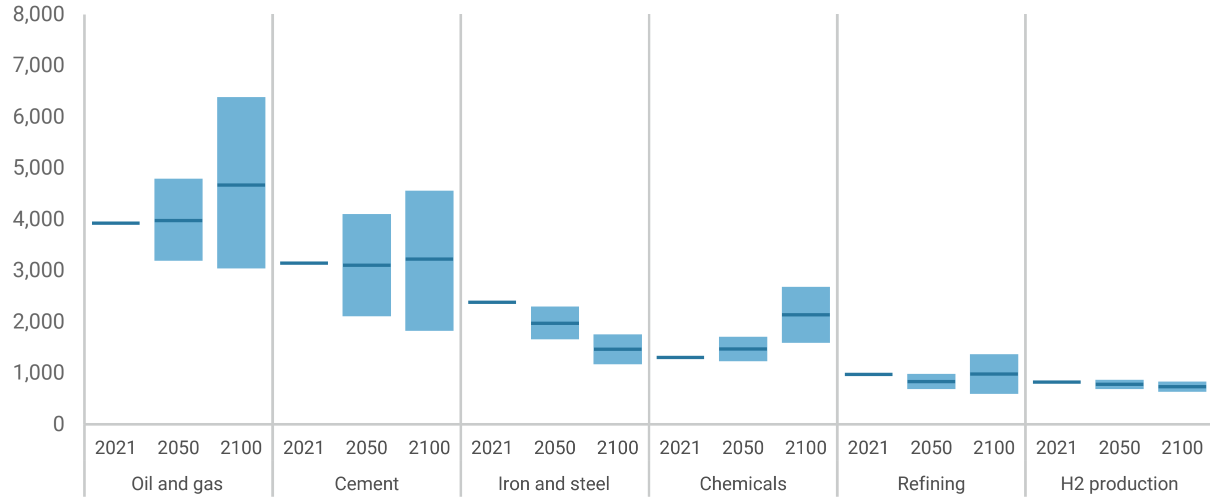
While further behind than in other sectors, low-carbon technologies deploy in industries where proven alternatives exist and in regions with more mature policy. We find that carbon capture *likely* deploys on 14-33% of iron production by 2100, with the vast majority in OECD countries and China. In these same regions, we also see a switch from coal-based blast furnaces to lower-emitting natural gas and hydrogen-based direct reduced iron technologies (DRI). Currently, fossil-based DRI accounts for 8% of global iron production

[4] This excludes industrial hydrogen production for fertilizer and other chemicals, which is included in a separate H2 production subsector.

FIGURE 12

Emissions by industrial sub-sector

Million metric tons of CO_2e, *likely* range (67% chance)

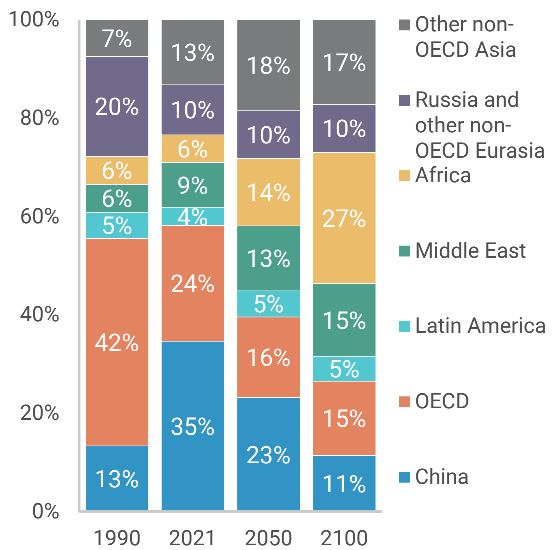


Source: Rhodium Climate Outlook

FIGURE 13

Regional share of industrial emissions

Percent, projection mean



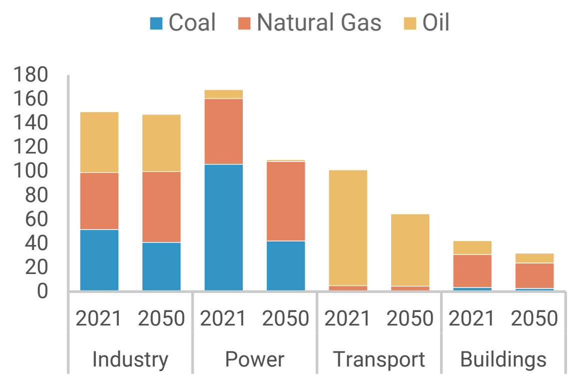
Source: Rhodium Climate Outlook

and the first commercial H2 DRI plant has yet to be built. Across our *likely* range, these technologies produce 10 to 41% and 1 to 17% of global iron by 2100 (average of 24% and 9%), respectively.

By 2100, 0.7 to 1.8 gigatons of carbon capture *likely* deploys in the industrial sector (average 1.28 Gt), including in iron and steel, cement, refining, and hydrogen production. Clean hydrogen produced via fossil with carbon capture, electrolysis, or biomass grows, *likely* rising to 66 to 130 million metric tons in 2050 and 112 to 334 million metric tons by 2100 from less than half a million tons today. This helps lower the emissions intensity of industrial hydrogen used in chemicals and refining and supplies new sources of demand from ironmaking and transport. However, emissions from hydrogen production *likely* level off post-2060 as demand growth outweighs the pace of clean hydrogen cost reductions.

Without more substantial policy ambition and affordable alternatives, industry's demand for fossil energy remains strong in the coming decades. While coal generation goes into free-fall in the power sector, industry continues to burn it in large quantities. Likewise, natural gas consumption grows, and oil falls only slightly. By 2050, industry replaces power as the highest-consuming sector of fossil fuels (Figure 14).

FIGURE 14
Fossil fuel consumption by sector
Quadrillion Btu, projection mean



Source: Rhodium Climate Outlook

Fossil fuels' likely fate

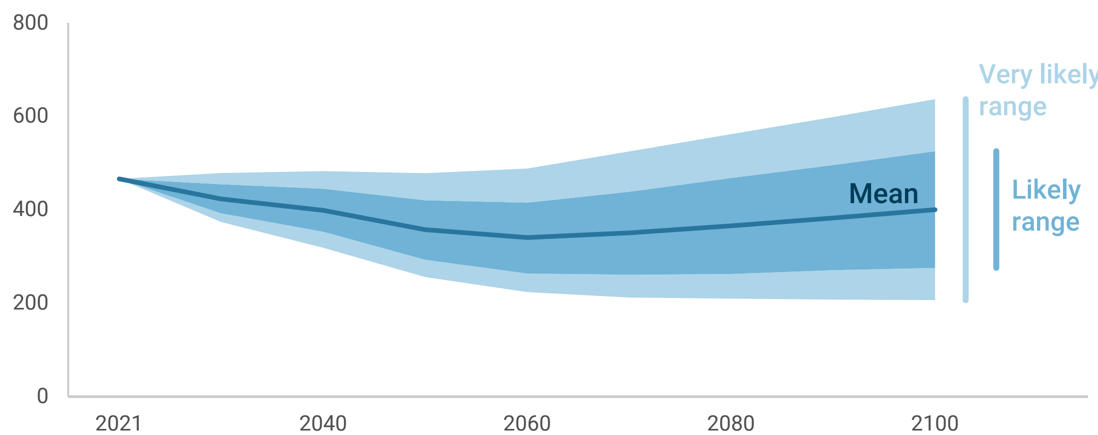
There is no doubt that staying on track to meet the Paris Agreement goal of keeping temperature rise below 2°C requires the rapid phasedown of the consumption of fossil fuels worldwide. Fossil fuel consumption has grown fairly steadily since the industrial revolution, but in the last few years it has shown signs of reaching a critical threshold—global peaking. There has been significant debate about whether the world is on track to see a fossil peak this decade, with a wide range of energy outlook scenarios claiming everything from an imminent decline, to a peak with a long-term plateau, to a continued rise in demand.

The answer is not quite so straightforward. With so many uncertain factors driving the outlook for fossil, analysis that captures all sources of uncertainty provides important insights for understanding the potential for fossil peaking. We find that overall fossil fuel consumption—including for coal, natural gas, and oil—is *likely* (at least 67% probable) to peak this decade (Figure 15). If policy continues to evolve at its historical pace, the good news is that there is a greater than 50% chance that fossil demand peaks and declines by more than 20% by mid-century. At the same time, however, there is a 17% chance that fossil demand plateaus or even rises from today's levels through 2040.

This is not the end of the story, however. We find a greater than 83% chance that fossil fuel consumption plateaus after 2060, remaining stubbornly high at more than 60% of today's levels. There is a greater than 50% chance that fossil fuel consumption beings to rise again post-2060.

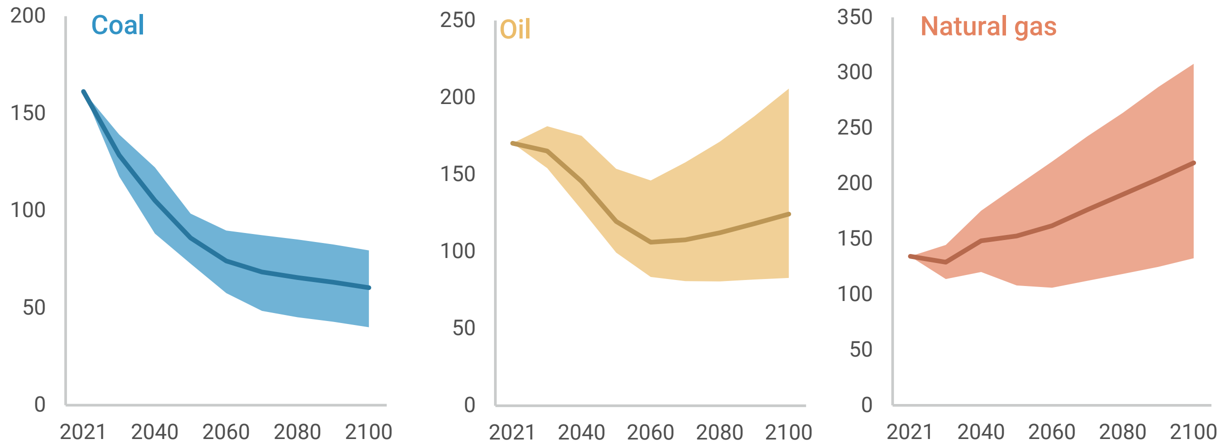
Looking deeper, the story differs significantly across fossil fuel types (Figure 16). In the good news category, there is a greater than 90% chance that coal consumption declines by more than one-third by 2050, driven by a precipitous decline in coal-fired electric power generation. Post-2050 this trend flattens out, however, with some persistent coal demand in power and steady demand from industry.

FIGURE 15
Global fossil fuel consumption
Quadrillion Btus, *very likely* and *likely* range, projection mean



Source: Rhodium Climate Outlook

FIGURE 16
Global fossil consumption by fuel
Quadrillion BTUs, *likely* range and projection mean



Source: Rhodium Climate Outlook

The story is more mixed for oil, as the progress in decarbonizing road transport *very likely* (greater than 90% chance) helps peak and then reduce oil demand through mid-century. Post-2050, as transportation demand rises and emissions intensity gains peter out absent additional innovation or policy ambition—coupled with growing demand for plastics—oil demand likely ticks up again. Oil consumption rises to about three-quarters of today's levels by the end of the century on average.

The outlook for natural gas is less mixed. There is a greater than 50% chance that global natural gas consumption rises from today's levels through the end of the century, and a greater than 80% chance it does not decline below today's levels. Because gas is less carbon-intensive than coal, less gets pushed out by renewables in the power sector, which means natural gas demand in the power sector rises 21% by 2050 and 77% by 2100 (projection mean). Meanwhile, demand for natural gas in the industrial sector is *very likely* to rise steadily throughout the rest of the century, *likely* rising 4-45% above today's levels by 2050 and 40-136% by 2100.

Agriculture and waste

Today, emissions from agriculture and waste total 8.6 gigatons of CO_2e, contributing 17% of global GHG emissions. The vast majority of emissions from these sectors comes from methane (60% of agriculture and 90% of waste emissions) (Figures 18 and 20). Over time, emissions from both sectors *likely* rise, driven by population and economic growth. In this version of the RCO, we do not model an evolution in policy in these sectors, due to lack of sufficient historical experience of mitigation policy measures across a sufficient cross-section of countries. As a result, our projections show the *likely* emission trajectory for agriculture and waste emissions absent additional policy to drive deployment of cost-effective solutions that exist today and innovation in new mitigation solutions to address the hardest-to-abate sources from agriculture and waste.

In agriculture—which includes emissions from livestock, crops, and fuel consumption[5]—we find that emissions *likely* rise 12% to 16% through mid-century, (Figure 17). The bulk of this emissions increase occurs in emerging economies that expect to see significant population growth, including Africa, India, Brazil and

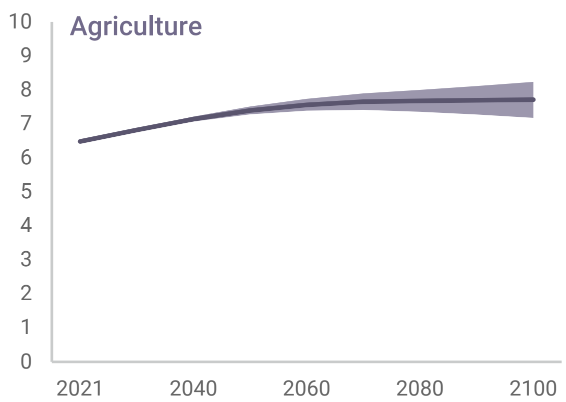
[5] Note: Emissions from agriculture exclude emissions from land use change. We include projected emissions and removals from forestry and other land use (FOLU) in our global emissions totals, but we do not model the potential range of possible FOLU outcomes. See the Technical Appendix for more details on how we treat FOLU.

other non-OECD countries in Asia. That momentum in emissions from agriculture *likely* levels off after 2070, where we see a 50% probability that emissions plateau or start to decline.

FIGURE 17

Agriculture emissions

Billion metric tons of CO_2e, *likely* range

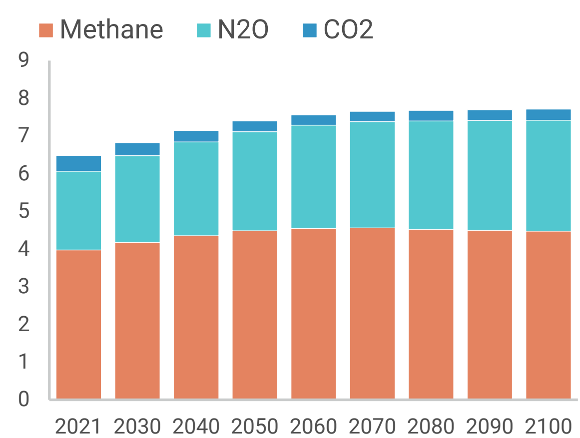


Source: Rhodium Climate Outlook

FIGURE 18

Agriculture emissions by gas

Billion metric tons of CO_2e, projection mean



Source: Rhodium Climate Outlook

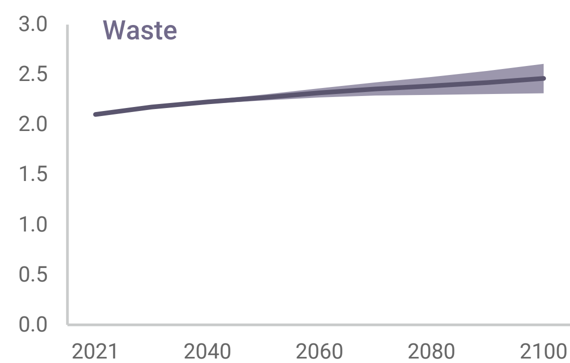
We find a similar trend in emissions from waste—including from landfills, wastewater treatment, and composting—with emissions *likely* rising 7% to 10% by mid-century and 10% to 24% by century's end (Figure 19).

Without additional policy and innovation to help scale affordable mitigation solutions for agriculture and waste, especially in regions that expect to see significant population growth, emissions from agriculture and waste become a growing share of global emissions. In our projection mean, emissions from agriculture and waste grow from 17% of the global total today to 23% in 2050.

FIGURE 19

Waste emissions

Billion metric tons of CO_2e, *likely* range

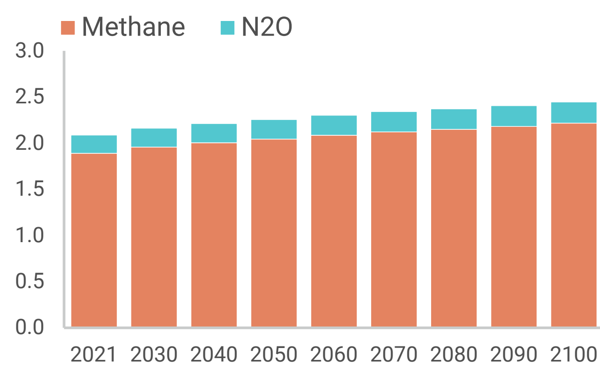


Source: Rhodium Climate Outlook

FIGURE 20

Waste emissions by gas

Billion metric tons of CO_2e, projection mean



Source: Rhodium Climate Outlook

CHAPTER 4

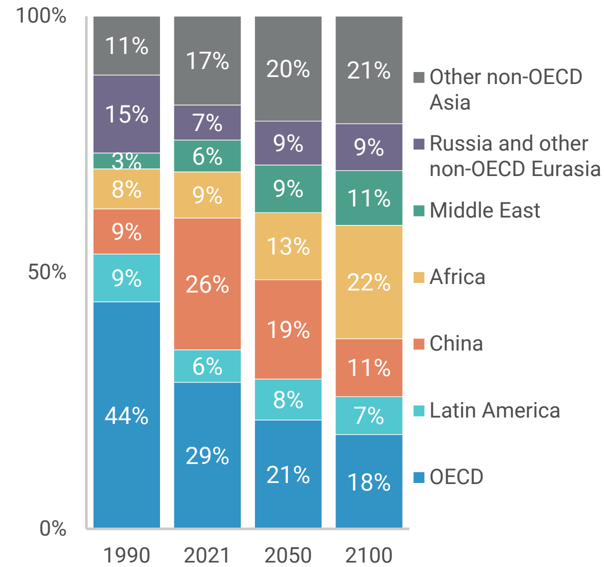
Regional Emission Dynamics

Due in large part to structural population and economic trends, the regional distribution of emissions in the coming decades will look very different than it does today. The developed world (here defined as countries that are members of the Organization for Economic Cooperation and Development or OECD) has long been a predominant source of global GHG emissions. In 1990, OECD emissions were nearly half of the global total, despite being home to only 20% of the global population. Since 2007, however, OECD emissions have been in decline, just as emissions in China have soared and emissions from India and other non-OECD countries in Asia have also risen steadily, leading to a much more distributed share of emissions across regions today (Figure 21). Looking ahead, emissions from today's largest emitters—OECD countries and China—are *very likely* to decline significantly through mid-century. OECD emissions likely plateau sooner, leveling off at around 3 gigatons higher than China by century's end in our projection mean (Figures 22 and 24).

FIGURE 21

Global emissions shares by region

Percent of global total, historical and projection mean

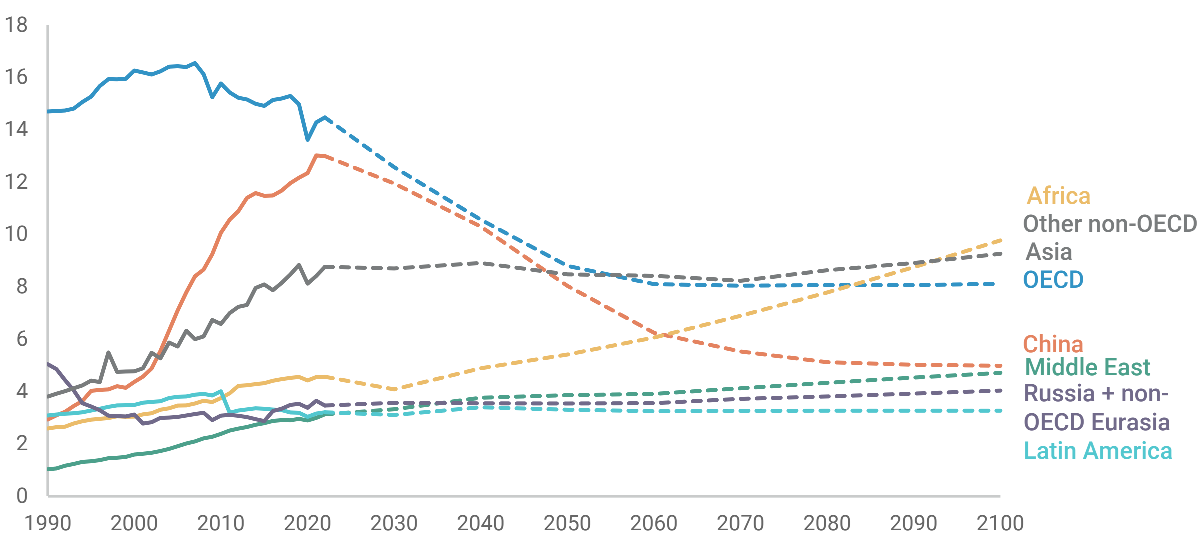


Source: Rhodium Climate Outlook, ClimateDeck

FIGURE 22

Mean global emissions by region

Billion tons of CO_2e

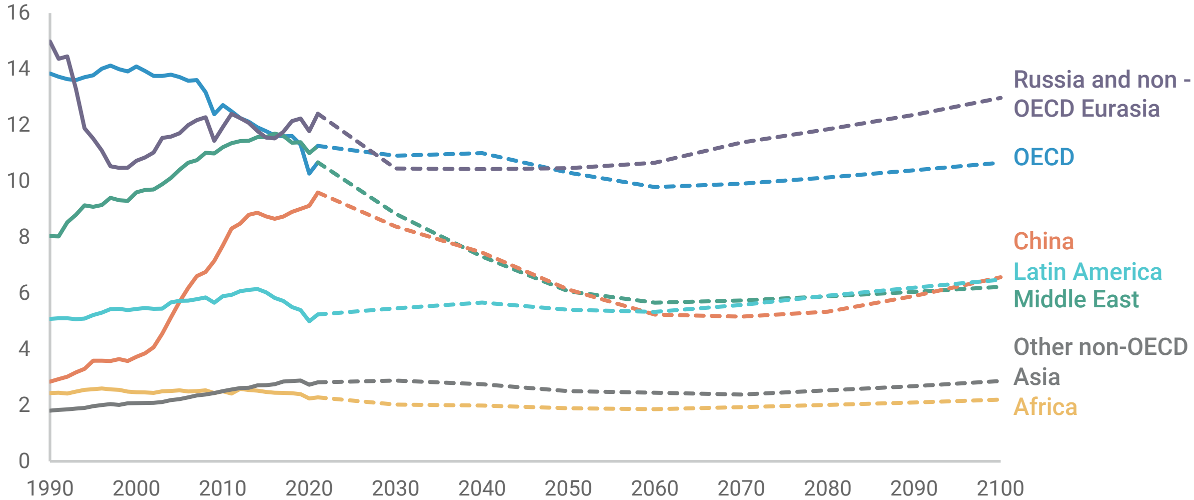


Source: Rhodium Climate Outlook, ClimateDeck

FIGURE 23

Per capita GHG emissions by region

Tons of CO_2e per capita, excludes emissions and removals from forestry and other land use



Source: Rhodium Climate Outlook, UNDP

The bulk of the growth in emissions over the next few decades *likely* comes from Africa, the Middle East, India, and other non-OECD countries in Asia, driven predominantly by economic growth. In the latter half of the century, emissions plateau in many regions—including OECD countries, China, India, and Latin America in our projection mean. But emissions continue to climb steadily across Russia and other non-OECD countries in Eurasia, Africa, the Middle East, and India and other non-OECD countries in Asia through century's end (Figure 24).

As a result, the share of global emissions becomes even more distributed across a wider range of regions than it is today. The share of global emissions produced by the two highest-emitting regions—OECD countries and China—drops from 55% today to 40% by 2050 and 29% by 2100 (Figure 21 – projection mean). Africa sees the most dramatic rise in its share of global emissions—from 9% today to 13% by 2050 and 22% by 2100 (projection mean). India and other non-OECD countries in Asia also see their share rise from 17% today to 21% by century's end.

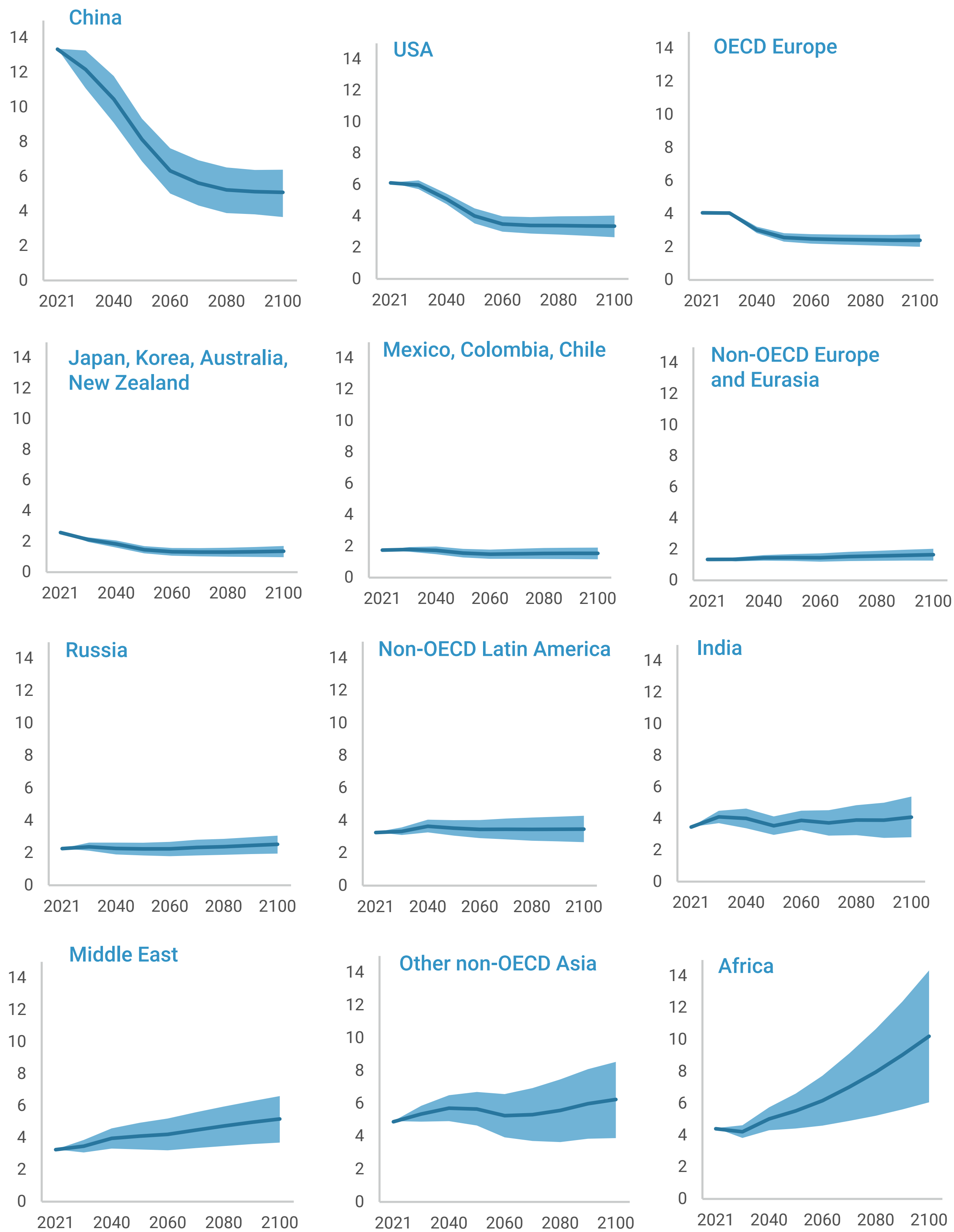
The distribution of emissions across regions masks a large disparity in per capita emissions that has persisted for decades. In the 1990s, regions' per capita emissions largely fell into one of two categories, with OECD countries, Russia & Eurasia, and the Middle East at relatively high levels (8 to 15 tons/capita), and the rest of the world (Asia, Africa, and Latin America) clustered together at much lower emissions per capita (2 to 5 tons). Over the past two decades, per capita emissions have fallen across OECD economies, from about 14 tons/capita to 10.7 today. At the same time, per capita emissions more than doubled in China, from 2.9 to 9.6 tons/capita, and rose markedly in the Middle East, Russia and Eurasia. Looking ahead, regional per capita emissions cluster together into three tiers in our median projection. At the highest level is the Middle East, Russia and other non-OECD countries in Eurasia at around 11-12 tons/capita. The middle tier consists of China, OECD countries, and Latin America, all converging around 6 tons/capita. Finally, per capita emissions in Africa, India and other non-OECD countries in Asia remain relatively low, at around 2 to 3 tons/capita.

In the next chapter, we assess the relative contribution of various drivers of emissions in our outlook. Key drivers—in particular the pace of economic growth—explain a good deal of the likely change in emissions across the regions of the world we highlight in this chapter.

FIGURE 24

GHG emissions by region

Million tons of CO_2e, *likely* range (67% chance)



Source: Rhodium Climate Outlook

CHAPTER 5

Unpacking Uncertainty

The outlook for the energy system and global emissions will be driven by the evolution of policy, economic, demographic, energy market, and behavioral factors – all of which are highly uncertain. The sensitivity of the climate to a given emissions future is also uncertain. We capture these unknowns through a Monte Carlo Analysis which produces fully probabilistic projections for energy market outcomes, emissions, and temperature rise. The ranges presented in this report reflect how evolution of these drivers, i.e. the known-unkowns, might affect emissions and temperatures through the end of the century.

While our our *likely* and *very likely* projected ranges are significantly more contained than the full suite of SSPs developed for the IPCC Sixth Assessment Report, our analysis highlights that the range of plausible emission outcomes given current policy and innovation trends is still quite large. The primary benefit of such a probabilistic approach to emissions and temperature projections is better planning and risk management: it allows decision-makers to assess their options against a full range of outcomes, ensuring the robustness of choices made to these uncertainties.

Another major benefit of our Monte Carlo simulation approach is it allows us to decompose the various contributions of uncertainty in temperature and emissions outcomes, to pinpoint which of these drivers matter most.

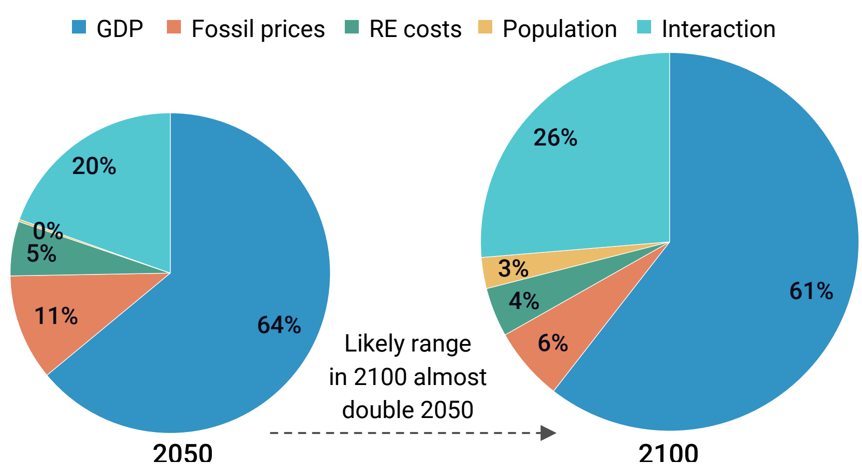
We find that 68% of uncertainty in global mean temperature rise in 2100 stems from climate sensitivity (i.e., the amount of warming resulting from a given increase in GHG concentrations in the atmosphere), while uncertainty in global emissions account for 23%. The remainder can be attributed to interactions between these sources of uncertainty in the model.

Within our emissions projections, economic growth, specifically GDP per capita, is the largest contributor to uncertainty. This reflects the high degree of uncertainty in long-term economic growth, particularly for emerging economies. Energy market factors are next, including fossil fuel prices and renewable generation costs. Population uncertainty has a negligible impact on emissions in 2050, but a larger contribution towards the end of the century.

FIGURE 20

Sources of global emissions uncertainty

Contribution to variance



Source: Rhodium Climate Outlook. Likely range is caluclated as one standard deviation of global emissions in 2050 and 2100.

In addition to the first order effect of each input on overall uncertainty, we also consider the interactions of these variables in the model. The combined contribution of these interactions across all uncertainties is large, reflecting the high degree of non-linearity in the energy system. Overall variance increases as uncertainties widen over time, and the likely range for global emissions doubles from 2050 to 2100 (Figure 20).

The focus of mitigation efforts is generally on policy and investments that create markets for low-carbon technologies. Our uncertainty decomposition analysis suggests that driving down the costs of clean technologies indeed contributes to reaching lower emission pathways. However, other contributors to global emissions uncertainty are not directly within the control of most decision-makers.

The pace of economic growth, as the largest contributor to uncertainty in global emissions, is not a policy lever in itself to achieve climate goals. The growth in global emissions post-2050 largely reflects economic development for billions of people in today's poorest nations. As such, a human welfare-centered approach for meeting our climate objectives should focus on rapid decoupling of emissions from economic growth. This includes the fast-paced deployment of mature clean technologies in emerging economies, in order to avoid detrimental carbon-intensive technology lock-ins along their development pathways. But, as our results in previous sections show, this decoupling of emissions and economic growth will also depend on an acceleration in the pace of policy and innovation in sectors considered hard-to-abate—industry, maritime transport, aviation—in developed and developing economies alike.

Conclusion

In this inaugural edition of the Rhodium Climate Outlook, we hope to provide a bit more nuance to the question "what are we on track for?" so that a much wider array of stakeholders—including policy-takers—can make more informed decisions about what must be done to achieve global decarbonization.

We find that while we have successfully avoided the most catastrophic temperature rise projected just a decade ago, we are *very unlikely* to be on track for keeping temperature rise below 2°C, absent accelerated policy and innovation. Despite significant progress decarbonizing power and road transport, we see diminishing returns unless accelerated policy helps make mature technologies available to all regions of the world and additional innovation helps deliver solutions that can meet the growing demand that results from widespread economic growth. Addressing the rise of industrial emissions will also require significant additional policy and innovation to bring emerging clean technologies to market and bring their costs down sufficiently to be cost-competitive with their fossil counterparts in all regions of the world.

Each year, the Rhodium Climate Outlook will provide an updated look at what the world is on track for given a wide range of developments that impact our key variables. As we narrow down uncertainty, add emerging technologies that have reached sufficient maturity, and incorporate new policies as they become adopted, we hope to see the outlook for global emissions and temperature rise improve. In the years ahead, the RCO will be an important barometer to assess what really matters, where the world must focus, and how our efforts are paying off.

For more information about accessing all the rich, underlying data from the RCO, jump to the next section on our free ClimateDeck data visualization platform.

About this Report

About Rhodium Group

Rhodium Group is an independent research provider combining economic data and policy insight to analyze global trends. Rhodium's Energy & Climate team analyzes the market impact of energy and climate policy and the economic risks of global climate change. This interdisciplinary group of policy experts, economic analysts, energy modelers, data engineers, and climate scientists supports decision-makers in the public, financial services, corporate, philanthropic and nonprofit sectors. More information is available at www.rhg.com.

The ClimateDeck

The ClimateDeck—a partnership of Rhodium Group and Breakthrough Energy—is an interactive data visualization platform that provides global and US 50-state greenhouse gas (GHG) emissions inventory data and projections, energy market outlooks, and analysis of energy and climate policy developments. The ClimateDeck equips users with comprehensive datasets, unique and responsive insights, and a robust set of tools for tracking pathways to climate targets and understanding the emissions and economic implications of major developments at the international, national, and state levels.

Data Platform

All of the underlying data from the Rhodium Climate Outlook is available to explore and download for free from the ClimateDeck. This data visualization platform enables users to explore datasets through user-friendly visualizations and tailor them to different scenarios and comparisons by adjusting inputs such as timeframe, geography, sector, gas and uncertainty ranges. The adjustable datasets can be exported as production-ready visualizations and as CSV files. Users are encouraged to integrate ClimateDeck data in their own analysis and external publications, with attribution to Rhodium Group.

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Disclosures

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