Pathways to Net-Zero: US Emissions Beyond 2030

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Over the last two years, the US has made historic investments in climate progress, and federal regulations and state policies have helped bend the projected greenhouse gas emissions curve further down. Additional policies could help put the US's target under the Paris Agreement within reach, to cut emissions by 50-52% below 2005 levels by 2030. However, there's a long way to go to get on track for achieving net-zero emissions by 2050. The emissions that remain in 2030, assuming the US reaches its Paris target, will almost certainly be more difficult to eliminate than the emissions abated through 2030. Much of the remaining emissions will come from sectors that have been less of a focus to date.

In this note, we revisit our 2023 updated Pathways to Paris scenarios, in which the Infrastructure Investment and Jobs Act plus the Inflation Reduction Act, as well as additional ambitious federal and state policies, reduce emissions to 41-52% below 2005 levels in 2030, and explore the sources of remaining emissions at the end of this decade. We identify the key emitting subsectors and the specific underlying emissions drivers within each, and we provide high-level decarbonization solutions that could address these drivers. Light-duty vehicles, the power sector, and residential and commercial buildings remain the top emitting sectors in 2030, despite some decarbonization gains, while other sources like freight trucks, chemical production, and natural gas systems increase their overall share of emissions contributions.

Cutting these remaining emissions will be challenging, but we find that a substantial fraction of emissions can be tackled using existing and widely available decarbonization solutions. Common areas of decarbonization focus across subsectors include increasing electrification, the use of low-carbon fuels and other sources of clean heat, improving energy efficiency, and use of point-source carbon capture. Additional policies will certainly be required to reduce these emissions, and future Rhodium Group work will identify sets of policies that can do just that.

Reaching the 2030 climate target

Climate policymaking has made huge strides over the past two years with the passage of the Inflation Reduction Act and the Infrastructure Investment and Jobs Act, progress on federal greenhouse gas (GHG) regulations, and the enactment of more ambitious state climate policies and targets. Under current policy, we estimate the US will reduce emissions to 29-42% below 2005 levels in 2030—a meaningful decline, but still not enough to meet the Paris Agreement target of a 50-52% reduction in 2030 (Figure 1).

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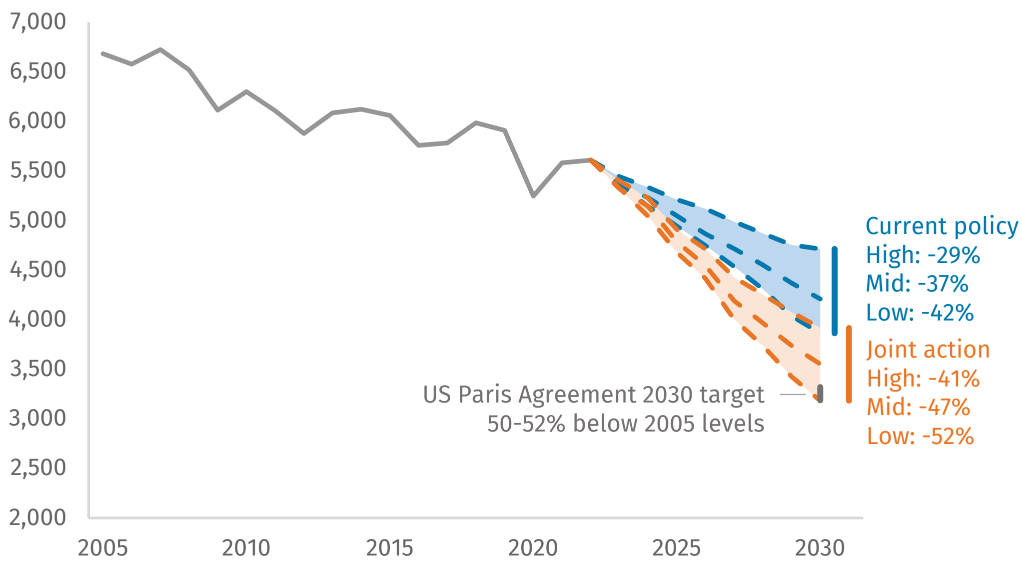
FIGURE 1

US net greenhouse gas emissions under joint action

Net million metric tons (MMT) of CO_2e



Source: Rhodium Group. The high, mid, and low ranges reflect uncertainty around future fossil fuel prices, economic growth, and clean energy technology costs.

As part of our recent Taking Stock 2023 report, we estimated the impacts of a suite of policy actions across all levels of government that could put the 2030 Paris target within reach. We found the policies in this "joint action" scenario could put the US on course to achieve a 41-52% reduction in emissions from 2005 levels in 2030—a further 10-12 percentage point reduction from the emissions trajectory under current policy on the books (Figure 1). The range in emissions outcomes reflects modeling the policies under three emissions cases—high, mid, and low—capturing sensitivities in macroeconomic growth, clean technology cost, and oil and gas price uncertainty.

The joint action scenario assumes both federal regulatory action and state climate policy ambition ramp up dramatically. Federal action includes EPA's adoption of its recently finalized oil and gas methane regulations and currently proposed power sector and light-duty vehicle (LDV) greenhouse gas pollution regulations, as well as tightened regulations of mercury emissions and medium- and heavy-duty vehicles GHG emissions. On the state side, climate-leading states establish and accelerate 100% clean energy and clean vehicle targets and enact policies to reduce energy consumption through increasing efficiency and reducing carbon intensity. The full list of policies modeled in the joint action scenario is available in the Taking Stock 2023 technical appendix, as well as further explanation of our high, mid, and low emissions cases.

Note that, consistent with EPA and IPCC conventions, we report all emissions in this note using 100-year global warming potential (GWP) values for non-CO_2 greenhouse gases from the Fifth Assessment Report.

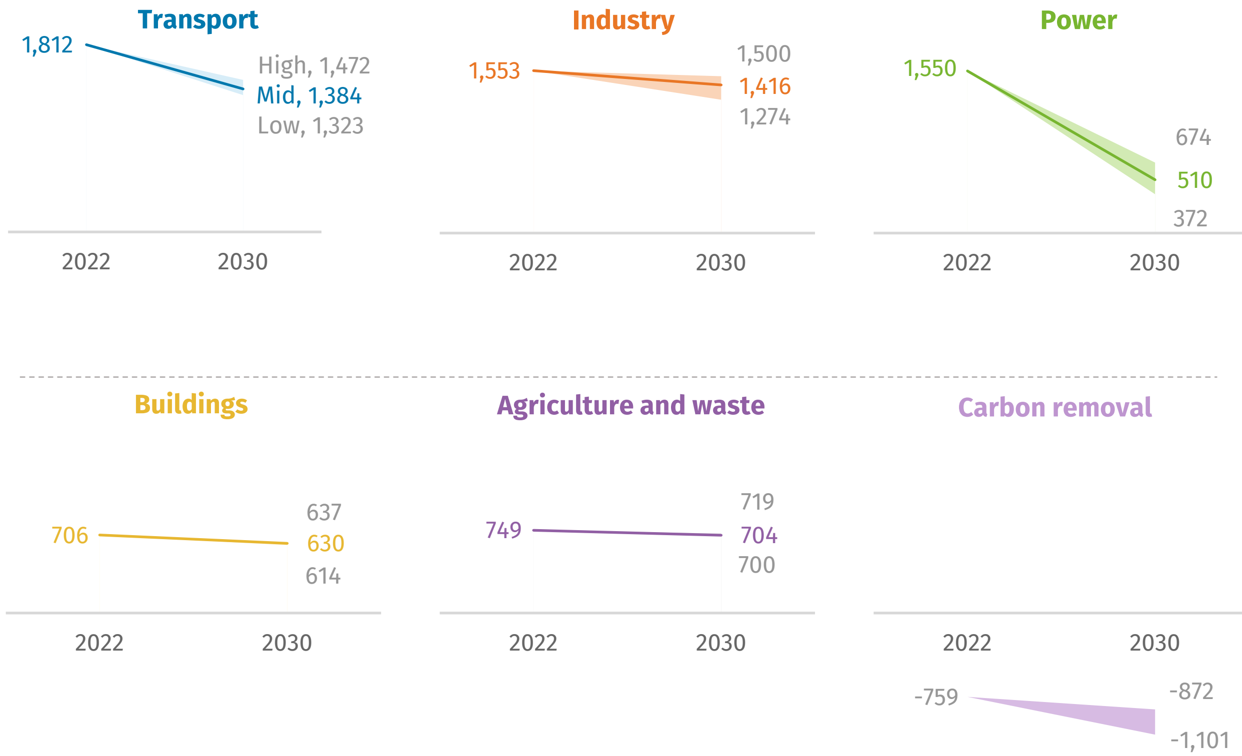
Achieving the 2030 Paris target will require unprecedented levels of policy ambition and historic levels of change to the energy system. And even if the US is able to rise to the 2030 challenge, there is still a yawning gap between emissions levels in 2030 and net-zero emissions in 2050. Policymakers have largely been focused on actions that drive deployment of commercially available clean technologies in the power sector and the light-duty vehicle fleet—and we see meaningful progress in decarbonizing those parts of the economy by 2030. But there remain a host of other, high-emitting sectors that today have fewer and more challenging decarbonization solutions.

In this note, we characterize what emissions remain in 2030 assuming, in the best-case scenario, that the US reaches its 2030 Paris climate target of a 50-52% reduction in emissions below 2005 levels. We also provide short overviews of the kinds of decarbonization solutions available to address these remaining emissions. We don't assess specific policies that could drive changes in the energy system in this note, but we plan to focus on the policy side of this decarbonization equation in work we'll publish later this year. That said, the policies that get the

FIGURE 2

2030 US greenhouse gas emissions under a joint action scenario

Net million metric tons of CO_2e



Source: Rhodium Group. The high, mid, and low ranges reflect uncertainty around future fossil fuel prices, economic growth, and clean energy technology costs.

US within reach of the 2030 target and the sectors in which the US makes the most progress won't be the same policies and sectors that can maintain and accelerate this momentum after 2030.

Sources of remaining emissions

The emissions landscape in 2030 under our joint action scenario looks meaningfully different than it does today (Figure 2). The power sector reduces its emissions by 56-76% below 2022 levels and becomes the least or second-least emitting major sector. The transport sector also declines meaningfully, by 19-27% below 2022 levels, but remains one of the two highest-emitting sectors in all cases. Industrial sector emissions, inclusive of emissions from oil and gas production, decline even less, by 3-18% over 2022 levels in 2030, and industry overtakes transport as the highest-emitting sector in our mid and high emissions scenarios. Emissions from residential and commercial buildings and from agriculture and waste remain largely untouched.

Though a sectoral understanding of emissions is useful, looking one layer deeper can be even more informative. Sectors are diverse, and the same decarbonization solutions that work for petrochemical production or light-duty vehicles may not be as effective when applied to cement production or heavy-duty vehicles.

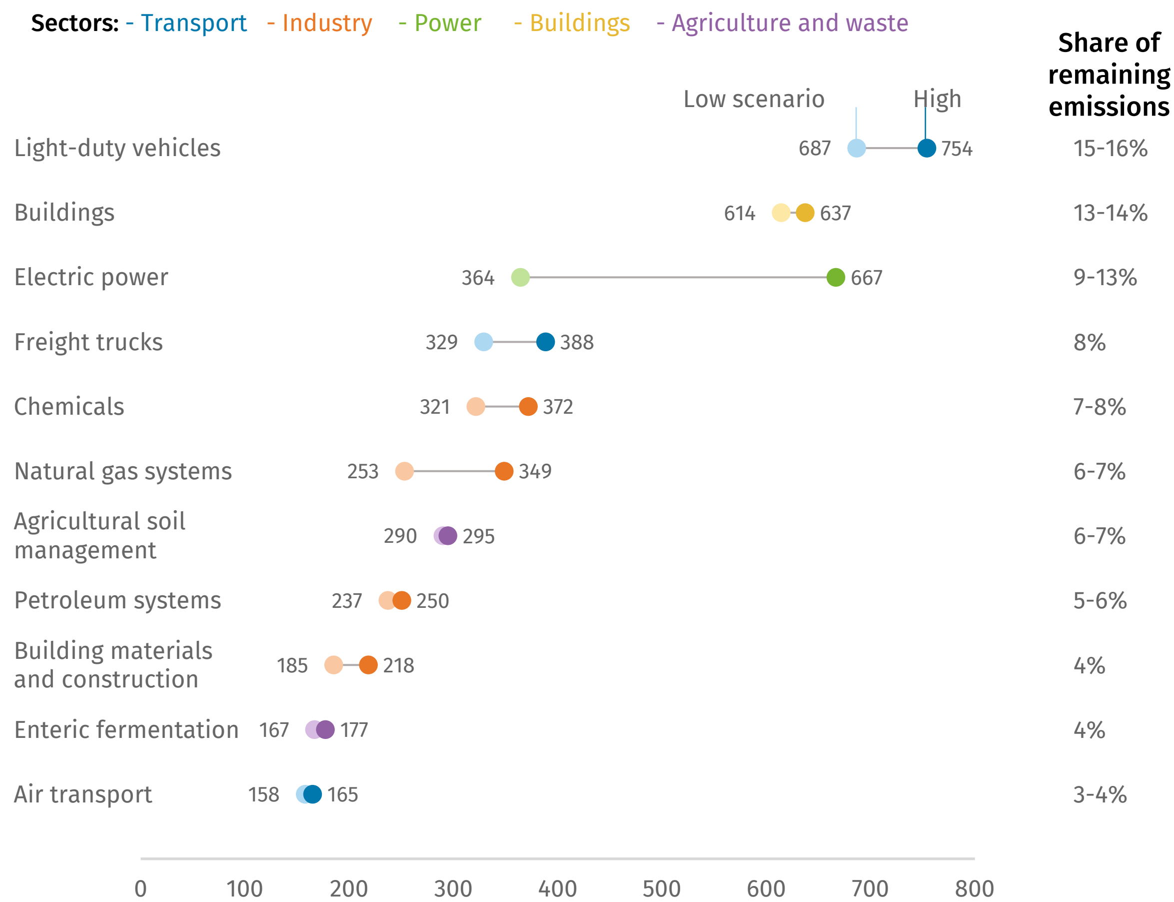
For the remainder of this note, we group emissions into more granular subsectors, and we find that the top-emitting eleven subsectors are responsible for 84-85% of total remaining gross emissions[1] in 2030 (Figure 3). We provide a breakdown of the remaining 15-16% of emissions in the appendix to this note.

[1] Throughout this report, we use gross emissions to refer to total emissions less a modest amount of technological carbon dioxide removal from direct air capture and ethanol facilities with CCS. We also model uptake of point-source carbon capture on key industrial sources and account for that abatement in the appropriate subsector.

FIGURE 3

2030 US greenhouse gas emissions in top-emitting subsectors under a joint action scenario

Gross million metric tons of CO_2e



Source: Rhodium Group. The range of each bar spans our low emissions and high emissions scenarios. Colors denote sectors (transport, industry, power, buildings, and agriculture & waste). The range in power emissions does not align with the range reported in Figure 2, because we break out power and transport emissions from US territories into its own subsector. See the appendix for more information.

The big three

The three highest-emitting parts of the economy[2] in 2030 are familiar: tailpipe emissions from light-duty vehicles (LDVs), direct emissions from using fossil fuels in buildings, and emissions from fossil-fired power plants (Figure 3). We find that these remain the most important in terms of total emissions to eliminate even after the US achieves its 2030 climate target, emitting about 40% of total remaining emissions in 2030.

One of the reasons that these high emitters remain the top three is the challenge of slow stock turnover—a common theme we'll return to across much of this note. In short, the equipment that consumers and businesses purchase tends to be long-lived in these sectors. The average light-duty vehicle on the road today is 12 years old, furnaces in buildings are expected to last 15-20 years, and large power plants often have multi-decade lifespans. As such, policymakers have limited chances to influence the purchase of lower-emitting technologies, and it takes a long time for high levels of sales of these technologies to propagate across the entire equipment stock. Put another way, if the US reaches 100% of electric LDV sales in 2030, it won't be until the early to mid-2040s that the entire LDV fleet is fully electrified.

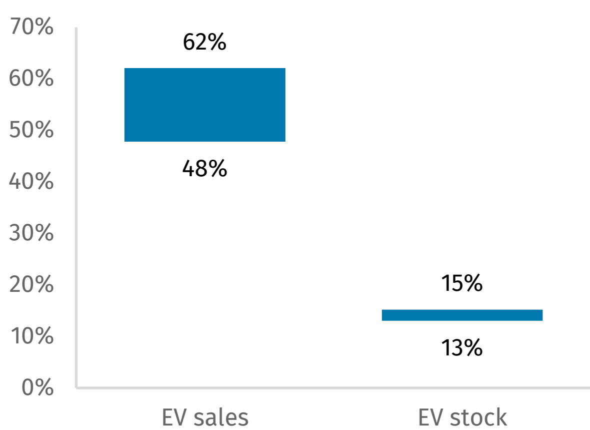
[2] Two of these high emitters – buildings and power – are major sectors. We group residential and commercial subsectors together because their emissions come from similar sources and, consequently, they have similar policy implications. Likewise, from a policy perspective, there isn't a clear and meaningful way to break down the power sector into subsectors.

Continued attention to LDVs, buildings, and power is necessary to achieve high levels of adoption of lower-emitting technologies, and further policy action could help accelerate stock turnover. Fortunately, increasing the share of electric vehicles (EVs) in the light-duty fleet, improving building electrification and appliance efficiency, and deploying zero-emitting power generators in the power sector have recently been core goals for policymakers and environmental NGOs, and the policy environment is favorable for continued increased adoption in these sectors. We unpack these sectors individually in the following pages.

Light-duty vehicles
687-754 MMT in 2030, 15-16% of remaining emissions

LDVs are the largest source of remaining emissions in 2030, despite meaningfully lower emissions from the subsector. Today, LDV emissions have declined by 11% from 2005 levels, driven in large part by fuel economy gains. That decline accelerates the historic pace by at least a factor of 4 through 2030 due to substantial increases in EV adoption, and LDV emissions reach 32-38% below 2005 levels in 2030. This decline is increasingly a function of penetration of EVs: EV sales shares of total vehicle sales rise from 8% today to 48-62% in 2030. Despite the large-scale deployment of EVs, internal combustion engine (ICE) vehicles still comprise 85-87% of all vehicles on the road in 2030 (Figure 4), equating to 226-244 million emitting vehicles that must be replaced with EVs or fueled with low-carbon fuels if the US is going to achieve net-zero emissions.

FIGURE 4
2030 LDV electric vehicle sales and stock shares
Percent share of total vehicles



Source: Rhodium Group

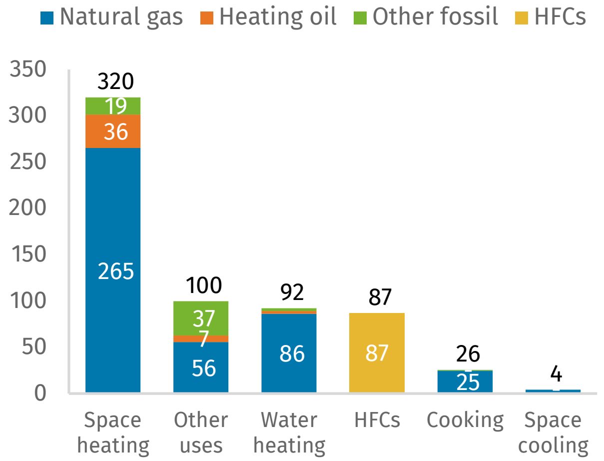
Achieving deep levels of decarbonization in the LDV fleet will likely require several approaches. First, EV sales must continue to accelerate such that the US achieves fully net-zero vehicle sales as rapidly as possible. Second, given the stock turnover issue identified above, accelerated retirement of existing ICE LDVs may also be warranted. At the same time, there will remain a large fleet of ICE vehicles on the road during the EV transition, and there may be a future need for some amount of liquid fuels for the LDV fleet as well. Cleanly produced biofuels, electrofuels and other drop-in fuels can help reduce emissions by displacing the consumption of fossil liquid fuels. Policies that reduce vehicle miles traveled, like expanded development of public transit infrastructure, can also help reduce emissions from LDVs.

Buildings
614-637 MMT in 2030, 13-14% of remaining emissions

Taken together, residential and commercial buildings are the second highest emitters in 2030 in two out of our three emissions scenarios, highlighting the continued challenges in decarbonizing buildings. Note that these are only direct emissions coming from the use of fossil fuels and HFCs in buildings and do not account for electricity use. Building emissions today are 16% higher than 2005 levels due to increasing use of HFCs in place of ozone-depleting substances following the Montreal Protocol and the Clean Air Act Amendments of 1990. Commercial refrigeration and residential air conditioning are the primary sources of HFCs in buildings and drive the increase in buildings emissions from 2005 to today. Though we find that aggressive energy efficiency measures and appliance standards, as well as EPA's rule to phasedown HFCs, can reverse this trend and start driving building emissions down, 2030 emissions are still 1%-5% higher than 2005 levels across our scenarios.

Space heating drives about half of these emissions (Figure 5), and it's responsible for an even greater share of residential sector emissions alone (~70%). In 2030, there are more than 80 million fossil-fueled space heating systems operating across the residential sector. Slow stock turnover is a significant barrier to space heating decarbonization. Even though millions of electric heat pumps deploy through 2030, only 5% of total space heating equipment stock gets replaced each year and an additional 1% comes from equipment deployed in new residential buildings. Water heating is the next highest emitting end use and faces similar stock turnover barriers, and the rest of emissions are spread over several end uses.

FIGURE 5
2030 direct emissions from buildings by end use, mid-emissions case
Million metric tons of CO_2e

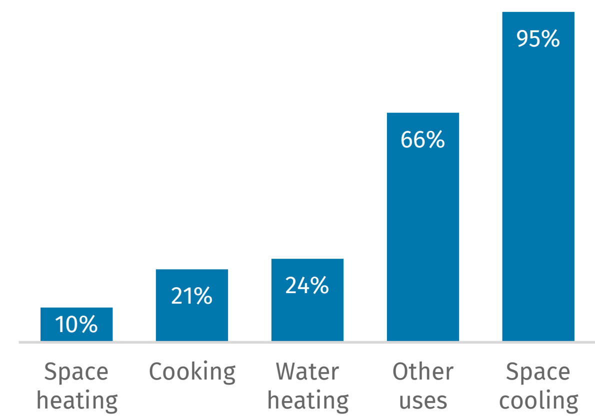


Source: Rhodium Group. "Other fossil" includes propane, residual fuel oil, motor gasoline, kerosene, and coal. "Other uses" includes end uses such as clothes dryers and electric generators.

There's a lot of headroom for electrification in buildings, with only 10% of total building fuel consumption for space heating coming from electricity (Figure 6). Heat pumps for space heating, space cooling, and water heating are available and cost competitive today, though they face non-cost barriers to deployment like split incentives between renters and building owners, contractor or installer lack of familiarity, and lack of cost-optimizing decision making in emergency replacement decisions. Overcoming these barriers and increasing deployment of heat pumps for space and water heating in new and existing buildings in all parts of the country will go a long way towards decarbonizing this sector. Other, smaller prizes also exist in the electrification space, like a transition to electrified cooking.

Beyond electrification, improving building shell efficiency in new and existing buildings will also reduce the energy required for space heating and cooling, and improving the efficiency of appliances can also lower overall energy demand. In light of some concerns about the viability and cost-effectiveness of achieving 100% electrification in buildings, especially in colder climates, some analyses have posed alternative decarbonization scenarios that rely on lower-carbon gaseous fuels like hydrogen and renewable natural gas for space heating in addition to high electrification rates.

FIGURE 6
2030 buildings electric share of fuel consumption by end use, mid-emissions case
Percent



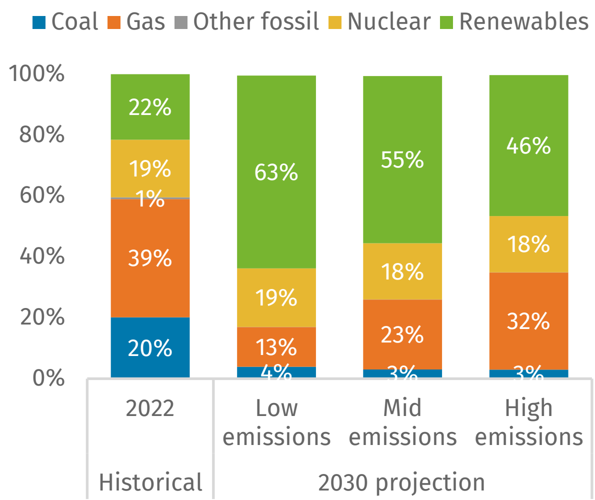
Source: Rhodium Group. "Other uses" includes end uses such as clothes dryers and electric generators.

Power
364-667 MMT in 2030, 9-13% of remaining emissions

While the power sector is the third highest-emitting sector in 2030 in two out of our three emissions scenarios, it's also the sector that has made the most decarbonization progress to date by far and the sector contributing the most to economy-wide emissions abatement in our projections. Today's emissions are down 36% from 2005 levels, and the pace of decarbonization accelerates two to three times over historic levels across our scenarios: even in our high emissions case, 2030 emissions are reduced by more than half relative to today's.

In the last decade, these emissions declines have been driven primarily by cheap natural gas outcompeting and replacing coal as a generating fuel. In our projections, renewables increasingly displace coal-powered generation and begin to displace natural gas generation (Figure 7). Achieving the highest level of emission reductions in the power sector in our modeling requires an unprecedented build-out of clean generating capacity and the grid, which may require additional policy action to overcome current headwinds like supply chain limitations, siting challenges, permitting delays, and crowded interconnection queues.

FIGURE 7
2030 power generation shares by fuel type
Percent of total generation



Source: Rhodium Group

Several key decarbonization solutions must combine to drive power sector emissions to zero as quickly as possible. Uncontrolled fossil generators need to be increasingly retired, and generation from those generators must be replaced with zero-emitting sources. This means both historic growth in deployment of widely available technologies like wind and solar as well as growth in clean, dispatchable or baseload generators like enhanced geothermal and advanced nuclear. Energy storage and flexible load shifting will also be crucial to integrating increasingly large shares of variable renewables onto the grid. Retrofitting fossil plants with carbon capture or the ability to blend large amounts of hydrogen as a fuel can also serve an important transition role.

Decarbonizing the power sector is key to unlocking decarbonization in many other sectors that have electrification options like LDVs and buildings. Electricity demand will increase with more electric vehicles on the road and more heat pumps in homes and commercial buildings, further amplifying the necessity and challenges of driving the power sector to zero emissions.

Other top-emitting subsectors

Beyond light-duty vehicles, buildings, and the power sector, a diverse range of subsectors contribute to the other half of emissions in 2030.

Freight trucks
329-388 MMT in 2030, 8% of remaining emissions

Freight truck emissions have been relatively flat over the past two decades with fuel economy improvements balancing increasing ton-miles traveled. Today's freight truck emissions are 6% higher than 2005 levels. In our modeling, deployment of zero-emitting freight vehicles (ZEV), with ZEV sales shares reaching 18-30%, bends the curve and drives emissions down 12-25% below 2005 levels in 2030.

Like LDVs, freight trucks face a stock turnover challenge. Despite the ambitious scale up in ZEV vehicles, 30-32 million ICE freight vehicles remain on the road in 2030 (Table 1). Heavy-duty vehicles, which have substantially lower fuel efficiency than medium-duty vehicles (MDVs) and drive more than double the distance of MDVs on average each year, contribute 62% of remaining freight emissions.

TABLE 1
2030 freight truck statistics
Millions of vehicles, vehicle-miles traveled (VMT) per vehicle

Vehicle class	ICE sales share	ICE stock share	Annual VMT per vehicle
Commercial light (Class 2b)	70-83% (0.5-0.6M)	95-97% (15-16M)	6,900-7,200
Light-medium (Class 3)	70-83% (0.2-0.3M)	94-96% (6M)	13,500-14,500
Medium (Class 4-6)	63-79% (0.1-0.2M)	93-96% (4M)	14,400-15,400
Heavy (Class 7-8)	72-83% (0.2M)	95-97% (6M)	30,400-33,400

Source: Rhodium Group

Continued deployment of ZEV freight vehicles is a vital step towards decarbonizing the subsector. However, electrifying long-haul trucks poses both logistical and technical challenges, and short-haul trucks that can charge their batteries overnight may be better suited for electrification. For those vehicles less conducive to electrification, low-carbon drop-in fuels like electrofuels and biofuels offer an alternate decarbonization solution. Hydrogen fuel cell vehicles are an additional option for long-haul heavy trucking. Finally, switching to more efficient modes of transportation, like freight trains, can also help decarbonize this subsector.

Chemicals
321-372 MMT in 2030, 7-8% of remaining emissions

Emissions from chemicals production are the fifth largest source of emissions in 2030, at 321-372 MMT. Today, chemicals emissions are 6% higher than in 2005 due to increased demand for chemical products and the increased domestic availability of inexpensive natural gas as a feedstock. More than half of current emissions come from the production of basic organic chemicals (like ethylene oxide), petrochemicals (like ethylene and benzene), and fertilizers (like ammonia and urea). Looking at chemicals production as a whole in 2030, we project that more than half of emissions are process CO_2 emissions. These are CO_2 emissions that come from reactions in various chemical synthesis processes as opposed to the combustion of fossil fuels. Given that some of these reactions required to convert feedstocks into chemical products result in CO_2 emissions, capturing and storing these process emissions will likely be an important pathway for emissions abatement. Substituting sustainable biomass- or clean hydrogen-derived feedstocks for those derived from fossil fuels can also play a role.

The other main source of chemical production emissions is CO_2 from combustion, mainly owing to the use of fossil fuels for on-site electricity and heat production. Combustion CO_2 can be addressed through the decarbonization of heat and power production, especially through electrification of industrial heat, as well as increased energy efficiency and targeted use of clean fuels.

Beyond decarbonizing process and combustion emissions, cross-cutting solutions that focus on reducing or avoiding demand for chemical products can also play a role in reducing emissions from the chemical sector. These solutions include measures that reduce the use of single-use plastics, increase rates of plastic recycling, or encourage more efficient fertilizer use.

Natural gas systems
253-349 MMT in 2030, 6-7% of remaining emissions

We define natural gas system emissions as those from leaking, venting, and flaring of methane and CO_2 associated with the production, processing, transmission, distribution, storage, and export of natural gas, as well as emissions from the combustion of fuels to produce heat and electricity for these processes.[3] Natural gas system emissions have increased by 17% from 2005 to today, while US dry natural gas production has more than doubled and domestic gas consumption has increased by 50% as new markets (especially in the power sector) shifted from coal to gas as the predominant fuel.

Operational changes, adoption of new equipment, increasing use of new infrastructure, and a shift in production to more productive wells have limited growth in these emissions while the US experienced the shale boom. Compressor stations that power natural gas pipelines are the main driver of this increase. CO_2 emissions have also risen from increased flaring, but this change has also resulted in lower fugitive methane emissions, as some methane that was leaking or being vented is instead being flared.

In our projections, EPA oil and gas methane regulations drive down methane and CO_2 emissions from leaking, venting, and flaring. Declining natural gas production in our low emissions scenario further drives down fugitive emissions. Emissions from liquid natural gas (LNG) export processing facilities rise as LNG exports increase 58-79% by 2030 relative to today. Emissions from generating heat and power at well, field, and lease operations rise and fall with natural gas production, which increases, decreases, and remains flat in our high, low, and mid emissions scenarios, respectively. Pipeline heat and power emissions track economy-wide natural gas demand. Altogether, 2030 natural gas systems emissions are effectively flat to as much as 25% lower than 2005 levels (Figure 8).

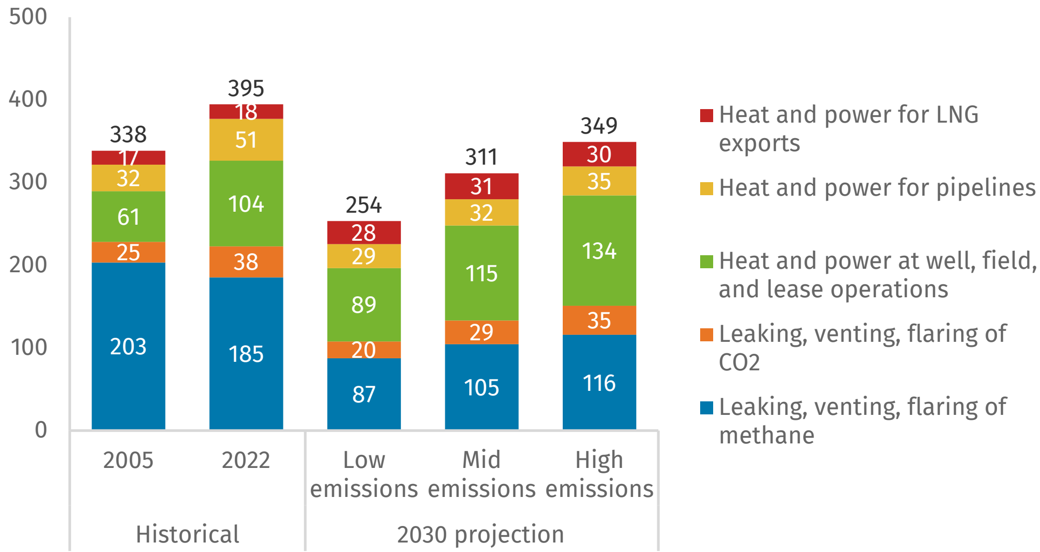
Nearly half of remaining natural gas systems emissions can be addressed by further minimizing methane leaks and further reducing flaring and venting. We reflect important progress on these fronts in the joint action scenario by including recently finalized EPA regulations on oil and gas operations—but requiring installation of new equipment and improving operational practices at a wider range of facilities can further drive these emissions down. Replacing gas-powered compressors and other gas-powered equipment with electric alternatives can reduce emissions from generating heat and power in this subsector. There are also limited opportunities for point-source carbon capture within natural gas systems, particularly at natural gas processing facilities with high-CO_2-purity flue gas streams.

[3] This is a broader definition of natural gas-related emissions than included in the "natural gas systems" category of EPA's annual emissions inventory.

FIGURE 8

Natural gas systems emissions by category and gas

Million metric tons of CO_2e



Source: Rhodium Group

As other sectors decarbonize through electrification, efficiency gains, and clean fuels, domestic demand for natural gas will decrease. This alone will drive emissions down substantially, though without further climate action, the US will very likely continue producing natural gas at lower levels to meet international demand and provide fuel for harder-to-abate sectors and technologies with carbon capture.

Agricultural soil management
290-295 MMT in 2030, 6-7% remaining emissions

Agricultural soil management, which includes both crop and livestock grazing land management, captures activities like fertilizer application and irrigation that increase nitrogen availability and influence the form it takes (e.g. through mineralization and fixation). Microbes then convert this nitrogen to nitrous oxide (N_2O). Agricultural soil management is both the highest emitting agriculture-related subsector and the highest emitter of N_2O in the US. Emissions from agricultural soils have generally stayed constant, with variability in some years, from 2005 to today, and we project continued flat emissions moving forward. High levels of bioenergy production, a potential decarbonization solution for other sectors, may also increase agricultural soil emissions, though we don't capture that dynamic here.

Decarbonization solutions for agricultural soils are currently limited and expensive, and, in some cases, their effectiveness may depend on the site-specific conditions. Improving the efficiency of fertilizer use is the main mitigation strategy cited across decarbonization studies. This strategy includes options like precision agriculture and nitrification inhibitors which involve applying appropriate amounts of water and fertilizer to crops and ensuring that the nitrogen stays in the form required for plant uptake. Other crop management practices like no tillage or reduced tillage, diversified crop rotation, and implementation of cover crops may reduce N2O emissions, but the effect likely depends on soil characteristics and climate. However, all these interventions reduce only a fraction of total N_2O emissions since some amount of fertilizer is still being used.

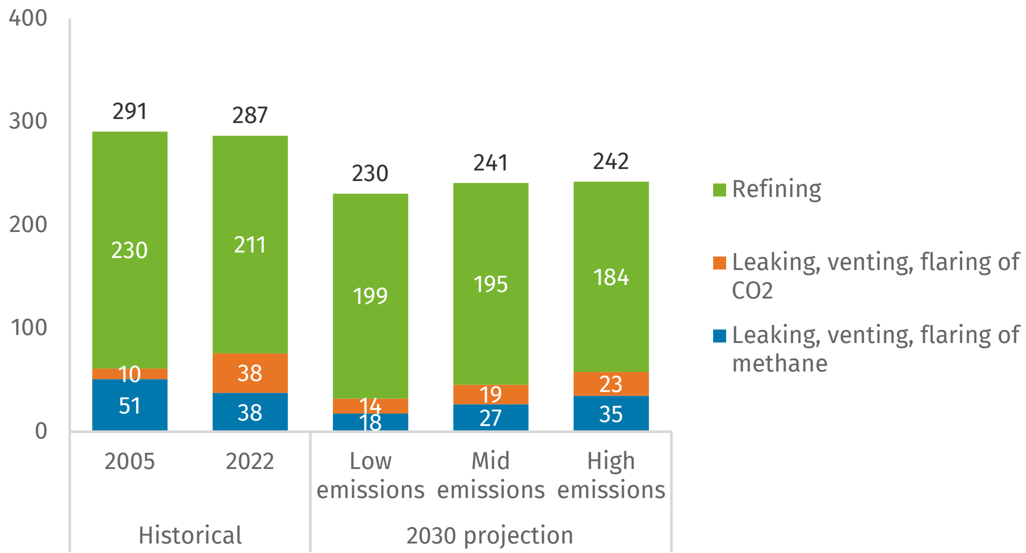
Petroleum systems
237-250 MMT in 2030, 5-6% of remaining emissions

Petroleum systems emissions, defined as leaking, venting, and flaring of methane and CO_2 associated with the exploration, production, transportation, and refining of crude oil as well as emissions from the combustion of fuels to produce heat and electricity for these processes, have

FIGURE 9

Petroleum systems emissions by category and gas

Million metric tons of CO_2e



Source: Rhodium Group

held mostly constant since 2005.[4] There are some similarities with natural gas systems: domestic production has increased by 140% since 2005, and emissions associated with oil production have increased by 40%. Like with natural gas, the increase in production emissions has been held down in recent years by an increase in flaring.

A key difference with natural gas is that, while domestic gas consumption has increased by 50% since 2005, domestic petroleum consumption has actually decreased by around 2% over the same period. Domestic production is displacing petroleum imports (largely crude oil), which are down 40% since 2005, as well as contributing to a growing US export trade of hydrocarbon liquids and refined products, which have increased by more than nine times. As a result, refinery and blender production has only increased by around 10%, and emissions from refineries are down 9% over the same period owing to process and efficiency improvements.

In our projections, petroleum systems emissions fall 17-21% below 2005 levels. EPA regulations drive reductions in leaking, venting, and flaring of methane and CO_2, and refinery emissions generally decrease to varying degrees depending on other energy sector dynamics.

While CO_2 and methane from leaking, venting, and flaring remain in 2030 across all scenarios and can be addressed using the same strategies outlined in the natural gas systems section, over 70% of remaining emissions comes from the energy consumed during refining operations (Figure 9). Electrification of some equipment is one possible decarbonization option, as is using other cleaner sources of heat like heat batteries. Carbon capture is also feasible on some waste gas streams, especially from the fluid catalytic cracker.

Similar to natural gas, we anticipate that domestic demand for petroleum products will decrease dramatically as the economy decarbonizes, naturally reducing emissions from petroleum systems. However, as we've outlined in this note, many sectors will require low-carbon fuels on their decarbonization pathways. It's plausible that existing oil refineries could shift towards producing these new, clean fuels given their ready-to-go infrastructure and large-scale operation.

Building materials and construction
185-215 MMT in 2030, 4% of remaining emissions

We estimate that emissions from building materials and construction—a subsector of industry that includes iron and steel, cement, construction activities, glass, and wood

[4] As with natural gas systems, this is a broader definition of petroleum system emissions than included in the EPA inventory.

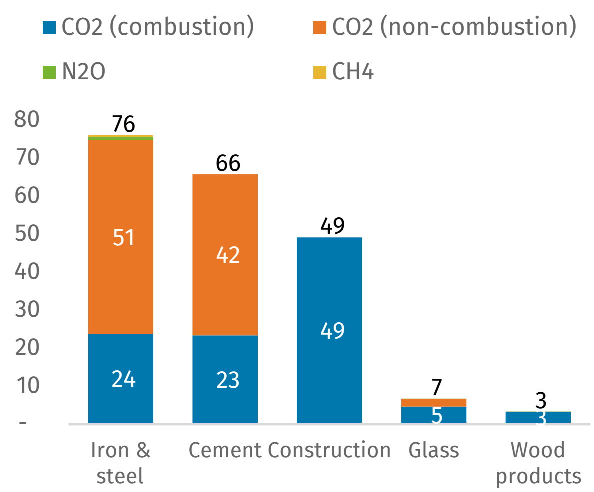
products—will be between 185-215 MMT in 2030. Since 2005, building materials and construction emissions have decreased by 19%, driven by shifts in the US economy and energy efficiency gains. In 2030, we project that iron and steel production will be the largest source of building materials and construction emissions in 2030, followed by cement and construction activities (Figure 10).

Collectively, these levels of emissions represent a 13-26% reduction from 2005 levels in 2030. That said, our 2030 estimates likely understate future emissions from these industries, as we don't currently account for higher levels of materials production in order to meet resource needs in a decarbonized future. For instance, by 2050, we anticipate higher demand for steel and glass than what's reflected in our 2030 modeling due to the substantial deployment of wind and solar required to achieve net-zero electric power generation.

FIGURE 10

2030 building materials emissions by subindustry and gas, mid emissions case

Million metric tons of CO_2e



Source: Rhodium Group

In terms of decarbonization strategies, key opportunities for iron and steel production include electrification (switching from the blast furnace production method to the electric arc furnace), decarbonizing the process of direct iron reduction using clean hydrogen, and deploying point-source carbon capture at any remaining blast furnaces. For cement production, strategies include deploying carbon capture on the lime kiln, using supplementary cementitious materials to reduce the clinker-to-cement ratio, and using clean fuels to produce low-carbon heat. Construction activity emissions are largely tied to construction vehicles and on-site generators, so decarbonization hinges on deploying zero emission vehicles and switching to clean fuels. Glass production emissions can be addressed through increased glass recycling and using clean fuels or electrification to decarbonize thermal energy generation. Wood production emissions, which result from lumber mills and manufacturers of finished wood products, can be addressed through electrification and switching to clean fuels. Additionally, increasing energy efficiency and strategies to minimize material use are important cross-cutting solutions.

Enteric fermentation
167-177 MMT in 2030, 4% of remaining emissions

Enteric fermentation emissions, a byproduct of the microbial fermentation process in animals' digestive systems and the largest source of methane in the US, have increased by 4% from 2005 to today. 97% of these emissions come from cattle, with over 70% from beef cattle. In our projections, dedicated agriculture policy from climate-leading states drives enteric fermentation emissions down to 6-10% below 2005 levels, though this subsector remains the largest source of US methane.

Food additives and vaccines are the most promising decarbonization strategies for enteric fermentation in terms of avoided tons, since these can limit the gut bacteria that produce methane in livestock. However, more research and experimentation are required to determine whether these are viable solutions at scale. Smaller gains are possible from increasing livestock productivity through breeding practices and improving pasture quality. Finally, shifting demand away from methane-intensive livestock products can lower enteric fermentation emissions.

Air transport
158-165 MMT in 2030, 3-4% of remaining emissions

Emissions from domestic air transportation have increased since 2005 as demand has grown, though fuel economy gains have tempered the increase. Since demand hasn't fully recovered to pre-pandemic levels, today's emissions are only 1% higher than 2005 levels. We project that demand steadily increases through 2030, pushing above pre-pandemic levels by the mid-2020s and driving emissions up 7-12% from 2005 levels.

A few options for decarbonizing aviation exist. Electrification is an option currently best suited for short-haul flights rather than regional or long-haul flights. For instance, battery weight and size constraints make it technically challenging to design an electric aircraft that can travel longer distances. Future aircraft might use hydrogen as a fuel, either through direct combustion or to power a fuel cell, but this solution requires undergoing the lengthy process of new aircraft design, development, and commercialization and would also likely be limited to short-haul flights.

Sustainable aviation fuels (SAF) are the most promising decarbonization strategy available and could be used in any type of flight. SAF can be produced from biological or non-biological feedstocks and used as a drop-in fuel to power existing aircraft. Today, the US produces about 4.5 million gallons of SAF each year. While this is meaningful progress, there's a long way to go before SAF can meet the bulk of domestic aviation fuel demand, currently about 11 billion gallons of jet fuel.

The role for carbon removal

Throughout this report, we have covered the main direct decarbonization solutions available to each of the top-emitting sectors. In subsequent work, we will discuss how certain policy levers and policy packages can be enacted to deploy decarbonization solutions in a way that puts US economy-wide emissions on track for net-zero by 2050. We expect to find that some of these decarbonization solutions will not be able to deploy at rates fast enough to fully decarbonize by 2050 due to technology availability, high costs, infrastructure scale-up constraints, and slow stock-turnover rates. Carbon dioxide removal (CDR) can offset these remaining sources of emissions, leading to *net-zero* economy-wide emissions.

CDR pathways are diverse and include ecosystems management, soil carbon sequestration, enhanced mineralization, biomass with carbon removal and storage (BiCRS), ocean alkalinization, direct air capture and direct ocean capture. Each CDR pathway has its unique costs, risks, permanence of CO_2 storage, technology readiness and monitoring, reporting and verification (MRV) profile. We will be releasing a report in March 2024 that dives deep into these details.

In our joint action scenarios, we estimate 243-257 MMT of natural and technological CDR in 2030. The industry has grown exponentially in the last few years and continues to receive both private sector attention and public policy support. Additional policy action will be needed to keep this pace for the CDR industry, but we expect a combination of pathways to play an important part in getting the US to net-zero by 2050. CDR can also push beyond achieving net-zero emissions and reduce global emissions to net-negative levels, reducing atmospheric concentrations of CO_2 and thereby helping to bring down temperatures from emissions already in the atmosphere.

The next wave of policy action

The emissions reductions we project under current policy aren't guaranteed, and there will be implementation challenges along the way. But the US has never been in a better position to achieve meaningful levels of decarbonization over the next decade. Additional policy actions, like those that we model in our joint action scenario, can push further on these reductions, potentially even keeping the US's 2030 climate target of a 50-52% emissions reduction from 2005 levels within reach. We can't take any of these reductions for granted.

But it's also critical to look beyond 2030 and begin to set up the next wave of policy action. The policies and progress on decarbonization that get the US within reach of the 2030 target may not be the same as what will be needed to maintain momentum after 2030. That's because of diminishing returns in some sectors and the increased prominence of other sectors traditionally not subjected to regulation, like industry and agriculture.

Looking ahead, increased efforts in subsectors that have historically been targeted by policy, like light-duty vehicles and the power sector, will be required to maintain and accelerate emission reductions, driving these sectors to zero emissions as quickly as possible. At the same time, policymakers need to build on recent successes and expand focus outside of these subsectors to areas that have received less attention. Across these subsectors, a common set of decarbonization approaches will be required, including increased electrification and efficiency, greater availability of low-carbon liquid and gaseous fuels and other sources of clean heat like heat batteries, and deployment of point-source carbon capture technologies. Additionally, increasing stock turnover and reducing service demand can help accelerate decarbonization in these sectors. Finally, limitations on technology and infrastructure availability and high costs mean it will be exceedingly difficult to fully decarbonize every corner of the US economy by 2050, pointing to an important need for a diverse set of commercially available CDR approaches as well.

This scene-setting note has identified the future emissions landscape and how these emissions can be addressed, though we haven't yet discussed how to accomplish that abatement. But watch this space: later this year, we will publish work that provides policy pathways to getting on track for a net-zero economy by 2050.

Appendix

Decarbonization study literature review

In writing this report, we reviewed a number of recent studies on economy-wide or sectoral decarbonization, listed in Table A1 below. This literature review helped inform our discussion on decarbonization strategies for top-emitting subsectors.

TABLE A1
Decarbonization study literature review

Organization	Report Name	Publication Year
Evolved Energy Research	Annual Decarbonization Perspective	2022
US Department of Energy	Industrial Decarbonization Roadmap	2022
International Energy Agency	Net Zero Roadmap	2023
Princeton University	Net-Zero America	2021
Duke University	Pathways to Net-Zero for the US Energy Transition	2022
Intergovernmental Panel on Climate Change	Special Report: Global Warming of 1.5 C	2018
US Department of State & US Executive Office of the President	The Long-term Strategy of the United States	2021

Other references

In addition to major economy-wide or sectoral decarbonization studies, we reviewed several other articles and reports to inform our discussion of subsector-specific emissions and decarbonization opportunities, listed in Table A2 below.

TABLE A2
Other references

Organization or Publication	Report Name	Publication Year
Rocky Mountain Institute	Five Ways US Oil Refineries Can Reduce Emissions Today	2023
Nature	Glass is the hidden gem in a carbon-neutral future	2021
Environmental Research Letters	Synthesizing the evidence of nitrous oxide mitigation practices in agroecosystems	2022
Shell	Decarbonising Construction: Building a Low-Carbon Future	2023

Remaining emissions from lower-emitting subsectors

As mentioned in the top-emitting subsectors section, this note focuses on the top subsectors responsible for 84-85% of 2030 emissions. The remaining 15-16% of emissions come from the 28 subsectors in Figure A1 below. Because transport and power emissions from US territories are small compared to US state emissions, we include them here as a single aggregated category. Similarly, methane and N_2O emissions from mobile combustion are miniscule compared to combustion CO_2 in the transport sector. Instead of apportioning a fraction of these emissions to LDVs and freight trucks in our top-emitting subsectors discussion, we include all mobile combustion emissions here. Nearly all actions that address combustion CO_2 in these two subsectors will also reduce non-CO_2 mobile combustion emissions.

FIGURE A1

2030 remaining emissions from lower-emitting subsectors

Gross million metric tons of CO_2e

Source: Rhodium Group

Disclosure Appendix

This nonpartisan, independent research was conducted with support from the Linden Trust for Conservation. The results presented in this report reflect the views of the authors and not necessarily those of the supporting organization.

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