THE GLOBAL STOCKTAKE: AN OPPORTUNITY FOR AMBITION

Mitigation Landscape Analysis: Themes and Trends

February 2022

The Center for Climate and Energy Solutions (C2ES) is working closely with the Environmental Defense Fund (EDF) on a project to help shape the Paris Agreement's global stocktake (GST) process, including by ensuring a strong focus on opportunities to scale up climate ambition. We have developed three landscape analyses,[1] or surveys, of promising opportunities that could provide substantial, near-term scalable enhanced climate action and support in the context of the Paris Agreement's long-term goals.

These landscape analyses are not intended to be comprehensive, but rather provide a snapshot of key opportunities and could serve as a basis for further work. They also address the draft cross-cutting guiding questions posed by the Subsidiary Body Chairs for the Technical Assessment component of the first GST, particularly around good practices, barriers, and challenges for enhanced action in mitigation, adaptation, and climate finance.[2]

A separate paper suggests some initial considerations relevant to how the GST could best translate the vast amount of inputs it will generate into clear signals that will ultimately be of use to decision-makers in raising climate ambition and implementing existing commitments.[3]

These considerations, together with the landscape analyses, comprise an 'opportunities framework' that may be helpful in adding further structure to information gathering and technical analysis under the GST, as well as towards generating clear outputs.

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[1] "Global Stocktake: An Opportunity for Ambition," Center for Climate and Energy Solutions (C2ES), last modified February 28, 2022, https://www.c2es.org/content/global-stocktake-an-opportunity-for-ambition.

[2] See Guiding questions by the SB Chairs for the Technical Assessment component of the first Global Stocktake, paras 21–22, updated February 16, 2022, https://unfccc.int/sites/default/files/resource/Draft%20GST1_TA%20Guiding%20Questions.pdf.

[3] See *Distilling Critical Signals from the Global Stocktake* (Center for Climate and Energy Solutions, February 2022: Arlington, VA), www.c2es.org/document/distilling-critical-signals-from-the-global-stocktake.

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Executive Summary

This landscape analysis intends to identify the most salient opportunities to enhance unilateral and collective climate action, with an emphasis on near-term decarbonization at a level that can keep the world on track to limit average global warming to 1.5 degrees C. The GST process provides a critical platform to assess progress towards the goals of the Paris Agreement and an opportunity to drive the ambition needed from the Parties, and the ecosystem of non-Party stakeholders that surrounds them. As of 2021, the preparatory phase of the GST process has already begun, including updating sources of information, a call for inputs, and informal consultations with Parties. The process will intensify throughout 2022 with information collection and preparation, synthesis reports, and technical dialogues, and then culminate in 2023 at COP28.

Part I gives a brief update of the latest climate science, drawing heavily from the IPCC's 1.5 degrees C Report and the 2021 UNEP Emissions Gap Report. With every year of increased emissions and delayed transformation to a low-carbon society, the pathways for staying below 1.5 degrees C have become steeper, starker and more daunting than ever. This section describes the role and importance of the GST process in the Paris Agreement, and the opportunity it presents to help steer governments and the world to stay on track with steep and urgent emissions reductions in this critical decade.

Part II provides a synthesis of existing sources and publications that have analyzed the pathways, actions and interventions for maintaining the feasibility of the 1.5 degree C goal. Instead of presenting new analyses, this reviews the existing literature and summarizes the key opportunities for scaling up mitigation to a level needed for transformational change by 2030 and through to mid-century. We contextualize the collection of technology, policy and finance opportunities available for rapidly enhancing the level of mitigation around the world, taken by governments and supported by the entire ecosystem of non-party stakeholders. These solutions are meant to inform thinking around the ways in which coalitions of countries and other actors might utilize the GST to advance ambition in the context of the 2025 NDC update. Lastly, while our goal was to conduct a comprehensive review of existing work in this area, we recognize this is a rapidly evolving space with new papers and publications being released on a continuous basis, which will accelerate even more as the GST proceeds.

Part III gives some concluding remarks and outlines the next steps for taking this work forward in support of maximizing the effectiveness and impact of the GST process.

The **Annex** contains information that was systematically collected in support of the development of this paper. Here, a number of high-impact, wide-ranging climate solutions are organized by sector. The table describes the solutions and identifies key actors driving each solution at the international or regional level. Each solution is also accompanied by a short analysis of key geographies and policies, as well as a list of influential actors (e.g., initiatives, coalitions, organizations) and barriers to deployment at scale. There exist interlinkages, trade-offs and tensions between solutions. While a few are highlighted, these are not systematically addressed in the paper. Social and environmental implications are also addressed briefly but are largely outside of the scope of this report. In some cases, solutions are applicable to more than one sector, so the table entries reference each other. The information in the Annex will also support the next phase of this project.

PART I: The Scientific Context and the GST process

The Scientific Context

The Paris Agreement establishes the goal of limiting global temperature increase to well below 2 degrees C, while pursuing efforts to limit the increase to 1.5 degrees C. These goals were established to avoid the most catastrophic effects of climate change. Nevertheless, even with an increase of 1.5 degrees C, the world will face increased risks to health, livelihoods, food security, water supply, human security and economic growth.[1] Indeed, we are already seeing these impacts first-hand around the world. There is increasing focus on holding temperature rise to 1.5 degrees C (instead of well below 2 degrees C), and this limit was further mainstreamed by the 2021 Glasgow Climate Pact.

The latest Emissions Gap Report from October 2021 shows that the existing updated NDCs and other mitigation measures put the world on track for a global temperature rise of 2.7 degrees C by the end of the century. In fact, there is a fifty-fifty chance that global warming will exceed 1.5 degrees C in the next two decades, and unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to 1.5 degrees C or even 2 degrees C by the end of the century will be beyond reach.[2]

Keeping the window open to limiting warming to 1.5 degrees C requires rapid decarbonization at an unprecedented pace. Overall, 1.5 degrees C-consistent pathways are characterized by the rapid phase out of carbon dioxide emissions and deep reductions in other greenhouse gases, with the global economy becoming carbon-neutral by 2050 and emissions halved by 2030.[3] The Emissions Gap Report specifically indicates that to get on track to limit global warming to 1.5 degrees C, the world needs to take an additional 28 gigatons of carbon dioxide equivalent ($GtCO_2e$) off annual emissions by 2030, over and above what is promised in updated unconditional NDCs. For the 2 degrees C Paris Agreement target, the additional need is lower: a drop in annual emissions of 13 $GtCO_2e$ by 2030.

This leaves eight years to enhance mitigation ambition, design and implement action, and to deliver the needed emissions reductions.[4] It is a monumental task. Given the extreme urgency of the situation, it is imperative that the GST be more than just a technical exercise or a political moment: it must represent a turning point for delivering ambition.

The GST Process

Alongside its binding obligation for each Party to maintain and implement an NDC, the Paris Agreement establishes two essential mechanisms. The first is an enhanced transparency framework requiring all parties to regularly report on their greenhouse gases and on the implementation and achievement of their NDCs, subject to two layers of international review. This system provides some measure of accountability and—to the degree that it demonstrates that countries are fulfilling their commitments—can strengthen collective confidence to do more. The second essential feature is a **GST process in which, every five years, countries assess collective progress toward the agreement's long-term goals, considering mitigation,**

adaptation and finance, as well as equity and the best available science. Each country, informed by this periodic stocktake, is then to submit an updated NDC reflecting a "progression" beyond its current NDC and "its highest possible ambition." This combination of GST and NDC updating is known as the "ambition cycle." Properly executed, the GST process can provide the critical foundation for a regular series of high-level political moments that progressively ratchet up climate ambition.

Although the GST is, formally, a process among countries, it will be taking place within an evolving climate regime in which non-state actors play an increasingly prominent role. Traditionally relegated to the role of observers, NGOs, companies, subnational governments and other non-Party stakeholders have been afforded greater opportunity in recent years to engage more directly in UNFCCC processes, through the Marrakech Partnership on Global Climate Action[5] facilitated by the UNFCCC High Level Champions and the Technical Examination Process.[6] The GST's modalities explicitly provide for "participation" by non-Party stakeholders, including through an invitation for them to provide submissions, thereby opening the way for them to exert a stronger presence in the negotiations and subsequent country action. Moreover, the GST is now widely accepted even beyond the UNFCCC process by a wide range of actors, who will also be working to enhance action alongside Parties and non-Party stakeholders that formally participate in the GST process.

The GST is widely understood as an exercise in assessing action to-date against the Paris Agreement's long-term goals. However, in designing the GST, countries put strong emphasis on identifying "opportunities for enhanced action and support," a clear recognition that the goal of higher ambition will be best served by highlighting both urgency and opportunity. The success of the GST depends on adequate attention to both dimensions and an emphasis on near-term scalable action. The GST provides an opportunity to refocus global efforts on the actions and opportunities that can be scaled to achieve long-term goals, including by identifying clear strategies for sectoral decarbonization. Indeed, there is already a large body of work that analyses these mitigation opportunities that will be immeasurably useful for inputting into the GST process.

The next section of this paper provides a compilation of that work.

PART II: Summary of critical opportunities for enhancing mitigation ambition in the context of the GST

One of the guiding features of the GST is the separation of the technical assessment process from the political decision-making process. The technical assessment process, which comes first, will produce a factual synthesis report. Focused attention will be given to each of the thematic areas in the Paris Agreement, including mitigation, adaptation and finance, with numerous sources of information for each. The technical assessment process will be led by two co-facilitators—one each from a developed and developing country, who will organize thematic events and decide on modalities as appropriate for sourcing inputs—followed by the preparation of factual reports.

The mitigation element of the technical assessment will benefit from a wealth of existing information on opportunities for enhancing mitigation ambition. Since the Paris Agreement was adopted and ratified, numerous publications have studied the type of actions that will be required to scale-up mitigation efforts and keep the average global temperature increase well below 2 degrees C—and what additional interventions will be needed to not surpass 1.5 degrees C. Ultimately, the challenge of the GST will be translating the excesses of available evidence and information into action and implementation by Parties, together with the ecosystem of non-state actors (mainly subnational actors and the private sector).

This paper does not present any new research, analysis or modelling efforts, but instead draws from a number of recent sources, aiming to extract and synthesize the opportunities with the highest mitigation potential. Key sources include: the IPCC's "Special Report on Global Warming of 1.5 degrees C," the UNFCCC's "Global Climate Action Pathway" reports, the IEA's "Net Zero by 2050 Report," the "Exponential Roadmap—Scaling 36 Solutions to Halve Emissions by 2030," Oxford Economics' "White Paper on Mitigation Pathways to Address Global Warming," the "Climate Policy Initiative Global Landscape of Climate Finance 2019," and numerous sector-specific publications referenced and cited in the Annex. Additionally, new analysis becomes available on a regular basis, and will continue to do so as the GST process intensifies. For example, even while finalizing this document, the Bezos Earth Fund, Climate Analytics, NewClimate Institute, and the World Resources Institute published a joint paper on the State of Climate Action in 2021: Systems Transformations Required to Limit Global Warming to 1.5 degrees C.

This approach uses the lenses of technology, policy and finance to group and summarize the solutions that can have the greatest impact on global mitigation, with a focus on near-term potential and long-term transformation. We highlight critical, scalable opportunities within key economic sectors. While the general grouping of solutions under these three themes is intended to make the information more easily digestible and, ultimately, actionable within the context of the GST, they also cannot be completely extricated from one another. A more complete description of each solution can be found in the annex.

Landscape of Technology Solutions

Since the industrial era began, some 2.3 trillion tons of carbon dioxide have been released into the atmosphere. Over the last 250 years, technological advances have led to explosive growth in economic productivity and accelerated environmental degradation. Technology, until very recent history, has been leveraged to optimize fossil fuel extraction to fuel that growth, leading global temperatures to currently reach over 1 degree Celsius above pre-industrial levels. As we confront the climate crisis in order to prevent the most devastating impacts of climate change, we must now leverage technology to completely reshape our economies and societies once again, this time without greenhouse gas emissions.

Over the next decade, the world needs to accelerate the implementation of existing technology, while also fostering technological solutions that will disrupt and transform all the key sectors of the economy, dramatically reducing their greenhouse gas emissions. The Net Zero by 2050 report published by the International Energy Agency (IEA) states that all the technologies needed to achieve the necessary deep cuts in global emissions by 2030 already exist, and the policies that can drive their deployment are already proven. According to the Exponential Roadmap, digitalization is the key to halving emissions by 2030: it can directly enable around a third of the necessary emissions cuts and influence the rest.[7]

Halving emissions by 2030 will be enabled by scaling technologies at different levels of development. IEA highlights 45 technology areas which are specifically important for climate mitigation. Key technologies such as solar photovoltaics, wind energy, LED lighting, energy storage, electric vehicles, data centers and bioenergy are growing rapidly and following exponential trajectories. Others, however, are not. Heating and cooling technologies for buildings, smart grids, concentrated solar power, geothermal energy and low-carbon materials must all scale faster.[8]

Across the literature there are a number of key technologies that can contribute to the reduction in global emissions at the scale needed to meet the Paris goals. These have been compiled primarily from the UNFCCC's Climate Action Pathways Action Tables and the Exponential Roadmap Initiative as well as IEA, ICAO and others. They fall into the following categories: energy, land transportation, aviation, shipping, industry, buildings, nature-based solutions, and the reduction of methane emissions.

Energy

According to the Climate Action Pathway for Energy prepared by the UNFCCC, Paris Alignment requires at least a 30 percent share of solar and wind in electricity by 2030, or at least a 60 percent share of all renewables. While much of this technology exists, **research and development will be needed into the next generation of solar and wind technologies, such as advanced solar panels, floating solar, floating offshore wind, and tall-tower wind, as well as into recycling the raw materials in solar panels.**

Also critical to fully enabling the transition to renewable energy will be the development of **complementary technologies needed for large-scale renewables** (e.g., energy storage, demand response, zero carbon sources of flexible and dispatchable generation). **Energy storage**, in particular, plays an important role in IEA's net zero scenario, which envisions a massive scale up to 3,100 GW of storage in 2050 (with four-hour duration on average).[9] Energy storage can provide grid stability and grid flexibility, enabling high levels of renewable energy deployment. Nevertheless, annual installations of energy storage technologies declined for the first time in nearly a decade in 2019, with grid-scale storage installations dropping by 20 percent.[10] Installations in 2019 totaled 2.9 GW. Still needed are **research and development into recycling of the raw materials in batteries and into the next generation of storage, including long-duration energy storage.**

Given the variability of wind and solar, advances in energy storage will need to be accompanied by "clean firm power," or carbon-free power sources that can be dispatched whenever they are needed. These technologies can complement renewable energy, ensuring reliability and keeping system costs low. Options include gas-generated power with carbon capture and storage (CCS); nuclear power, including small modular reactors and next generation technologies; geothermal power; and fuels without lifecycle emissions.[11] Nuclear fusion power could also reach commercial viability by the early 2030s. These all carry unique risks (e.g, methane leakage, nuclear waste) and are contested within the environmental community.

Increasingly, **building-to-grid integration** will be a major step to increasing energy efficiency and reducing the demand for energy. According to the U.S. Department of Energy:

> Intermittent and variable generation sources, such as photovoltaic systems, as well as new load sources, such as electric vehicles, are being installed on the grid in increasing numbers and at more distributed locations. At the same time, smart sensing, metering and control technology is increasing grid operators' situational awareness, helping building owners pinpoint efficiency opportunities, and allowing homeowners to see and adjust their energy use on their smart phones. The economic opportunities are vast; for example, transforming demand responsive devices to be fully dispatchable could provide billions of dollars per year in reduced energy costs while offsetting new generation and transmission infrastructure.[12]

When incorporated into COVID-19 stimulus and recovery plans, the energy transition can successfully align economic recovery with global climate goals. An investment package focused on the energy transition will help to overcome the economic slump and create much-needed jobs for the short-term and beyond. According to the UNFCCC's Global Climate Action Pathway for Energy, "**renewables could account for 2.46 million of these additional jobs, energy efficiency for 2.91 million, and grids and energy system flexibility for 0.12 million**. In contrast, these gains far outweigh the loss of 1.07 million jobs in the fossil fuel and nuclear sectors."

Land Transportation

In land transport, the pathway to zero carbon is technically feasible, and the transition is underway. According to the International Council on Clean Transport's Vision 2050 report, it is estimated that about **85 percent of carbon dioxide emission reductions that are needed to meet the 1.5 degrees C target can be achieved with existing and emerging policies and technologies, such as electrification and efficiency improvement**. The remaining 15 per cent can be met with changes in behavior, such as reductions in distance travelled through the expansion of teleworking, integrated land-use and transport planning and shifts to more sustainable modes, such as walking, public transit and cycling. The road to zero carbon for transport will require a smart combination of different strategies.[13]

We are already seeing a momentous change in land transport. Indeed, electric cars already compete favorably with gasoline engines on range and will soon reach a tipping point where prices consistently fall below traditional gasoline and diesel models, even without subsidies. Global sales of electric vehicles rose 43 percent in 2020 and, responding to this trend, most major car manufacturers have now set dates to phase out the combustion engine. With price parity approaching, there is an opportunity and a need for governments to set ambitious targets for a full transition to electric vehicles. **By 2030, leading markets should aim to achieve zero carbon for 75 percent of new light-duty vehicle sales**. This level of penetration is forecasted to be the tipping point required to enable **full transition to zero-emission vehicles by 2035 in leading markets. Leading markets should also target zero carbon for 100 percent of new bus sales and 40 percent of new truck sales by 2030 for the same reasons.**[14]

This transition will need to be complemented by unprecedented investment in **charging infrastructure** and should also include the development and deployment of complementary policies, including renewable energy standards to ensure clean power sources for the vehicles, as well as **vehicle-to-grid systems**, where plug-in electric vehicles can communicate with the power grid to sell demand response services by returning electricity to the grid or adjusting their charging rate.

Aviation

While the global pandemic has temporarily altered the trajectory of aviation emissions, analysis by McKinsey & Company predicts that business travel will recover to around 80 percent of pre pandemic levels by 2024, while leisure travel is expected to rebound sooner.[15] Even with a delayed recovery, aviation will soon be trending back toward accounting for over 2 percent percent of global emissions.

Technological barriers associated with alternative propulsion and design are now being overcome; however, difficult industry factors such as low profit margins, job losses, stakeholder complexity and the need for international regulatory frameworks make decarbonizing aviation challenging. An International Civil Aviation Organization (ICAO) analysis suggests that **improved technology and operations can achieve up to a 33 percent emission reduction versus a 2050**

business-as-usual scenario. This analysis also considered the long-term availability of sustainable aviation fuels (SAF), finding that, **by 2050, it would be physically possible to meet 100 percent of international aviation jet fuel demand with SAF, corresponding to a 63 percent reduction in emissions.**[16] Though promising, these fuels are not carbon neutral, and the emissions reductions they provide vary. It is important that SAF is held to a high standard for environmental integrity, with transparent and accurate accounting for emissions reductions.

Additionally, this level of fuel production could only be achieved with extremely large capital investments in sustainable aviation fuel production infrastructure and substantial policy support. The effort required to reach these production volumes would have to significantly exceed historical precedent for other fuels such as ethanol and biodiesel for road transportation.[17]

E-fuels are expected to play a critical role in aviation decarbonization from 2030 onward. E-fuels can provide lifecycle emissions reductions of close to 100 percent as compared to fossil jet fuel. Their deployment requires a sufficient supply of surplus renewable energy. The cost of e-fuels is expected to decline significantly as renewable energy and electrolyzer costs fall, bringing the e-fuel cost in line with other SAF by 2040.

Shipping

Feasible fuel pathways exist in shipping but accelerated action and cross-industry collaboration are needed to accelerate research and development (R&D) and realize large-scale system demonstrations by 2025. Emissions from shipping currently amount to approximately 0.9 gigatons of carbon dioxide (almost 3 percent of global carbon dioxide emissions) but could grow by 84 percent under a business-as-usual scenario. Operational efficiency measures can reduce emissions by 30–50 percent, but **zero-carbon fuels are needed for full decarbonization**. There is growing evidence that **green ammonia produced from green hydrogen is the most feasible candidate for deep sea shipping**, but the industry has yet to reach consensus on the decarbonization pathway and **zero-carbon vessel technology is still in early stages of development**.

In technology and supply there is therefore an **urgent need for accelerated R&D to develop zero-carbon vessels and electrolysis technology to bring down the costs of green hydrogen. Large-scale system demonstrations are needed by 2025** to demonstrate viability and draw lessons learned. These will require collaboration between governments, industry and finance, with governments playing a larger role early on.

Industry

Industry is responsible for 29 percent of all global energy use and around a fifth of all greenhouse gas emissions.[18] Due to production and consumption patterns, roughly 20 percent of emissions are generated by advanced economies and 80 percent originate in developing economies.[19] Three heavy industries—steel, cement, and chemicals—account for around 70 percent of direct carbon dioxide emissions from the industrial sector.[20,21]

Under IEA's Net Zero scenario, industry emissions fall from 8.48 Gt of carbon dioxide in 2020 to 6.89 in 2030 and 0.52 in 2050. Notably, **hydrogen and carbon capture, utilization and storage (CCUS) technologies contribute ~50 percent of the emissions reductions in heavy industry in 2050**.[22]

To promote hydrogen, **targets for electrolysis manufacturing and support for key technologies such as new forms of bulk hydrogen storage are needed**.[23] For industrial applications, the Hydrogen Council proposes **support for "large-scale pilots in steel manufacturing, power generation, and clean or green hydrogen feedstocks for the chemicals, petrochemicals, and refining industries."**[24] Once technologies are proven, a long-term regulatory framework should follow.

CCUS contributes to the transition to net zero in multiple ways: addressing emissions from existing and newly built energy assets, providing solutions in hard-to-abate sectors, supporting low-emission hydrogen production, enabling carbon dioxide removal, and providing low-carbon dispatchable power.[25,26] Today, **CCUS projects around the world have the capacity to capture about 40 Mt of carbon dioxide each year. IEA's net zero pathway would require 7,600 Mt of carbon dioxide to be captured in 2050, with 5,245 Mt of carbon dioxide captured from fossil fuels and processes**.[27] In this scenario, almost 40 percent of CO_2 captured in 2050 would be from industry and 20 percent would be from the electricity sector. Unfortunately, CCUS technologies remain at an early stage of development and some experts view such a massive scale up of CCUS capacity as unrealistic, even with strong policy support.

Buildings

To decarbonize the built environment, whole-life carbon emissions (operational and embodied) must be assessed and tracked on all new and existing developments to determine how best to minimize emissions while ensuring adaptation and resilience for the future. System decarbonization requires minimizing energy use and material demand and implementing low-carbon and renewable heating, cooling, material and construction technologies at scale, while promoting the decarbonization of the energy, transportation, and material manufacturing sectors (e.g., steel and cement) in parallel.[28]

Technology providers and innovators have a crucial role to play in enabling the transformation of the built environment. The UNFCCC's Climate Action Pathway for human settlements suggests they carry out the following concrete actions: **1) Develop and promote widespread use of digital solutions to accurately measure and automatically optimize built asset operational performance in real time and to measure and freely share as-built embodied carbon emissions over the asset life cycle; 2) Develop and promote widespread use of low carbon construction processes and materials; 3) Develop energy efficient and clean energy**

solutions for the built environment; and 4) Enable low carbon operation and maintenance of built assets.

Traditional energy efficiency technologies—including building envelopes, controlled ventilation, LED lighting, properly sized heating and cooling systems, and efficient appliances—can significantly reduce energy usage while delivering increases in the occupant's comfort, health, and productivity.

Electrified devices such as **electric heat pumps** offer both heating and air-conditioning and can achieve over 100 percent efficiency in temperate climates.[29] IEA's Net Zero scenario would require 50 percent of heating demand to be met with heat pumps by 2045.[30] Other key technologies are **electric ranges, induction cooktops, and modern biomass stoves and boilers, which could replace traditional biomass**.[31] IEA's Net Zero scenario would require no new sales of fossil fuel boilers after 2025.[32]

Nature-Based Solutions

To limit global warming to at least 2 degrees C land-based mitigation responses, especially reduced deforestation, need to be expanded. As the future of humanity relies on nature, ambitious actions need to be taken to flatten and reverse the loss of nature through effective conservation action paired with transformational changes in our production and consumption systems.[33]

Digital technology in particular holds immense promise for protecting nature, specifically by providing tools to support transparent, timely and consistent reports on the status of protected areas; building capacity and access to technology to stem illegal logging operations; facilitating the implementation of open-access tools for monitoring forests and land use to carry out rapid, reliable and transparent assessments; disseminating good practices to inform and guide implementation; applying new technologies to the challenge of measuring sources and sinks of emissions from the land sector in a spatially explicit manner; and establishing the accuracy of monitoring tools through transparent scientific frameworks.

Methane Emissions

In the short-term, reducing methane leaks should be a first-order priority for all. Methane emissions should be 75 percent lower than 2020 values by 2030.[34] If all of the technologies and measures identified in IEA's Methane Tracker 2020 were deployed, "around 75 percent of total oil and gas methane emissions could be avoided."[35] Notably, the oil and gas industry could achieve a two-thirds reduction of methane at no net cost.[36]

Technologies to prevent vented and fugitive emissions are well-known. Abatement options include replacement of existing devices, installation of new devices (e.g., vapor recovery units, blowdown capture), and leak detection and repair, among others. A new wave of **technologies linked with big data** also holds promise for remote monitoring of methane.[37] "The remote monitoring of well pads, processing plants, and distribution systems could help energy companies recover much of the $30 billion of methane they waste or flare every year. They would also spot super emitters faster, and quickly drive down millions of tons of potent climate pollution."[38]

Equity Considerations

The necessary technological shifts must be swift and comprehensive to enable society to bend the curve to a 1.5 degrees C trajectory. The widespread adoption of existing and new technologies, and the changes that they will bring, have the potential to help relieve or to further exacerbate inequalities that exist today. Policy makers should set ambitious targets for technological adoption and must stay attuned to the risks and opportunities presented by burgeoning technologies, intervening as appropriate. Financiers must take bolder risks early in the research and development phase of climate technologies and should continue to make headway in divesting from dirty technologies and investing in clean ones. Their support is especially needed so that developing countries can truly "skip over" dirty technologies in favor of clean ones, truly supporting a more sustainable trajectory of development.

Landscape of Policy Solutions

The urgency of the climate crisis is increasingly apparent, and there is growing awareness that it is not confined to the realm of environmental policy. Agricultural policy, trade policy, tax policy, and other policy arenas are critically important in the effort to mitigate and adapt to the effects of climate change.

Under the Paris Agreement, NDCs are the primary vehicle through which national climate targets and underlying policy efforts are communicated to a global audience. In many cases, they detail actions across a wide range of sectors, and they are collectively seen as indicators of global ambition. In advance of COP26, countries were required to submit updated NDCs. While several large emitters submitted significantly more ambitious NDCs, others turned in new submissions that weakened previous pledges. Overall, progress is uneven, and ambition remains insufficient. Recognizing the significance of the ambition gap, Parties agreed at COP26 to "revisit and strengthen the 2030 targets in their nationally determined contributions as necessary to align with the Paris Agreement temperature goal by the end of 2022."[39]

There is an increasing expectation that the NDCs and long-term low-emission development strategies that countries submit to the UNFCCC outline pathways to net zero carbon emissions by 2050. This concept has become increasingly entrenched in global climate policy, with thousands of cities, regions, businesses, investors, and educational institutions committing to achieve net zero carbon emissions by 2050 as part of the High-Level Climate Champions' Race to Zero initiative.[40] Net zero by 2050 is rooted in scientists' evolving understanding of the climate system, the implications of 1.5 degrees C versus 2 degrees C of warming and the emissions pathways consistent with the Paris Agreement's temperature targets.

Growing alongside the focus on net zero is an acknowledgement that implementation is a prerequisite for credibility. Countries and other stakeholders must move from commitments to action. COVID-19 recovery packages present one opportunity for countries to direct investment toward climate priorities and "build back better." Unfortunately, spending on climate-friendly priorities represents less than one-quarter (21 percent) of total COVID-19 recovery spending thus far in Organisation for Economic Co-operation and Development (OECD), EU, and key partner countries, according to the OECD.[41] Furthermore, "annual support to fossil fuels will likely surpass all the one-off green recovery spending in just a few years." The Oxford University-led Global Recovery Observatory reaches a similar conclusion—that 21.7 percent of recovery spending can be categorized as "green"—after reviewing spending by 50 leading economies.[42]

With the world slowly starting to emerge from the COVID-19 pandemic, the GST process offers an opportunity for mutual learning among countries and stakeholders across all levels of governance, including by exchanging lessons learned and highlighting best practices in driving transformational change through policy. If designed properly, this global exercise should highlight areas of future collaboration and support the revision and achievement of targets enshrined in NDCs.

Regardless of the policy vehicle employed—recovery packages, national plans, sectoral regulations—the transition to a low-carbon economy will require unprecedented transformation of all sectors. An analysis of "mitigation pathways" by Oxford Economics identified common stepping stones to a stable climate, including a phase out of CO_2 emissions around mid-century, with carbon dioxide emissions halved by the end of this decade; deep reductions in other greenhouse gas emissions; and offsetting residual emissions from hard to abate sectors through steeper reductions in other sectors and natural or technological carbon dioxide removal.[43] 1.5 degrees C pathways are generally characterized by lower energy demand, faster decarbonization of the electric sector, and faster electrification of end-use sectors.[44] As such, the prioritization of energy efficiency, expansion of renewables, and electrification—where possible—of transport, industry, and buildings are key. The importance of achieving net zero emissions during this decade in the land use sector cannot be overlooked. The solutions summarized in the section above and described in detail in the Annex below each play a role in delivering a safer climate future.

The climate policies required to catalyze these changes present a range of opportunities. Governments that set a clear direction for the future of travel can enable companies and other real economy actors to align efforts to secure a safe climate future—and turn challenges into opportunities. While there is no substitute for comprehensive and ambitious government policy, these actors can support policy formation by credibly demonstrating their own climate ambitions.

A policy overhaul at the scale required to address the climate crisis also presents opportunities to address historical injustices and chart a better course for the future. To deliver this future, climate policies must be aligned with the goal of net zero emissions by mid-century. Beyond this imperative, countries have a suite of options available to them, some of which are summarized below.

Command and control measures such as emissions caps, technology mandates (e.g., zero emission vehicle mandates), blend mandates (e.g., to increase use of renewable fuels), performance standards (e.g., building performance standards that improve energy efficiency and reduce emissions), and phase outs or bans of polluting technology or activities (e.g., to end the use of internal combustion engines or halt forest conversion).

Market-based measures that incentivize the development and deployment of solutions, such as putting a price on climate pollution (e.g., carbon, methane) to reflect the true environmental cost of activities; disclosing emissions-related information about facilities or products (e.g., ecolabels); and aligning subsidies with low-carbon development and technologies (e.g., phasing out fossil fuel subsidies and harmful agricultural subsidies), including tax incentives (e.g., tax credits for sustainable fuels) and procurement mandates (e.g., for the purchase of low-carbon building materials).

Equity Considerations

Governments must craft climate policies with a focus on equity—including intergenerational and international equity. Policymakers need to broadly consider the implications of potential policy decisions, including which communities, countries or other stakeholders might disproportionately bear the costs or accrue the benefits. Populations that have been historically overburdened by pollution—and those most vulnerable to climate change—must see real benefits from climate policies, and communities dependent on the polluting activities of the past need to be included in the clean energy transition. Technologies like those detailed in the previous section will help deliver a safer climate future, but the policies surveyed in this section will shape how the world gets there.

Landscape of Financial Solutions

The Paris Agreement aims to strengthen the global response to the threat of climate change by aligning finance flows with low greenhouse gas emissions and climate-resilient development. Current estimates suggest that between three and six trillion USD of investment will be required annually for the next three decades to transform the world economies to achieve a net zero world by 2050, while also eliminating public subsidies for fossil fuel extraction and use as well as harmful agricultural practices. The IPCC estimates that an annual investment of 2.4 trillion in the world's energy systems alone is needed until 2035 in order to hold the global temperature increase below 1.5 degrees C.[45]

Undoubtedly, there has been a strong increase in climate finance during the last decade, exceeding 500 billion USD in 2017 and 2018,[46] but the investment in low carbon solutions is still insufficient to lock in a pathway aligned with the Paris Agreement objectives.

Notably, 75 percent of the investment is needed in developing countries—and most of this capital needs to be provided by the private sector. This presents a huge hurdle but also a huge opportunity: the IFC estimates that 23 developing countries alone hold over 23 trillion USD in climate-smart investment opportunities through 2030.[47]

Meanwhile, developed countries have not reached the goal of mobilizing 100 billion USD in climate finance per year starting in 2020. Under current commitments, 100 billion USD annually will not be met until 2023.[48] Projections indicate that levels will reach 113-117 billion USD per annum in 2025. Investment needs are felt across all areas of the real economy. With adequate planning, bridging that gap will bring extraordinary social, economic and developmental co-benefits.

Latest Developments in Finance

The swath of individual commitments seen in the lead up to the Paris Agreement have evolved and become articulated around scaled initiatives that aim to transform the entire finance system in line with Article 2.1(c) of the Paris Agreement. To this end, the Marrakech Partnership Climate Action Pathway for Finance laid out the reforms needed across the finance sector in order to align with net-zero objectives.[49] In parallel, we see the development of a regulatory reform agenda, notably by the Task Force on Climate-Related Financial Disclosures and the G20 Sustainable Finance Working Group, which is set to develop and update annually the Roadmap for Sustainable Finance.

The private finance sector has shown a strong capacity to coordinate around climate objectives and environmental priorities, and now a myriad of sectoral and geographic initiatives provide clear frameworks under which individual private financial institutions can articulate their commitments and actions. The Investor Agenda, launched in 2018, is an investor-led climate action initiative that facilitates investor transition towards a net-zero world. In 2019, the UN established the Net-Zero Asset Owner Alliance as the 'gold standard' for all other elements of the finance sector to follow, aligning investment portfolios with a 1.5 degrees C degree pathway, and today brings together more than 60 institutions representing ten trillion USD in assets. Banks, insurers and financial service providers have also moved to establish similar alliances.

These galvanizing efforts resulted in the establishment in April 2021 of the Glasgow Finance Alliance for Net Zero (GFANZ), bringing together all cogs of the financing machinery. Conceptualized as an umbrella of constituencies with net zero objectives, it aims to generate a sector-wide commitment framework that broadly and coherently advances net-zero objectives for the entire finance sector. Despite these remarkable mobilization efforts, key challenges remain, notably, articulating a mechanism that ensures the integrity of commitments and that renders institutions accountable, bridging the gap in financing for developing countries, and accelerating learning curves of proven solutions.

Such coordination efforts have not been as evident within the public finance space. The current international finance architecture was born in a post-war era and is not equipped to support the transition towards a net zero world. Governments are not only being called to align coherent, global regulatory frameworks with net zero pathways, but they are also being asked to request a revision and alignment of the mandates of all international finance institutions (i.e., International Monetary Fund, World Bank Group, Financial Stability Board, etc.).

Notably, development finance institutions and development banks have not coalesced around a normalized set of best practices, metrics and a commitment framework that would guide the decarbonization of their portfolios, which is required to support countries along their transition towards a net zero world. This constituency is not only being asked to considerably scale up Paris Agreement-aligned investment in emerging markets and developing countries—including via blended finance in partnership with private investors—but also to move from a traditional lending role to a market-making position to catalyze investment in developing countries at the pace needed (see E3G's recent Closing the Trillion Dollar Gap to Keep 1.5 Degrees within Reach report).[50]

Standout Solutions

The Marrakech Partnership for Climate Action Finance Pathway identified five impact areas to transition finance to support a 1.5-degree C world.[51] These areas are broad and relate to all constituencies:

1. Closing the "valuation gap"
2. Tackling the "tragedy of the horizon" and short-termism
3. Creating systemic transformation tools and building capacity
4. Improving incentives and risk management
5. Zero carbon, resilient infrastructure and real assets

GFANZ and associated groups have similarly condensed and articulated the highest priority areas for governments to act on to drive the transition towards a net-zero economy. Their Call to Action to governments includes:[52]

- Setting economy-wide net zero targets for 2050 or earlier,
- Greening the multilateral and international financial architecture to deliver net-zero,
- Committing to pricing the externalities of carbon emissions,
- Creating incentives to help people, businesses and communities to go green as countries recover from the pandemic,
- And mobilizing capital flows to emerging markets and developing countries.

The standout solutions listed above are high-level priorities that will need to be translated into specific programs, initiatives and policies that can catalyze action on the ground. Some of the most promising solutions include:

- **Capital risk mitigation and scale:** Public budgets are especially strained after the COVID-19 pandemic, due to reduced fiscal revenues and increased public spending. In such a context, and with the private sector lined up with commitments and mandates to invest in the net zero transition, it is paramount that public finance capital sources are used optimally to catalyze that investment. Guarantees or blended finance structures, in which the risk and return are asymmetrically distributed, are increasingly being touted as ways to mitigate investment risk at scale.

- **Policy developments, rather than project design improvements, will be key to catalyzing the scaling up of investment.** Interventions with governments and public institutions need to address specific areas in enabling environments that are preventing the inflows of investment. An immediate priority would be to scale up technical assistance in emerging and developing economies, where the greatest investment and capacity building needs are.

- **Capacity building support for capital mobilization**: Most developing countries lack institutional capacity to develop cohesive and comprehensive capital-raising strategies linked to their climate objectives and other developmental targets. International institutions and governments have put capital aside to provide technical assistance to developing countries to operationalize and support the execution of their NDCs; however, these pockets of money often support initiatives that are narrow in scope and lack coordination between efforts. There is an opportunity to provide patient and coordinated technical support to emerging and developing economies to design and execute plans to attract capital to fulfill national climate and developmental objectives.

- **Policy financing pipeline development**: DFIs and investors in public debt solutions have the chance to use debt documentation and covenants as a tool to enforce certain policy actions that support the transition to net zero.

The outlined solutions offer some of the best existing tools to galvanize capital at the scale and pace required. They will have to be applied across all high-potential technology and policy solutions in order to limit warming to 1.5 degrees C.

The GST Process

The GST process is an important milestone for both private and public finance to demonstrate progress towards Article 2.1(c). It will be important to identify what proportion of the finance system have committed to net zero by 2050 and have adopted commitment frameworks with mid-term targets as well as robust tracking systems, which build confidence that actors will deliver on their commitments.

Unearthing the progress of public finance institutions is equally relevant. To the extent that no clear commitment frameworks have been established, the GST process will illuminate these gaps and elevate the need to accelerate progress.

Similarly, through the GST process, the extent to which the financial ecosystem has mobilized (or not) capital for developing countries will be made public. The GST process, which will inform parties' NDC updates in 2025, is an opportunity to elevate climate ambition ahead of that political moment.

Equity Considerations

The economic transition to net zero poses a great challenge to countries and workers, especially those reliant on high-carbon industries. It is critical to understand the role that finance can play in linking climate action with developmental advancement. As the transition unfolds, all actors must ensure that no workers or countries are left behind, and that the new green economies and systems provide quality livelihoods for its members. Capital providers need to incorporate this lens into their investment assessments, while governments must design policy frameworks that support it. Likewise, as we make progress on the above, and other, priorities, equity needs to be factored into how we track progress.

PART III: Conclusion

The UNFCCC recently projected that under current NDCs, global emissions will rise 16 percent over 2010 levels by 2030—dauntingly far from the 45 percent reduction needed to hold the global temperature increase to 1.5 degrees C. Yet, hope remains. According to analyses by the Climate Action Tracker in May 2021, global warming by 2100 could be as low as 2 degrees C, assuming full implementation of the net zero targets that countries have announced or are considering.[53] Notably, the key to moving closer to the Paris temperature goals is stronger short-term targets.

If approached appropriately, the GST presents a unique and invaluable opportunity to support enhanced national and global ambition by 2030. In this critical decade for avoiding climate catastrophe, the first GST could realistically make a difference in correcting the course of global emissions onto a climate safe path. We must not squander this opportunity.

Since the Paris Agreement affirmed the goal to hold warming well below 2 degrees C above pre-industrial levels, pursuing efforts to limit the temperature increase to 1.5 degrees C above pre-industrial levels, and reaching net zero global emissions around mid-century, a wealth of information has been made available on the emissions pathways for achieving these goals, as well as the opportunities and actions that can support their achievement. This paper has sought to review the multitude of existing literature and present a summary of the most promising opportunities for scaled-up, transformational mitigation. Much of that information points to a transformation that is technically feasible and beginning to take shape, although there is clearly so much more to be done in all sectors, by all actors and in all areas of the world. "Urgency, scale and a fair transformation" must be our mantra.

The GST process has already begun. The challenge will be to use the information summarized here in a way that can support the GST process and, at the same time, leverage the process to enable Parties to deliver enhanced ambition in the next NDC cycle. With that in mind, this project have used the solutions highlighted here to develop an evaluation framework, or "opportunities framework" that includes considerations for prioritizing the mitigation opportunities that could be highlighted through the GST process. With all hands on deck to bolster the effectiveness and impact of the GST, we can support the trajectory to 1.5 degrees C.

ANNEX: Solutions

Purpose

The annex is intended to provide concrete examples of how key economic sectors can come together to drive deep greenhouse gas emissions reductions in the coming decade **and enhance climate ambition in line with the goals of the Paris Agreement and the latest IPCC science**. It surveys existing literature on climate change mitigation solutions and challenges, and it breaks new ground by identifying key actors driving each solution at the international or regional level. It is not meant to be a complete summary of the many available climate solutions or to duplicate existing bottom-up modeling. Instead, it highlights key solutions from existing literature that offer some of the most significant greenhouse gas emissions reductions and removals in each sector and that could be advanced through a multilateral approach. These solutions, accompanied in this report by key actors, and taken in combination with forthcoming and recently released reports (e.g., World Resource Institutes updated State of Climate Action report, the Marrakech Partnership's detailed Climate Action Pathways) are meant to inform thinking around the ways that coalitions of countries and other actors might utilize the GST to advance solutions in the context of the 2025 NDC update.

Context

In the absence of deep reductions in carbon dioxide and other greenhouse gas emissions, global warming will exceed of 1.5 degrees C during the 21st century, according to the Intergovernmental Panel on Climate Change (IPCC).[54] Holding global temperature rise to this limit is critically important to avoid the worst effects of climate change. It will require rapid decarbonization and unprecedented sectoral transitions. The next decades are pivotal, and emissions reductions through 2030 will be key to securing a 1.5 degrees C-compatible pathway to net zero carbon dioxide emissions by 2050. IPCC's recent physical science report estimated the remaining carbon budget from the beginning of 2020 to be 500 Gt of carbon dioxide, if we're to have a 50 percent likelihood of limiting global warming to 1.5 degrees C.[55]

"All the technologies needed to achieve the necessary deep cuts in global emissions by 2030 alr eady exist, and the policies that can drive their deployment are already proven."[56] However, current policies are projected to result in nearly 3 degrees C of warming and, when recent announcements by the United States and other major emitters are considered, the world is still on track for 2.4 degrees C of warming by the end of the century. The emissions gap between current pledges and targets (as of May 2021) and a 1.5-compatible pathway is 20 to 23 $GtCO_2e$.[57] Every sector has a role to play in closing this gap.

Scope

Sectors are highlighted in this report based on their contribution to climate change. Solutions are organized by sector, which include electric, transport, industry, and buildings, as well as nature-based solutions and cross-cutting solutions.

Fossil fuel use in the first four sectors—electricity, transport, industry, and buildings—was responsible for 32 Gt of carbon dioxide emissions in 2020, with other energy sector sources responsible for an additional 2 Gt of carbon dioxide emissions. Overall, energy sector emissions in 2018 were responsible for 66 percent of total warming from greenhouse gas emissions on a 20-year timescale and 76 percent of total warming on a 100-year timescale.[4,58] In this EDF/C2ES report, emissions from industrial processes are addressed in the industry section, along with emissions from fossil fuel combustion. These emissions contributed 3 percent (GWP20) or 4 percent (GWP100) of total warming, depending on the metric used.

The next sector, nature-based solutions, encompasses solutions available through the improved use of earth's land and oceans. It is divided into three sub-sections: forests, agriculture, and blue carbon. Emissions from agriculture, land-use change, and forestry contributed 22 percent (GWP20) or 15 percent (GWP100) of total warming, depending on the metric used.

Finally, cross-cutting solutions, such as energy efficiency and methane emissions reductions, encompass solutions relevant to multiple sectors. Other solutions do, of course, have implications beyond the sector in which they're represented, so this is an imperfect categorization.

Solutions are technologies and approaches that offer promising emissions reductions and removals in each sector. These solutions were identified through a survey of relevant reports and selected based on potential greenhouse gas emissions reductions. It is important to note that there are interlinkages, trade-offs and tensions between solutions. While a few are highlighted, these are not systematically addressed in the paper. Social and environmental implications are also addressed briefly but are largely outside of the scope of this report. In some cases, solutions are applicable to more than one sector, and so the tables below reference each other.

Each solution is accompanied by a short analysis of key geographies and policies, as well as a list of influential actors (e.g., initiatives, coalitions, organizations) and barriers to deployment at

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[4] The quantification of each sector's climate impact depends on the metric used to convert emissions of non-CO_2 gases into CO_2-equivalent (CO_2e) units. GWP100, which evaluates the climate impacts of a pulse of non-CO_2 GHG emissions over 100 years, is the metric commonly relied upon in climate policies and assessments to reflect greenhouse gas emissions in terms of CO_2e. However, relying solely on GWP100 overlooks the near-term impacts of potent short-lived climate pollutants, thereby masking important trade-offs between short- and long-term policy objectives.[4] The use of GWP100 as a single metric systematically undervalues short-lived greenhouse gases' contribution to warming and, in doing so, also undervalues the importance of reducing emissions in methane-dominated sectors, such as oil and gas, agriculture, and waste. In this report, we evaluate both the near-term (20-year) and long-term (100-year) impacts of sectoral emissions by using a dual metric approach with GWP20 and GWP100 and present sectoral contributions to total global emissions with both metrics, when possible.

scale. The description of each solution is intended to inform the opportunities framework designed by C2ES and EDF. Aspects of this mitigation landscape will be further elaborated in the next phase of the project.

Solutions

Electricity solutions

<table>
<tr><td colspan="2">The power sector accounts for about 25 percent of total global greenhouse gas emissions, and global demand for electricity is projected to grow.[59] In IEA's Net Zero scenario, "total electricity generation increases over two-and-a-half times between today and 2050."[60]

This sector is important in its own right but is also seen as a pathway to the decarbonization of other sectors, from transportation to industry and buildings. Two key solutions to decarbonize this sector are renewables and energy storage. While this section largely focuses on policies and actors relevant to front-of-meter renewables and energy storage, behind-the-meter applications are also critical to grid decarbonization. High penetration levels of renewable energy and energy storage must be paired with reduced and flexible electricity demand. Some demand-side/behind-the-meter solutions are incorporated into this section, as well as throughout other sections. Solutions also include important complementary efforts such as grid modernization and the expansion of transmission and distribution infrastructure.

Under IEA's net-zero scenario, electricity sector emissions fall from 13.50 Gt of carbon dioxide in 2020 to 5.82 in 2030 and -0.37 in 2050. Under the stated policies scenario, emissions from this sector remain at 13.50 Gt of carbon dioxide in 2050.

Emission reductions on this scale would require a substantial increase in investment in the near-term. To decarbonize the sector, annual investment in electricity generation would need to increase from ~USD 0.5 trillion over the past five years to a peak of USD 1.6 trillion in 2030, then decline by one-third by 2050.[61]</td></tr>
<tr><td colspan="2">Renewables</td></tr>
<tr><td>Description of solution, quantification of opportunity
Renewable capacity additions brought renewables' share in global electricity generation up to 29 percent in 2020. IEA's Net Zero scenario assumes this will rise to 61 and 88 percent in 2030 and 2050, respectively,[62] while WRI's State of Climate Action report assumes this will rise to 98 to 100 percent in 2050. The High-Level Climate Champions' 2030 Breakthroughs envision a decarbonized global electricity system by 2040, with solar and wind generating at least 40 percent of global electricity by 2030 (with other renewables bringing that total to 60 percent by 2030).[63]

Global renewable capacity grew by nearly 280 GW in 2020, driven by a 90 percent increase in annual wind capacity additions and a 23 percent increase in annual solar</td><td>Influential actors (i.e., initiatives, coalitions, and organizations)
International Energy Agency (IEA)
International Renewable Energy Agency (IRENA)
Clean Energy Ministerial
Sustainable Energy for All (SEforAll)
Power Past Coal Alliance, led by United Kingdom and Canada</td></tr>
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installations. Similar renewable capacity additions are expected in 2021 and 2022.[64] IEA's Net Zero scenario would require 1,020 GW of annual solar (630 GW) and wind (390 GW) additions by 2030.[65] Note: Accompanying this rise in renewables is a phase-out of coal. IEA's Net Zero scenario would require no new unabated coal plants approved for development after this year, phase-out of unabated coal in advanced economies by 2030, and a full phase-out of all unabated coal and oil power plants by 2040.[66] The phasing out of fossil fuels may be accompanied by investments in renewable jobs and technology that promote economic growth and benefit local communities. The costs of wind and solar have fallen rapidly over the last decade, with utility-scale renewables seeing the most dramatic cost reductions. "Wind and solar power are now the least-expensive options for bulk electricity for two-thirds of the global population, 71 percent of global GDP, and 85 percent of global power generation."[67] Given the variability of wind and solar, these renewables will need to be accompanied by "clean firm power" or carbon-free power sources that can be dispatched whenever they're needed. These technologies can complement renewable energy, ensuring reliability and keep system costs low. Options include gas-generated power with CCS, (carbon capture technology is addressed in "Industry" section), nuclear power including small modular reactors and next generation technologies, geothermal power, and fuels without lifecycle emissions.[68] Nuclear fusion power could also reach commercial viability by the early 2030s. These all carry unique risks (e.g., methane leakage) and are contested within the environmental community. It is important to note that definitions of "renewable" and "clean" energy vary. These terms can include a range of technologies (gas with CCS, nuclear, geothermal, hydropower, low-carbon fuels), depending on the jurisdiction. Renewable power as defined by WRI's State of Climate Action report includes hydro, geothermal, solar,	and includes 41 national governments • Task Force for Clean Energy Transition, announced by Special Envoy for Climate Action, Mike Bloomberg[77] • SIDS Lighthouses Initiative, supported by the International Renewable Energy Agency (IRENA) • Towards Cleaner Electricity in Latin America and the Caribbean, led by Colombia and composed of 8 countries • Coalition for Sustainable Energy Access, composed of LDC countries and coalition member countries (Indonesia, Palau, Denmark, Colombia, Italy)[78] • Latin American Energy Organization • National Renewable Energy Laboratory • International Trade Union Confederation's Just Transition Centre • Mission Innovation • Large energy users and buyers, including corporations, municipal/local governments, and governmental entities/branches

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wind, tide, wave, biofuels, and the renewable fraction of municipal waste.[69]

Key geographies
“Policy deadlines in China, the United States and Viet Nam spurred an unprecedented boom in renewable capacity additions in 2020. China alone was responsible for over 80 percent of the increase in annual installations from 2019 to 2020.” In contrast, India, Brazil, and Ukraine led renewable capacity additions in the prior year (2019).[70]

Looking ahead, China is expected to continue to lead in renewable capacity additions, despite a projected slowdown in 2021 (driven by the phase-out of wind and solar subsidies). Meanwhile, projected annual capacity additions in Europe would make it the second-largest renewable power market (led by Germany, France, the Netherlands, Spain, the UK, Turkey). Other notable markets include the United States, India, and Latin America (with new projects coming online in Brazil, Mexico, and Chile).[71]

Countries with the highest electricity consumption (2017) include China, United States, India, Japan, Russia, Germany, Brazil, South Korea, Canada, France, United Kingdom, Italy, Saudi Arabia, Mexico, Iran.[72]

Countries with the most power sector greenhouse gas emissions include China, United States, European Union, India, Russia, Japan, South Korea, Germany, South Africa, Saudi Arabia.[73]

Countries with highest clean energy investment potential, based on Climatescope index include India, Chile, Brazil, China, Kenya, Jordan, Argentina, Ukraine, Peru, Morocco.[74]

Key actions and policies

Carbon pricing schemes that reflect the environmental cost of power generation (e.g., emissions trading schemes such as those in the European Union and China). China’s new ETS “will initially involve 2,225 companies in the power sector. Those companies are responsible for a seventh of global carbon emissions from fossil fuel combustion, according to calculations by the

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Coalitions of large energy users and buyers with renewable energy targets e.g., RE100, Global Covenant of Mayors for Climate & Energy, C40, Renewable Energy Buyers Alliance
Electric service providers, including investor-owned utilities, municipal utilities, and electric cooperatives
Grid operators, including independent services operators and regional transmission operators (ISOs/RTOs)

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Policy and other barriers

While the costs of wind and solar are competitive, their variability poses challenges. Excess solar and wind capacity to meet demand during weather fluctuations would be expensive and require vast amounts of land.[79]
Short-term PV price uncertainties due to supply chain constraints and rising commodity prices.[80]
Infrastructures and markets designed around old technologies.[81]

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International Energy Agency."[75] Carbon pricing schemes may be accompanied by rebates or investments in vulnerable communities to combat the regressive effects of pass-through costs. • Long-term contracts that reduce financing costs for zero emission generation. • Market participation models for renewable energy and regulatory policies that provide price certainty. • Mandates that require electric service providers to produce a proportion of their power from zero emission sources. • Rate structures or tax credit policies that incentivize deployments. • Market reforms that ensure available zero emission sources are dispatched first. • Coordinated procurement of renewable power by governments and businesses (e.g., RE100). Corporate renewable power purchase agreements grew 18 percent in 2020 despite the pandemic.[76] • Coordinated phase-out of unabated fossil fuels (especially coal power) and tightening of air quality standards. • Mutual learning for a just transition (e.g., Canada's Just Transition Taskforce, Germany's Coal Commission). Just transition recommendations include funding for locally operated transition centers in coal-dependent communities, pension bridging programs for early retirement, local infrastructure projects, and funding programs for workers to stay in the labor market. Just transitions also involve the active engagement and participation of impacted communities. • Development of complementary technologies needed for large-scale renewables (e.g., energy storage, demand response, zero carbon sources of flexible and dispatchable generation). • Coordination between multilateral funds and bilateral donors on investment and assistance in clean power. • Retirement of fossil fuel plants, especially peaker plants.	• Challenges of siting new renewable energy projects (and transmission infrastructure) near population centers. • Land required for a high-renewables scenario (and associated social and environmental impacts, including land clearing). • Lack of attention to end-of-life considerations, including the recycling of old solar panels, which contain valuable and toxic materials.[82] • Regional economies and government revenues dependent on coal. • Need for complementary efforts (e.g., expansion of transmission and distribution infrastructure). • Need for market design and policy framework reform (including wholesale power market reform) to ensure investment and deployment of climate-friendly technologies at scale and increase power system flexibility to integrate high shares of variable renewables. • Lack of environmentally responsible end-of-life

• Investment in grid modernization and transmission and distribution infrastructure to enable high levels of renewable deployment. • Streamlined "soft costs" of renewable power, including interconnection, siting, and permitting. • R&D into recycling for raw materials in solar panels. • R&D into next generation of solar and wind technologies, such as advanced solar panels, floating solar, floating offshore wind, and tall-tower wind. • Policies, markets, and regulations to encourage demand-side and distributed energy resources, generation resources sited closer to load, demand response, demand flexibility, load shifting, peak shaving, and energy efficiency.	disposal and economic recycling options. • Lack of supportive renewable energy policies and financial incentives for incumbent electricity providers to invest in renewables. • Cumbersome, time-consuming, and costly soft costs. • Local opposition to certain types of development, often described as NIMBYism (NIMBY stands for "Not In My Backyard").
Energy storage	
Description of solution, quantification of opportunity Energy storage plays an important role in IEA's net zero scenario, which envisions a massive scale-up to 3,100 GW of storage in 2050 (with four-hour duration on average).[83] Energy storage can provide grid flexibility and enable high levels of renewable energy deployment. Annual installations of energy storage technologies declined for the first time in nearly a decade in 2019, with grid-scale storage installations dropping by 20 percent.[84] Installations in 2019 totaled 2.9 GW. The term "energy storage" applies to a diverse set of technologies. Storage technologies generally fall into five different technology categories: mechanical storage, electrochemical storage, thermal storage, electrical storage, and chemical storage. Pumped hydropower—a type of mechanical storage—is a well-established technology that accounts for the majority of the world's storage capacity. Meanwhile, lithium-ion batteries—a type of electrochemical storage—have experienced the fastest	**Influential actors (i.e., initiatives, coalitions, and organizations)** • Energy Storage Initiative[94] • Energy Storage Partnership • Clean Energy Ministerial • Mission Innovation Ministerial • International Energy Agency • IEA's Energy Conservation and Energy Storage Technology Collaboration Programme • Energy Storage Initiative

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<td rowspan="2">growth in recent years. Other types of storage include lithium-ion phosphate batteries, nickel manganese cobalt batteries (produced primarily in Korea), compressed-air, gravity storage, aqueous-air batteries, and hydrogen (longer term seasonal storage).

There is also an important temporal component of energy storage. Different technologies have different storage durations and can meet different capacity and grid needs (e.g., providing operating reserves, peaking capacity, diurnal capacity, seasonal capacity, etc.), providing storage for increments ranging from 15 min, 4 hours, 8+ hours or across seasons.

The scale-up of battery manufacturing and use in Evs has driven deployment in the power sector. Another driver of growth has been the “co-location of renewable energy production facilities with energy storage assets, which stabilizes production and ensures firmer capacity during peak demand periods.”[85] Such co-location, however, could result in congested transmissions lines, which could be avoided by locating storage closer to demand. And, in California, growth in storage has been driven by concerns over grid resilience to wildfires.[86]

The cost of energy storage using lithium-ion batteries is falling rapidly, with the current levelized cost of energy storage from these systems at $132 per MWh. “Lithium-ion battery pack prices fell 89 percent from 2010 to 2020,” and that trend is expected to continue.[87]

Key geographies
• Countries that have historically led on energy storage deployment include Korea, China, the United States, and Germany. See deployment by country in IEA’s energy storage tracking report.[88]
• The U.S. Department of Energy recently announced a new goal to reduce the cost of long-duration (10+ hours) energy storage by 90 percent in one decade.[89]
• Despite being a global leader, Korea has faced challenges in the last few years (elaborated in barriers section).[90]</td>
<td>• Electric service providers
• U.S. Department of Energy’s Energy Earthshot Initiative</td>
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<td>Policy and other barriers

• Lack of rules and regulations to clarify the role of battery energy storage systems.[95] Also, in many markets, “storage is considered a generation asset and system operators (for transmission as well as distribution) are not allowed to own storage devices.”[96]
• Lack of markets for certain system services that storage can provide.[97]
• Technical or design risks. A decline in energy storage deployment in Korea from 2018 to 2019 was due to several fires at grid-scale storage plants in 2019.[98]
• Technical limitations to long-duration energy storage (LDES).
• Supply chain limitations and geopolitical risks associated with raw materials (e.g., cobalt and lithium) used in batteries.</td>
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Australia, ranked fifth in the world for market size, is a key market for behind-the-meter storage. In addition, sales of behind-the-meter storage in Japan grew after the phaseout of solar incentives, as consumers sought to use more of their own electricity production.[91]

Key actions and policies
Energy storage technologies “continue to depend heavily on policy intervention through direct support or market creation.”[92] While “direct support for storage through mandates and policies remains the most common option to 31ncentivize deployment, […] greater emphasis should be placed on making regulations transparent and open, and on developing markets for capacity, flexibility and ancillary services so that storage can compete with other technologies and measures.”[93]
IEA recommends the following:

Focusing policy design on flexibility (rather than individual technologies) and understanding technologies in the context of the services and applications they provide.
Creating clear and transparent regulatory frameworks.
Expanding the role of storage, including aggregated distributed storage, in ancillary service and flexibility markets.
Prioritizing the most easily accessible applications (such as co-siting renewables and storage).

Additionally:

Streamlined “soft costs” of energy storage, including interconnection, siting, and permitting.
R&D into recycling for raw materials in batteries.
R&D into next generation of storage, including long-duration energy storage.
Policies, markets, and regulations to encourage demand-side/customer-sited/behind-the-meter energy storage.

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Mineral demand and associated negative environmental and social impacts of mining.
Lack of environmentally responsible end-of-life disposal and economic recycling options.
Data and analysis gaps that could deter investments.[99]
Limited remaining sites for new pumped hydro development and associated negative social and environmental tradeoffs.[100]

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Transport solutions

<table>
<tr><td colspan="2">The transport sector—aviation, shipping, rail, and road transport—accounts for approximately one quarter of global anthropogenic carbon dioxide emissions.[101] Within this sector, on-road vehicles contribute 77 percent of carbon dioxide emissions, with marine and aviation contributing 11 and 10 percent, respectively.[102]

Under IEA's Net Zero scenario, transportation sector emissions fall from 7.15 Gt of carbon dioxide in 2020 to 5.72 in 2030 and 0.69 in 2050. Under the stated policies scenario, emissions from this sector are 9.33 Gt of carbon dioxide in 2050.

Decarbonization solutions for this sector are at varying stages of maturity. For this reason, dramatic emission reductions will likely happen first in light-duty vehicles (which can use low-emission technologies on the market). Significant progress in decarbonizing heavy-duty vehicles is possible over the coming decade, while ships and airplanes could require a longer runway.

A transition will require (1) "a shift towards electric mobility" (Evs and FCEVs) and (2) "shifts towards higher fuel blending ratios and direct use of low-carbon fuels" (biofuels and hydrogen-based fuels).[103] In IEA's net zero analysis, "biofuels are increasingly used for aviation and shipping [after 2030], where the scope for using electricity and hydrogen is more limited. There is ongoing debate over the extent to which biofuels may compete with growing demand for crop production, although certain biofuels are sourced from agricultural residues and waste products. Biofuels may have an adverse effect on food prices, forest conservation, soil health, and biodiversity, which may negatively impact greenhouse gas emissions. Hydrogen carriers (such as ammonia) and low-emissions synthetic fuels also supply increasing shares of energy demand in these modes." In addition to alternative fuels, there are important gains to be made in the efficiency of operations and technologies.

Other solutions include efficiency gains (addressed briefly in the "Cross-Cutting" section), electrifying other forms of ground transport (including public transit and rail), and climate-smart urban planning and infrastructure development.</td></tr>
<tr><td colspan="2">Electric vehicles (Evs)</td></tr>
<tr><td>Description of solution, quantification of opportunity
Road transportation is responsible for 11.9 percent of global greenhouse gas emissions,[104] with cars contributing about 7 percent of global greenhouse gas emissions and trucks contributing 3 percent.[105] Since on-road transportation is also a significant contributor of local air pollution (e.g., particulate matter), emissions reductions can have far-reaching benefits.</td><td>Influential actors (i.e., initiatives, coalitions, and organizations)

• International Zero Emission Vehicles Alliance
• Transport Decarbonization Alliance
• International Transport Forum</td></tr>
</table>

Overall, battery electric vehicles are the predominant decarbonization technology. Other technologies include efficient internal combustion engines, biofuels, and hydrogen fuel cells. At present, hydrogen fuel cell vehicles are being deployed at far lower rates than battery electric vehicles but are experiencing rapid growth and attention due to their potential to decarbonize classes of vehicles that may be harder to electrify. While biofuels may have a role in decarbonizing long-haul trucks,[106] certain medium- and heavy-duty market segments are poised for swift electrification.[107] There are dozens of available zero-emission models for medium- and heavy-duty vehicle types (e.g., delivery vans, transit buses, garbage trucks), and additional models (both battery electric and hydrogen fuel cell) expected in the long-haul market over the next few years.[108] Challenges posed by recharging times, the weight of batteries, and instantaneous power requirements could make hydrogen (in some form) more attractive for use in medium- and heavy-duty trucking than batteries. Estimates of total EV deployment vary: • IEA: By the end of 2020, there were 10 million electric cars on the world's roads and, in that year, Evs comprised 4.6 percent of global car sales. Electric bus and truck registrations also expanded in 2020, reaching global stocks of 600,000 and 31,000, respectively.[109] • BNEF: "There are now 12 million passenger Evs on the road and electrification is spreading to other segments of road transport. There are over 1 million commercial Evs, including buses, delivery vans and trucks, and there are over 260 million electric mopeds, scooters, motorcycles and three-wheelers on the road globally." EV share of total sales: 1 percent (vans and trucks), 4 percent (passenger cars), 39 percent (buses), 44 percent (two and three wheelers).[110]	• World Economic Forum's Global Battery Alliance • Clean Energy Ministerial (Electric Vehicles Initiative) • EV100 • C40 Cities • ICLEI • Global Covenant of Mayors for Climate & Energy • G20 Transport Task Group (esp. heavy-duty vehicles) • Smart Freight Centre (and its Global Logistics Emissions Council) • International Council for Clean Transportation (ICCT) • Action Towards Climate Friendly Transport (ACT), led by UN Habitat[135] • ICLEI • Clean Air Initiative[136] Select manufacturers (w/ medium- and heavy-duty vehicle targets/investments) • Daimler (all new trucks and buses in North America will be carbon neutral by 2039, allocated $85 billion) • Volvo (target of fossil free by 2040) • Cummins • Ford • General Motors Select fleets (w/ medium- and heavy-duty vehicle targets/investments) • Walmart (zero-carbon operations, including long-haul trucks, by 2040) • FedEx • Amazon

IEA's Net Zero scenario would require 60 percent of global car sales to be electric by 2030 (and no new ICE car sales after 2035) and 50 percent of heavy truck sales to be electric by 2035.[111] The High-Level Climate Champions' 2030 Breakthroughs envision the following: by 2025, 15 percent of total global passenger vehicle and van sales are ZEVs, 8 percent of global heavy goods vehicle sales are BEVs and FCEVs, and 75 percent of global bus sales are BEVs and FCEVs. By 2030, 100 percent of bus sales in leading markets are BEVs and FCEVs; by 2035, 100 percent of passenger vehicle and van sales in leading markets are ZEVs; and by 2040, 100 percent of heavy goods vehicle sales in leading markets are BEVs and FCEVs. "Leading markets" means China, European Union, Japan, and the United States.[112]

Factors driving the market include government policy and industry investment. Also key are increasing average battery density (rising at 7 percent per year) and charging speeds, as well as falling lithium-ion battery prices (down 89 percent from 2010 to 2020).[113] Analysts expect price parity between Evs and conventional vehicles around the mid-2020s.[114]

IEA's net zero pathway would require a significant percentage of vehicles to be electric by 2050 (86 percent of cars, 79 percent of buses, 59 percent of heavy trucks), with annual battery demand for Evs rising from 0.16 TWh in 2020 to 6.6 TWh and 14 TWh in 2030 and 2050, respectively.[115]

Bloomberg's net zero scenario (in which the entire road fleet runs on electric or hydrogen) foresees global electricity demand from Evs increasing to 8,500 TWh by 2050.[116] "As soon as 2030, nearly 60 percent of new car sales must be zero emissions, to stay on track for the Net Zero Scenario."[117]

Key geographies

Emissions
"The four largest vehicle markets, in terms of new vehicle sales—United States, China, the European

- Ikea
- U.S. Postal Service

Policy and other barriers

- High up-front costs of Evs, especially high cost of zero emission trucks.[137]
- In the case of electric trucks, weak demand due to lack of policy in most markets.[138]
- Incumbent industry pushing for weak policy.[139]
- Lack of charging infrastructure, particularly in low-income and rural communities, as well as a supply-and-demand problem.[140]
- Technical challenges that need to be solved to improve the performance, lifetime, and energy density of batteries.[141]
- Lack of familiarity with Evs and "range anxiety"
- Supply chain limitations and geopolitical risks associated with raw materials (e.g., cobalt and lithium) used in batteries.
- Negative environmental and social impacts of mining of raw materials, including lithium and cobalt.
- Lack of environmentally responsible end-of-life disposal and economic recycling options.

Union, and India—account for 46 percent of global carbon dioxide emissions from transportation."[118] *Sales of Evs* *Cars*: Ten countries account for about three quarters of all EV sales (China, US, Germany, India, Japan, UK, France, Brazil, Italy, Canada), and three regions (EU, China, California) account for more than half of global EV sales.[119] In 2020, Europe overtook China as the world's largest EV market.[120] Until then, around half of all EV sales were in China, and most of the rest were in developed countries. In Europe alone, the number of EV models on the market increased from about 40 in 2019 to 333 by 2025.[121] "Electric vehicle sales are close to or well above 5 percent of sales for almost every manufacturer selling in Europe."[122] *Trucks*: Five countries plus the EU comprise over half of the global heavy-duty vehicle market (China, US, EU, Canada, Japan, India). These countries and regions provide various forms of policy support (further detail in IEA's Global EV Outlook). New Zealand has also recently established a zero-emission public transit mandate, while Chile and Colombia have national targets to electrify their bus fleets.[123] Over 75 percent of global lithium can be found in the "Lithium Triangle" of Chile, Argentina, and Bolivia.[124] In 2020, mining in the Democratic Republic of the Congo was responsible for nearly 70 percent of total cobalt mined.[125] The current geographic concentration of raw material extraction limits the scalability of Evs and poses questions of equity and social responsibility, as production has historically been accompanied by exploitation and human rights abuses.[126] **Key actions and policies** • Regulatory standards to cap allowable emissions of key pollutants or limit emissions intensity. In the United States, multipollutant standards for passenger vehicles that ensure all vehicles sold in 2035 are zero-emitting could deliver	

significant reductions in climate and local air pollution (as well as consumer savings, jobs, etc.) and nearly eliminate all tailpipe carbon dioxide emissions from light-duty vehicles by 2050.[127] Combined with similar standards for medium- and heavy-duty vehicles, they could eliminate more than 16.2 billion tons of greenhouse gas emission cumulatively by 2050.[128] • Fuel economy standards, such as those in place in the United States. • Coordinated phase-out of fossil fuel vehicles and trucks, including provisions to protect impacted populations from fuel price increases and ensure adequate access to transportation infrastructure and alternatives. Mexico City, Paris, Madrid, and Athens have committed to end diesel engine use by 2025. By the end of 2020, 20+ countries announced bans on the sales of conventional cars or mandated all new sales to be ZEVs.[129] Bloomberg reports that 15 countries and 31 cities/regions have announced plans to phase out internal combustion engine vehicles.[130] • Purchase incentives (and taxes on fossil fuels) to lessen upfront cost differential and provide cost parity at an earlier date. In Norway, a tax and subsidy combination has made ZEVs cheaper than fossil-fuel powered models.[131] Fossil fuel taxes can have a regressive effect, with increases in fuel costs disproportionately harming low-income and environmental justice communities. Taxes can be accompanied by rebates or targeted investments. • Public investment in infrastructure and standardization of charging and refueling infrastructure to ensure inter-operability. Cities, states, and provinces on the same freight routes could coordinate infrastructure investments.[132] • International cooperation on standards for charging infrastructure and coordinated deployment of charging and refueling infrastructure on international routes. [133]	

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- Subnational and city-level policies that incentivize ZEVs (e.g., mandates, access to special lanes, clean air zones).
- With respect to light-duty vehicles, coordinated tightening of regulatory trajectories across key markets (see list of key EV markets in above section). Note: Trucks are traded across borders much less than cars and, since the nature of demand varies, manufacturers are used to designing different products for different regions. There is consequently less potential for standards in one country to shift investment patterns internationally.
- Coordinated procurement by governments, businesses, and logistics and retail companies.
- Mutual learning on market-creating policies (e.g., purchase incentives, regulatory standards).
- Coordinated development and deployment of complementary technologies and policies (e.g., vehicle-to-grid charging).
- Gasoline and diesel taxes "at rates that reflect their environmental and human health impacts can provide government revenue, reduce their negative impacts and hasten the transition to electric mobility. Differentiated taxation of vehicles and fuels that reflect their environmental performance can further align markets with the climate benefits of Evs."[134]
- Decarbonization of electricity generation (see "Electricity" section).
- Education around lifecycle costs of electric vehicles.
- EV mandates.

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<tr><td colspan="2">Alternative shipping fuels</td></tr>
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Description of solution, quantification of opportunity
Alternative fuels and technologies include hydrogen (see "Industry" section for further detail), ammonia (which has a higher energy density than hydrogen) and biofuels (which can be blended and used in today's engines but have significant downsides). Other

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Influential actors (i.e., initiatives, coalitions, and organizations)

- International Maritime Organization
- Global Maritime Forum
- World Economic Forum

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solutions include methanol, electric propulsion, and nuclear power. Electric propulsion (either batteries or hydrogen fuel cells) holds the most promise on short-haul routes. Biodiesel, hydrogen, and ammonia are options on long-haul routes, of which the latter two are used in combustion engines or fuel cells.[142] In the near-term, there is likely to be interest in using fuels that are largely compatible with existing engines (e.g., biodiesel and ammonia), given the long timeframe of vessels.[143] Biodiesel is likely to be constrained by a limited supply of sustainable biomass, which "leaves ammonia looking like a tentative front-runner for long-haul shipping."[144] Ammonia can be produced from green hydrogen and could be competitive with heavy fuel oil with a carbon price of 145 USD/tCO2 in 2050.[145] While retrofitted ships powered by ammonia, for example, could more easily operate between cooperating ports, dual fuel engines that accommodate multiple fuel types could enable ships to traverse global routes. There is also some interest in using LNG in "fuel-agnostic" fuel cells, which could later be swapped for cleaner alternatives like hydrogen and ammonia.[146] Switching to LNG, however, risks creating lock-in or stranded assets, as it does not represent a long-term decarbonization option.[147] Regardless, it will be important for both methane and hydrogen leakage to be included in any lifecycle assessment of fuels. **Key geographies** Categories below defined by Selin et al. In all instances, 69 percent to 75 percent of total carbon dioxide emissions can be attributed to the top ten countries.[148] • Top 10 flag countries: Panama, Liberia, China, Marshall Islands, Singapore, Malta, Bahamas, United Kingdom, Greece, Denmark • Top 10 owner countries: Japan, Greece, Germany, China, United States, United Kingdom, Singapore, South Korea, Denmark, Norway	• World Ports Climate Action Program (seven ports that account for ~6 percent of global shipping freight) • Mission Innovation • World Economic Forum • High-level Panel for a Sustainable Ocean Economy, led by Norway and Palau and composed of 14 countries • Getting to Zero Coalition, which is endorsed by 14 countries (Belgium, Denmark, France, Korea, the Netherlands, Palau, Sweden, Chile, Finland, Ireland, Morocco, New Zealand, Poland, and the United Kingdom)[163] • Ports (e.g., Port of Rotterdam has partnered with Shell to explore green hydrogen network)[164] • Segments of the shipping industry that could coordinate action (e.g., cruising industry, owners and operators of ammonia transport ships).[165] • Consumer goods companies and logistics providers, which could offer sustainable shipping guarantees to customers.[166]
	Policy and other barriers • "High cost of low emission options prohibitive in competitive global industry (without coordination)."

• Top 10 operator countries: Japan, Greece, China, United States, Germany, Singapore, Denmark, South Korea, United Kingdom, Switzerland • Top 10 manager countries: Greece, Germany, Japan, China, Singapore, United States, United Kingdom, South Korea, Denmark, Norway • Top 10 bunker fuel countries: Singapore, China, United States, UAE, the Netherlands, Russia, South Korea, Spain, United Kingdom, Belgium Also important are shipbuilding countries (e.g., China, Japan, South Korea). Small groups of highly interconnected ports could coordinate standards and infrastructure assessment. Examples include ports in Asia/North America (world's busiest shipping corridor) and Europe/North Africa (with fuels produced by cheap hydropower from Nordic countries or solar power from Mediterranean countries). The top 20 ports are in 12 countries and jurisdictions and control 45 percent of global container freight. Fifteen are in Asia, with eight on the Chinese mainland. There are also state-owned ferry services in a number of countries (e.g., Canada, Scotland, Finland, and Indonesia).[149] "While shipbuilding is largely concentrated in developed countries, the reconfiguration of the sector presents an opportunity for economic benefits to be spread more widely. A total investment of around US$6 trillion in renewable energy and low carbon ammonia production plants could be required to 39ecarbonize a large share of international shipping freight by mid-century. Developing countries with plentiful renewable energy resources could be well placed to attract this investment, and to create jobs through the establishment of supporting supply chains and services."[150] One recent study found that South Africa is particularly well-placed to produce zero carbon shipping fuels, given its renewable energy potential and geographic	Switching from heavy fuel oil to zero carbon fuels could increase operating costs by 180 to 240 percent.[167] • "Supply-and-demand problem for low emission fuels and infrastructure."[168] • Technology for low emission options such as hydrogen and ammonia has not yet demonstrated at scale.[169] Hydrogen faces space constraints. Energy density of batteries could be improved. • Assets have long lifespans • Cost of fuel cells today, which are more expensive than internal combustion engines.[170] Fuel cells do, however, have competitive operating costs. • Existing energy efficiency mandates are unlikely to make a dent in emissions, given the sector's projected growth. • Five containership operators own over half the total capacity of the global fleet (could be a barrier or an opportunity).[171]

location on established shipping routes.[151] Its G20 and BASIC membership make it an important influencer. **Key actions and policies** • Coordinated standards and infrastructure investment, including by a small group of highly interconnected ports or segments of the market (e.g., cruising industry). Potential application of zero emission standards to all global shipping or among largest ports and countries.[152] • Coordinated purchase of low emission shipping services by businesses in consumer goods and logistics industries," such as a buyers alliance of consumer goods and logistics firms, similar to RE100 and EV100.[153] • Coordinated procurement of low emission vessels or fuels on routes that are state-owned, operated, or licensed" (e.g., ferries).[154] • Large-scale demonstration and testing to pilot and prove technology, resolve storage and safety questions, and refine economic assessments.[155] Additional research and development.[156] • Policies that reduce the cost of green hydrogen (see "Industry" section for further detail), which can be used to produce ammonia.[157] • Expansion of infrastructure used to supply and store alternative fuels.[158] • Green port fees (though they are unlikely to be high enough to be impactful).[159] • Coordinated action across countries on the minimum corporate tax rate can generate revenues from shipping that could be used for climate purposes. • Policies that price carbon dioxide and other emissions, including market-based measures under discussion at the International Maritime Organization (IMO). • Policies that incentivize or require operational efficiency, such as those adopted by the IMO. • Allocating emissions to national governments based on ships' flag country, owner country,	

operator country, manager country, or bunker fuel country.[160] • Green port fees, though they're unlikely to be high enough to be impactful.[161] • Coordinated action across countries on the minimum corporate tax rate can generate revenues from shipping. The European Commission recently proposed to include shipping in the EU ETS. However, there are concerns that unambitious targets for the carbon content of marine fuels in the EU's "Fuel EU Maritime" proposal could boost the use of LNG and biofuels instead of zero carbon fuels.[162]	
Alternative aviation fuels	
Description of solution, quantification of opportunity Sustainable aviation fuel (SAF) is ASTM International-certified drop-in aviation fuel that is derived from renewable sources or waste feedstocks. It currently represents less than 0.1 percent of global aviation fuel due to insufficient, disaggregated demand and cost barriers.[172] The High-Level Climate Champions' 2030 Breakthroughs envision 10 percent of aviation fuels will be SAF by 2030.[173] SAF can include: (1) fuels of biogenic origin; (2) fuels derived from hybrid feedstocks such as municipal solid waste; (3) liquid hydrogen; (4) recycled-carbon-based fuels (e.g., off-gases of fossil origin from steelmaking); and (5) electro-fuels (e-fuels, also known as "power-to-liquids"). Contrary to what is often reported, SAF is not carbon neutral and the emissions reductions it provides vary depending on the fuel. However, SAF has the potential to unlock greater emission reductions than what could be achieved through other technological improvements if it meets a high standard for environmental integrity, and accounting for its emissions reductions is transparent and accurate.[174]	**Influential actors (i.e., initiatives, coalitions, and organizations)** • International Civil Aviation Organization (ICAO) • World Economic Forum's Clean Skies for Tomorrow Initiative • Sustainable Aviation Buyers Alliance • Eco-Skies Alliance • Airlines for America (A4A) • International Air Transport Association (IATA) Sustainability Certification Schemes (CORSIA-approved) • International Sustainability and Carbon Certification (ISCC) • Roundtable on Sustainable Biomaterials (RSB) Companies • SABA: Boston Consulting Group, Boeing, Deloitte,

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<td rowspan="2">To date, eight SAF pathways have been approved, of which only one, the hydro-processed esters and fatty acids (HEFA) pathway, is technically mature and commercialized. The HEFA pathway has the potential to cover between 5 and 10 percent of total jet fuel demand and achieve emissions reductions as high as 73 to 84 percent compared to fossil jet fuel.[175]

In the medium-term, both the alcohol-to-jet and gasification/Fischer Tropsch pathways are expected to reach technical and commercial maturity. Both offer greater emissions reductions than HEFA: as high as 85-94 percent compared to fossil jet fuel.

By some estimates, there is a sufficient supply of advanced and waste feedstocks to produce almost 500 Mt of SAF per year, greater than the 410 Mt of jet fuel demand expected in 2030.[176] Replacing 100 percent of international aviation fuel demand with high-integrity SAF from biofuels could achieve 10 Gt of carbon dioxide emissions reductions through 2050 (17 Gt of carbon dioxide if domestic flights are included). This is equivalent to 40 percent of total forecasted carbon dioxide emissions from international aviation. Further emissions reductions could be achieved using e-fuels.

E-fuels are expected to play a critical role in aviation decarbonization from 2030 onward. E-fuels can provide lifecycle emissions reductions close to 100 percent compared to fossil jet fuel. Their deployment requires a sufficient supply of surplus renewable energy. The cost of e-fuels is expected to decline significantly as renewable energy and electrolyser costs fall, bringing the e-fuel cost in-line with other SAF by 2040.[177]

Overall, the combination of biofuels and e-fuels has the potential to fully decarbonize aviation by 2050. The right policy and regulatory incentives are crucial to support the uptake of these technologies (EDF, SAF Guide).</td>
<td>JPMorgan Chase, Microsoft, Netflix, Salesforce
• Other buyers: American Airlines, Amazon Air, etc.
• SAF Producers: Neste, LanzaJet, World Energy, SkyNRG, Gevo, Velocys, Red Rocks

Airports
• e.g., San Francisco (SFO)
• At the start of 2019, five airports were using biofuels: Bergen Airport (Norway), Brisbane Airport (Australia), Los Angeles International Airport (United States), Oslo Airport (Norway), and Stockholm Arlanda Airport (Sweden).[180]</td>
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<tr>
<td>Policy and other barriers

• Technological and commercial barriers, as only one of eight approved production pathways is technologically mature and commercialized.
• Cost premium, since SAF is still cost-prohibitive for most airlines. Conventional jet fuel is already the largest overhead expense for airlines.
• Availability. Despite limited use, demand for SAF exceeds production capacity. And only seven airports regularly distribute SAF.</td>
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Key geographies States coordinate on action related to international aviation via the International Civil Aviation Organization (ICAO), a UN agency with 193 Member States. At the national and sub-national level, the European Union and United States are both leading on establishing policies and regulations that incentivize SAF use. Both jurisdictions are also major sources of aviation emissions. Of Annex I countries, the US has the highest aviation emissions (both domestic and international) and EU Member States France and Germany round out the top five.[178] As investment in SAF increases, states that have abundant sustainable biomass and low-cost renewable energy stand to benefit. **Key actions and policies** The international framework for SAF policy is fairly well developed and operational. However, national and sub-national policy incentives for aviation alternative fuels are generally embedded in broader alternative fuel and emission reduction policies, which vary in their design and effectiveness. The International Civil Aviation Organization (ICAO)'s Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), adopted in 2016, caps the net CO_2 emissions of international flights. CORSIA allows airlines to meet their caps by reducing emissions directly by purchasing ICAO-approved offsets and utilizing CORSIA-eligible fuels that, on a lifecycle basis, reduce emissions below those of conventional jet fuel. The CORSIA framework for SAF holds enormous potential to incentivize the production of truly climate-beneficial SAF: the market is large; the framework's lifecycle emissions calculation methodologies are comprehensive; and the framework avoids problems that arose with earlier attempts to stimulate alternative fuel development. The CORSIA Pilot Phase launched in 2021, but due to COVID-19 impacts and ICAO's decision to change the pilot phase baseline to 2019 levels,	• Current maximum blend ratio of SAF to conventional jet fuel approved by ASTM International is 50 percent. • Lack of a robust accounting framework that prevents double counting of emissions reductions. • Lack of SAF-specific incentives. Most incentives for SAF are embedded in broader alternative fuel policies. Because the road sector has a higher incentive, it outcompetes aviation for alternative fuel volumes.

airlines are not expected to have offsetting obligations for at least the first three years of CORSIA.[179] In the United States, two federal policies incentivize alternative fuels deployment: (1) the Biodiesel Tax Credit (1 USD/gallon) and (2) the Renewable Fuel Standard. In Congress, negotiations on a SAF-specific tax credit are ongoing. At the subnational level, California's Low Carbon Fuel Standards includes an opt-in for aviation fuel. The added incentive means that in the US, volumes of SAF are currently concentrated in California, although this may change as more states adopt fuel policies and action is taken at the federal level. In the European Union, two policy measures incentivize alternative fuel deployment: (1) the Recast of the EU Renewable Energy Directive (EU RED II), effective 2021, and (2) the EU Emissions Trading System (EU ETS). EU RED II requires that by 2030, 14 percent of all energy supplied to the road and rail transport sectors come from renewable sources, with an opt-in for aviation. The EU ETS includes all flights within the European Economic Area, and a rule requires that all biofuels have net zero CO_2 combustion emissions. The forthcoming "Fit for 55" package is expected to shift the policy landscape in Europe to create additional incentives for SAF. This package will include revisions to both EU RED II and the EU ETS as well as the new legislative RefuelEU Aviation initiative, which will introduce a SAF mandate for Europe.	

Industry solutions

Industry is responsible for 29 percent of all global energy use, and around a fifth of all greenhouse gas emissions.[181] Due to production and consumption patterns, roughly 20 percent of emissions are generated by advanced economies and 80 percent originate in developing economies.[182] Three heavy industries—steel, cement, and chemicals—account for around 70 percent of direct carbon dioxide emissions from the industrial sector. [183,184]

Emissions from this sector are the result of industrial processes (e.g., chemical reactions necessary for cement production) and the combustion of fossil fuels for heat and power required to drive these processes.

Emissions reductions can be achieved through various means, including fuel switching, capturing or otherwise reducing process emissions, efficiently using and recycling materials, and increasing energy efficiency (addressed in the 'Energy Efficiency' section). This section covers alternative fuels—hydrogen, in particular—as well as carbon capture. It concludes by addressing hydrofluorocarbons (HFCs), chemicals widely used in air conditioning, refrigeration, and other applications.

Reducing demand for primary resources can also play a key role in decarbonization of the industrial sector. For example, recycling used plastics can reduce demand for virgin ethylene, a chemical used to make plastics, and electric arc furnaces can be used to produce new steel from recycled material. Other solutions in this sector include circularity, electrification (e.g., electric arc furnaces for recycled scrap steel), new process designs (e.g., using hydrogen to oxidize iron ore in making virgin steel), and bioenergy (e.g., using biomass to heat kilns).

Under IEA's Net Zero scenario, industry emissions fall from 8.48 Gt of carbon dioxide in 2020 to 6.89 in 2030 and 0.52 in 2050. Notably, hydrogen and CCUS technologies (addressed below) contribute ~50 percent of the emissions reductions in heavy industry in 2050.[185]

Barriers to rapid emission reductions in this sector include the need for high-temperature heat (not easily provided by electricity), the ease with which industrial materials and products are traded (which means markets are competitive and margins are low), and the use of capital-intensive and long-lived equipment (slows deployment of new technologies).[186]

Additional context and background:
Within the industrial sector, steel, cement and chemicals were responsible for nearly 60 percent of all energy consumption and about 70 percent of carbon dioxide emissions. Further, emerging market and developing countries are responsible for 70 to 90 percent of the output of these commodities, with China producing about 60 percent of both steel and cement in 2020."[187]

<u>Steel</u> was responsible for 3.6 GtCO_2e and ~9 percent of total energy-related emissions in 2019.[188] It is produced largely by burning coal to melt iron ore. Potential decarbonization

options include using hydrogen or biomass (instead of coal), deploying carbon capture, using hydrogen to remove impurities from iron ore without a blast furnace, reducing demand for primary steel, and increasing in energy efficiency. Cement is responsible for ~7 percent of the global industrial energy use and, as of 2014, the sector had the second largest share of total direct industrial carbon dioxide emissions.[189] Thirty to 40 percent of direct carbon dioxide emissions are from fuel combustion, while 60 to 70 percent of direct carbon dioxide emissions are from the chemical reactions needed to convert limestone to calcium oxide. Industrial process emissions totaled 1.5 Gt of carbon dioxide emissions in 2019, of which 63 percent originate in the cement sector.[190] Solutions include (from least to most emission reduction potential): energy efficiency, switching to less carbon intensive fuels, reducing the clinker to cement ratio, and integrating carbon capture into cement production.[191] Reducing the clinker to cement ratio could entail increasing the use of blended materials and the market deployment of blended cements.	
Hydrogen	
Description of solution, quantification of opportunity There is growing consensus that hydrogen will play a key role in a net zero future, especially in industry (steel and cement) and transport (aviation and shipping). It may also have a role to play in the electric and buildings sectors and could also be considered a cross-cutting solution. There is ongoing uncertainty and debate, however, about its production and appropriate application, given the potential for hydrogen leakage and conversion losses. Investment is nevertheless accelerating rapidly. Since February 2021, 131 large-scale projects have been announced globally, increasing the total to 359 hydrogen projects, according to the Hydrogen Council.[192] Recent analysis by IEA, BloombergNEF, the Hydrogen Council, the Energy Transitions Commission, and others provide insight on the scale and scope of potential hydrogen use. Note: "Grey" hydrogen is fossil fuel-based and is the predominant variety used today. "Blue" hydrogen is fossil fuel-based with carbon capture technology, and "green" hydrogen is produced with renewable energy (via electrolysis).	**Influential actors (i.e., initiatives, coalitions, and organizations)** • International Energy Agency (IEA) • Hydrogen Council • Mission Innovation • Mission Possible • Clean Energy Ministerial's Hydrogen Initiative • UNFCCC's Green Hydrogen Catapult • U.S. Department of Energy's Hydrogen Energy Earthshot • World Economic Forum's Accelerating Clean Hydrogen Initiative • Green Hydrogen Coalition • The Leadership Group for Industry Transition, led by Sweden with support from the World Economic Forum and composed of 16 countries[216]

<u>Scale</u>: IEA's net zero pathway would require production and consumption of hydrogen-based fuels to scale from 87 Mt in 2020 to 150 Mt in 2030 to 528 Mt in 2050, with the vast majority of that (520 Mt) considered low-carbon. Of total low-carbon hydrogen, 38 percent would be fossil fuel-based with CCUS and 62 percent would be electrolysis-based.[193] In contrast, a report by the Energy Transitions Commission notes that blue hydrogen could make up just 15 percent of the 500 to 800 Mt of total hydrogen needed in 2050, with green hydrogen responsible for the other 85 percent.[194] The High-Level Climate Champions' 2030 Breakthroughs envision 500 to 800 MMT of green hydrogen production capacity deployed by 2050. In the interim, they aim for 25 GW of green hydrogen capacity deployed to bring the price below 2 USD/kg by 2026.[195] While a number of analyses include a role for fossil fuel-based hydrogen with CCUS, others note that scaling up fossil fuel-based hydrogen is inconsistent with calls for rapid phase out of fossil fuel use. Nearly all hydrogen produced today is fossil fuel-based.[196] Regardless, any lifecycle emissions analysis of fossil fuel-based hydrogen with CCUS would need to take into account methane leakage from gas production. *<u>Scope</u>:* There is some disagreement about the appropriate end-use of hydrogen. A number of reports note potential uses in the transport, power, industry, building, chemical, and other sectors. Analysis by the Hydrogen Council sees a broad role for hydrogen and suggests it could meet 18 percent of final energy demand in 2050.[197] BloombergNEF estimates it could meet between 7 to 24 percent of final energy needs, depending on policy support. However, BloombergNEF also notes that the "strongest use cases for hydrogen are the manufacturing processes that require the physical and chemical properties of molecule fuels in order to work" and a low carbon price would be enough to switch to green hydrogen.[198] Others argue that hydrogen production and use should be targeted at industrial processes or forms of	• European Climate Foundation • "Daimler AG and Volvo AB, the two largest makers of heavy trucks by revenue…formed a new company that aims to start building fuel-cell systems in Europe in 2025."[217] • ArcelorMittal invested 366 million USD in a program for low-carbon steel production.[218] **Policy and other barriers** • Cost—especially cost of green hydrogen. Hydrogen is produced rather than extracted, so it is likely to remain more expensive than fossil fuels.[219] Green hydrogen costs two to four times more to produce than grey hydrogen today.[220] Industry needs to bring down costs of hydrogen through scale.[221] • Infrastructure. Hydrogen's low density makes it hard to store, and low-cost options for storage are limited. Low density also makes it hard to transport by road or ship, and extensive upgrades to current infrastructure would be required to transport hydrogen via pipes.[222] • Renewable energy needs. If 24 percent of global energy demand were met with

transport (e.g.m shipping and aviation) not easily electrified (instead of cars, for example). In IEA's analysis, nearly half of hydrogen and hydrogen-based fuels are consumed by the transport sector (207 Mt), with sizeable proportions also allocated to the industry (187 Mt) and electric (102 Mt) sectors.[199] Hydrogen leakage can undermine climate benefits of decarbonization strategies reliant on hydrogen. Hydrogen's small molecular size creates enormous potential for leaks, and it is a powerful and often underappreciated indirect greenhiouse gas in the atmosphere. However, its climate effects have been reported over the past two decades through a long-term lens—[200] This has led to the misinformed perception that hydrogen leakage is not a concern from a climate perspective and to the omission of its effects in analyses that look at the potential climate benefits of deploying hydrogen, such as life cycle assessments. The empirical data on hydrogen leakage necessary for understanding the full climate implications of a hydrogen economy does not yet exist. More research is needed to fully understand the climate implications of replacing fossil fuel systems with hydrogen. A deeper dive into hydrogen leakage will reveal how important these impacts are in the context of effective climate change mitigation and inform the relative advantages and disadvantages of decarbonization pathways. EDF is taking a leading role in improving understanding of the climate impacts of hydrogen leakage. Other concerns to note are potential health impacts via increased tropospheric ozone and NOx and ammonia emissions; diverting renewables away from replacing fossil fuels to produce hydrogen, which is inefficient because of conversion losses; and greenhouse gas emissions from scaling up infrastructure. Subsequently, there is uncertainty surrounding hydrogen's potential, as production technologies and potential applications are rapidly evolving. **Key geographies** <u>Equipment</u>: The cost of alkaline electrolyzers made in North America and Europe dropped by 40 percent	hydrogen in 2050, around 31,320 TWh of electricity would be needed to power electrolyzers. Combined with power sector needs, this would require more than 60,000 TWh (compared to 3,000 TWh today). "China, much of Europe, Japan, Korea, and South East Asia may not have enough suitable land to generate the renewable power required."[223] • Lack of policy and funding, with promising use cases funded only with one-off grants for demonstration projects. BloombergNEF recommends comprehensive and coordinated policy with 150 billion USD of subsidies to 2030.[224] The Energy Transitions Commission sees a need for 15 trillion USD until 2050.[225]

between 2014 and 2019, and systems produced in China are already up to 80 percent cheaper."[201] IEA's Net Zero report identified hydrogen electrolyzers as one of the biggest innovation opportunities over the next 10 years (along with advanced batteries and direct air capture). Production + Use: There are 359 announced large-scale hydrogen projects across the globe. These are clustered in North America, Europe, East Asia (China and Japan), Australia, with additional projects in the Middle East, South Africa, and South America.[202] "China is emerging as a potential hydrogen giant: following its announcement to target net-zero emissions by 2060, plans to achieve "peak carbon" in various sectors, including aviation and steel before 2030, have been put forward and over 50 hydrogen projects have been announced." Further detail, particularly on recent developments in China, can be found in the Hydrogen Council's latest report.[203] Furthermore, "while Europe and East Asia continue to lead in hydrogen, regions rich in renewables and carbon storage are stepping in to supply clean hydrogen."[204] For example, South Africa's renewable energy potential could make it a leader in hydrogen production.[205] "With large-scale storage in place, hydrogen could be produced from renewable power that would otherwise be curtailed."[206] "Hydrogen is likely to be most competitive in large-scale local supply chains. Clusters of industrial customers could be supplied by dedicated pipeline networks containing a portfolio of wind- and solar-powered electrolyzers, and a large-scale geological storage facility to smooth and buffer supply."[207] Example clusters include existing refining, petrochemical and fertilizer clusters, ports, non-coastal transport and logistics nodes, and steel plants. See page 21 of the Energy Transitions Commission report for clean hydrogen industrial cluster locations across India.[208]	

BloombergNEF analysis suggests that “a delivered cost of green hydrogen of around \$2/kg (\$15/MMBtu) in 2030 and \$1/kg (\$7.4/MMBtu) in 2050 in China, India and Western Europe is achievable. Costs could be 20-25 percent lower in countries with the best renewable and hydrogen storage resources, such as the U.S., Brazil, Australia, Scandinavia and the Middle East. However, cost would be up to 50–70 percent higher in places like Japan and Korea that have weaker renewable resources and unfavorable geology for storage.”[209] Much of the world has sufficient estimated solar and wind resources to generate 50 percent of electricity and 100 percent of hydrogen from wind and solar in a 1.5-degree scenario, except for a small percentage of countries (including China, parts of Asia and Europe, and others).[210] Germany, Japan, and the Netherlands are potential importers, while Chile, Morocco, Saudi Arabia, and Algeria are potential exporters. Updates from select countries: • Australia is taking steps to achieve a price target of AU\$2 per kilo of hydrogen, as outlined in its 2019 National Hydrogen Strategy • Chile’s National Green Hydrogen Strategy aims to have 5 GW in electrolysis capacity (in operation and under development) by 2025, and to be among the leading RE-based hydrogen producing and exporting countries by 2030. • Saudi Arabia is currently building a 5 billion USD green hydrogen plant, which is slated to open in 2025. **Key actions and policies** There are few policies in place to support hydrogen production, but pricing carbon or valuing emissions reductions would help hydrogen compete with fossil fuels in hard-to-abate sectors. Sector-specific policies could also include mandates, voluntary private-sector commitments, green public procurement policies, and financial incentives for hydrogen uptake. Targets for electrolysis manufacturing and support for key	

technologies and capabilities will also be important (e.g., new forms of bulk hydrogen storage).[211] France is providing the largest subsidies to hydrogen (in GDP terms), followed by Korea, Germany, and Japan.[212] The U.S. Department of Energy is actively seeking to reduce the cost of hydrogen by 80 percent (to 1 USD/kg) in one decade.[213] For industrial applications, the Hydrogen Council proposes support for "large-scale pilots in steel manufacturing, power generation, and clean or green hydrogen feedstocks for the chemicals, petrochemicals, and refining industries."[214] Once technologies are proven, a long-term regulatory framework should follow. National action plans, such as those developed by Japan, would also help scale up hydrogen use. The Energy Transitions Commission emphasizes the importance of developing hydrogen clusters and focusing policy support on developments that benefit several companies and sectors.[215]	
Carbon capture, utilization, and storage (CCUS)	
Description of solution, quantification of opportunity CCUS contributes to the transition to net zero in multiple ways. These include (1) tackling emissions from existing energy assets, (2) providing solutions in hard-to-abate sectors (e.g., capturing emissions from the cement sector or enabling the production of synthetic aviation fuels), (3) supporting production of low-emissions hydrogen production, (4) enabling some carbon dioxide to be removed from the atmosphere, and (5) providing low carbon dispatchable power.[226,227] "CCUS can be retrofitted to existing power and industrial plants that could otherwise emit 600 billion tons of carbon dioxide over the next five decades—almost 17 years' worth of current annual emissions."[228] Retrofits of power plants will be particularly important	**Influential actors (i.e., initiatives, coalitions, and organizations)** • Global Cement and Concrete Association (GCCA) • Oil and Gas Climate Initiative (OGCI) • International Energy Agency (IEA) • Global CCS Institute • Zero Emissions Platform (technical adviser to the EU on CCS development) • International CCS Knowledge Centre

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<td rowspan="2">in countries with large numbers of new coal power plants.[229] CCUS technologies can also be deployed at new facilities.

While most operational projects are located at natural gas processing facilities, CCUS is a key technology for decarbonizing the cement sector and has a role to play in cutting emissions from steel and chemicals manufacturing. In these sectors, CCUS technologies remain at an early stage of development.

Today, CCUS projects around the world have the capacity to capture about 40 Mt of carbon dioxide each year (~three-quarters is captured from oil and gas operations). IEA's net zero pathway would require 7,600 Mt of carbon dioxide to be captured in 2050, with 5,245 Mt of carbon dioxide captured from fossil fuels and processes.[230] In this scenario, almost 40 percent of carbon dioxide captured in 2050 would be from industry, and 20 percent would be from the electricity sector. Some experts view such a massive scale up of CCUS capacity as unrealistic, even with strong policy support. Notably, "the scenarios assessed by the IPCC have a median of around 15 Gt of carbon dioxide captured using CCUS in 2050, more than double the level in the NZE."

Carbon capture technologies can be classified as follows: pre-combustion, post-combustion, and oxy-fuel combustion (use of O_2 instead of air for combustion). They include high-concentration, CaO looping, liquid absorption, membrane, and solid absorption technologies.[231] Particularly promising is the Allam-Fetvedt Cycle, which has a carbon capture cost near zero.

Captured carbon can either be stored or utilized. Until now, many projects have sold captured carbon for use in enhanced oil recovery. In the future, a more promising use is to produce synthetic fuels, especially for aviation.

<u>Cement</u>: Pre-combustion capture technologies have limited utility in cement production, since energy-</td>
<td>• European Innovation Fund (expected to be a major source of funding for CCUS)
• Carbon Engineering (developing large-scale DAC plant using liquid solvent capture system)
• Climateworks (uses solid sorbent system)
• Global Thermostat (uses solid sorbent system)
• Carbon XPRIZE
• Equinor has announced plans to build a CCUS-equipped hydrogen facility in Scotland. It has also invested in Norway's Northern Lights project.
• LafargeHolcim is piloting 20 carbon-capture utilization and storage projects.
• CarbonCure is a carbon dioxide utilization technology provider for the concrete industry, adopted in 15+ projects.
• HeidelbergCement AG received the green light to build an industrial-scale project.[246]
• ArcelorMittal invested 366 USD million in a program for low-carbon steel production.[247]</td>
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<td>Policy and other barriers

• Low margins. High costs of low emission production are prohibitive in a competitive global market,[248] though costs are</td>
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related carbon dioxide emissions are a small percentage of total emissions from cement production. On the other hand, "post-combustion capture technologies do not require fundamental modifications of cement kilns and could be applied to existing facilities provided there is enough physical space available on the site."

A 2018 report by Energy Innovation found that "capturing 80 percent of cement's process emissions (and none of the thermal emissions) by 2050 is sufficient to make cement carbon-neutral, as natural carbonation offsets the remaining emissions. If the thermal fuel supply were to be fully decarbonized by 2050, a process emissions capture rate of 53 percent achieves carbon-neutral cement."[232]

There are notable carbon capture demonstration projects in Norway (the Brevik Project), the United States, and elsewhere. Reducing the clinker to cement ratio can also reduce process emissions that need to be captured.

Key geographies

- Key countries investing in CCUS include the United Kingdom, United States, Norway, Australia, and Canada.[233] Japan is also driving international collaboration on this solution.
- Regions with CCUS projects: Americas (United States, Canada, Brazil), Europe (United Kingdom, Norway, the Netherlands, Ireland), Asia Pacific (China, Australia, South Korea, New Zealand), Gulf (Qatar, Saudi Arabia, UAE).
- China and India will be responsible for approximately half of global cement production in 2050.[234]

<u>Carbon capture</u>: There are 38 commercial facilities in operation or in various stages of development in the Americas, with another 13 in Europe, ten in Asia Pacific, and three in Gulf states. Southeast Asia is seen as an emerging hub for CCUS, and "Japan is driving international activities to develop clean hydrogen production using CCS."[235]

falling with learning and time.[249]

- High reliance on coal for high temperature heat.[250]
- Large share and quantity of process emissions.[251]
- Carbon dioxide utilization markets are small and cost sensitive.[252]
- Investment that has fallen behind that of other clean energy technologies.[253]
- Difficulties in integrating the different elements of the carbon dioxide supply chain.[254]
- Technical risks associated with installing or scaling up CCUS facilities in some applications.[255]
- Difficulties in allocating commercial risk among project partners.[256]
- Problems securing financing.[257]
- Unlimited long-term storage liability risk.[258]
- Public resistance.
- Long asset lifetimes.
- Long lead times needed to scale up infrastructure.
- Lack of consistent policy support.
- Permitting process is often scattered across different agencies and jurisdictions.
- Energy requirements of carbon capture technologies.

The United States leads in operational carbon capture capacity (51 percent), followed by Brazil (12 percent), Australia (10 percent), Canada (10 percent), Saudi Arabia (2 percent) and China (2 percent).[236] IEA's analysis found that 70 percent of carbon dioxide emissions from power and industrial facilities in China, Europe, and the United States are within 100 km of potential storage.[237] Carbon storage: CCS projects can store captured carbon in certain oil and gas fields (which can contain carbon dioxide and are relatively well-studied) or certain saline formations (which are relatively widespread but are less researched). Commercial readiness of storage sites is a key limiting factor for CCS scale-up. **Key actions and policies** After slow progress, policy incentives and enhanced emissions targets are driving new momentum. As with hydrogen, "the development of CCUS hubs—industrial centers that make use of shared carbon dioxide transport and storage infrastructure—could help accelerate deployment by reducing costs.[238] The Global CCS Institute reports 15 CCUS hubs and clusters operating or progressing through studies in 2019-20, largely in North America, Brazil, Europe, the Middle East, China, and Australia.[239] Hubs, however, could also increase the risk of earthquakes (compared with injection over broader areas), and would necessitate sophisticated management of this induced seismicity risk. There is strong bipartisan support in the United States to accelerate carbon capture deployment. One key policy incentive is the 45Q tax credit, which provides 50 USD per ton of carbon dioxide that is permanently stored.[240] And in 2018, the California LCFS was amended to enable CCS projects associated with the production of transport fuels sold in California to generate LCFS credits.[241]	

A carbon dioxide tax on offshore oil and gas activities in Norway made the first large-scale CCS project viable. Norway committed funding in 2020 to the Longship project, which will connect carbon capture projects with a storage facility under the North Sea. This could also provide a solution for neighboring countries.[242] And across Europe, "the unprecedented European Green Deal and Climate law converting the political commitment to climate neutrality into a legal obligation, has led to the development of additional EU policy supportive of CCS."[243] Australia has developed a framework for the licensing, management and reporting of carbon capture and storage projects, "including sophisticated mechanisms for handling long-term liabilities and environmental damage from failed projects."[244] IEA identified four high-level priorities for governments and industry: (1) value emissions reductions and provide direct support for early CCUS projects, (2) coordinate and underwrite the development of hubs, (3) identify and encourage the development of carbon dioxide storage in key regions (e.g., saline sites), (4) boost innovation.[245]	
HFC phase out	
Description of solution, quantification of opportunity HFCs are a group of industrial chemicals primarily used for air conditioning (~55 percent of HFC use), refrigeration (~30 percent of HFC use), insulating foams (~7 percent of HFC use), and aerosol propellants, among other things.[259] They represent around 1 percent of total greenhouse gas emissions but are powerful short-lived climate pollutants. Emissions of these chemicals are growing at rate of 10-15 percent per year, "largely as a result of increasing demand for refrigeration and air-conditioning, particularly in developing countries."[260]	**Influential actors (i.e., initiatives, coalitions, and organizations)** • Cool Coalition, which is composed of 24 countries (list of members and partners) • Kigali Cooling Efficiency Program • Sustainable Energy for All (SE4A) • United Nations Environment Programme (UNEP)

Unchecked growth of HFCs could add up to 0.5 degrees C to global temperatures by century's end. To tackle this issue, countries signed the landmark Kigali Amendment to the Montreal Protocol in 2016 to phase out HFCs. The agreement entered into force in January 2019 and aims to achieve an 80+ percent reduction in HFC consumption by 2047.[261] "A number of low-GWP alternative to HFCs are already commercially available across a large number of sectors and regions."[262] NRDC estimates that "the reduction of HFC use due to the Kigali Amendment will be equal to more than 70 billion tons of carbon dioxide over the next 35 years."[263] **Key geographies** Key geographies include countries with growing cooling needs due to rising temperatures, increasing consumer power, and rapid urbanization.[264] One such country is India, which published the India Cooling Action Plan and was very influential in the Kigali Amendment. Sustainable Energy for All has identified countries and populations most at risk due to lack of access to cooling. The countries with largest number of people at high risk include India, China, Indonesia, Pakistan, Bangladesh, Nigeria, Mozambique, Sudan, Brazil.[265] Under the Kigali Amendment, countries are divided as follows: Article 5 parties (developing countries) and non-Article 5 parties. These groups have different phase down schedules.[266] 127 countries have accepted, ratified, or approved the Kigali Amendment, including China (June 2021) and India (September 2021).[267] **Key actions and policies** With the Kigali Amendment in place, attention has shifted to implementation. NDCs provide countries with an opportunity to elaborate their plans for phasing out HFCs. In October 2021, the U.S. Environmental Protection Agency established an allowance allocation and trading	• Global Alliance for Buildings and Construction (Global ABC) • World Green Building Council • Climate and Clean Air Coalition • C40 • Clean Energy Ministerial • Leadership in Energy and Environmental Design (LEED) • Green Globe Standard **Policy and other barriers** • High cost of low emission cooling options • Concerns about intellectual property rights and patents held by a small number of Western companies

program for HFCs, implementing a key provision of the American Innovation and Manufacturing (AIM) Act of 2020. The AIM Act "directs EPA to phase down production and consumption of HFCs in the United States by 85 percent over the next 15 years."[268, 269] The U.S. has yet to ratify the Kigali Amendment. Similar efforts are underway in the Europe Union, where an HFC quota system established in 2015 is helping incentivize a shift to climate-friendly alternatives. "The quota system put in place by Regulation (EU) No 517/2014 on fluorinated greenhouse gases aims to reduce the use of HFCs by 79 percent by 2030." The European Commission has launched a review of HFC rules as part of its European Green Deal.[270] Australia, Canada, and Japan also have national regulations in place to expand the use of HFC alternatives.[271] Potential actions include: • Replacement of "high-global warming potential hydrofluorocarbons with low- or zero-global warming potential alternatives" and improvements in energy efficiency.[272] • Improvement of "insulation materials and building designs to avoid the use of or reduce the need for air-conditioners."[273] • Coordinated research, development and demonstration.[274] • Coordination on standards for efficiency of buildings, heating/cooling technologies (among leading cities, for example).[275]	

Buildings solutions

Residential and commercial buildings are responsible for 5.5 percent of global greenhouse gas emissions—a figure that jumps to 17.5 percent when buildings' electric and heating needs (i.e., indirect emissions) are included.[276] Carbon dioxide emissions from building operations are currently around 10 Gt of carbon dioxide (or 28 percent of global energy-related carbon dioxide emissions)[277] and final energy use in buildings increased from 118 EJ to 128 EJ between 2010 and 2019.[278]

Under IEA's net-zero scenario, buildings sector emissions fall from 2.86 Gt of carbon dioxide in 2020 to 1.81 in 2030 and 0.12 in 2050. Under the stated policies scenario, emissions from this sector are 2.71 Gt of carbon dioxide in 2050.

The global population is estimated to grow to 9.7 billion in 2050—the majority of whom will live in Asia, Africa, and Latin America—and demand for buildings and energy will continue to rise. Key factors in building sector emissions are the continuing use of coal, oil and natural gas for heating and cooking, improving access to energy in developing countries, increasing cooling needs (driven in part by extreme weather events), the proliferation of energy-consuming devices, and expanding floor area of buildings.[279] These trends have outpaced efficiency improvements and decarbonization of electricity and heat.[280]

Recent growth in buildings' energy use follows a plateau in building emissions (2013 to 2016) caused by the declining carbon intensity of the power sector. GlobalABC's new Buildings Climate Tracker (BCT) shows that the rate of annual improvement (due to decarbonization efforts like energy efficiency) has been declining since 2017.[281]

The buildings sector's "enormous emissions reduction potential remains untapped due to the continued use of fossil fuel-based assets, a lack of effective energy-efficiency policies and insufficient investment in sustainable buildings."[282] In IEA's Net Zero scenario, buildings' energy consumption drops by one-quarter by 2030, "largely as a result of a major push to improve efficiency and to phase out the traditional use of solid biomass for cooking."

"According to the World Energy Outlook (IEA, 2019a), cost-effective, proven, energy efficiency and decarbonisation measures in buildings could contribute over 6.5 Gt of carbon dioxide reductions in annual emissions by 2040, compared to the current course of action under the Stated Policies Scenario. Reductions in emissions from buildings represent one-third of the total reductions required to align with the IEA's Sustainable Development Scenario (IEA, 2019a)."[283]

"In addition to providing healthier, more resilient and more productive environments, the decarbonisation of the buildings sector presents a business opportunity in emerging markets with an estimated value of approximately USD 24.7 trillion by 2030 (IFC, 2019)."[284]

Final energy consumption in buildings includes lighting, space cooling, space and water heating, and appliances. This table focuses on energy efficiency and electrification. Taken together, these solutions have the potential to significantly reduce carbon emissions from the building sector. (Note that energy efficiency is also discussed as a cross-cutting solution.)	
Efficient and electric building appliances and systems	
Description of solution, quantification of opportunity It is well-established that enhancing the energy efficiency of building appliances, equipment, and systems (including the building envelope, material efficiency and low-carbon materials) is a critical climate solution. However, it is nonetheless regularly underfunded and under-deployed, and investment in efficiency has been declining since 2015.[285] Additionally, the advancement of the market for high-efficiency electrified equipment creates a new avenue for decarbonization, reducing the reliance on fossil fuel end-uses and transitioning to ever-cleaner electricity, all while typically producing a significant leap forward in the device's overall energy efficiency. Taken together, energy efficiency and electrification have the potential to produce a significant reduction in carbon emissions from the building sector. Traditional energy efficiency technologies include building envelopes, controlled ventilation, LED lighting, properly sized heating and cooling systems, and efficient appliances can significantly reduce energy usage while delivering increases in the occupant's comfort, health, and productivity. Enhancing the deployment of traditional energy efficiency is critical to prevent increases in wasteful energy demand. In addition, electrified devices such as electric heat pumps offer both heating and air-conditioning and can achieve over 100 percent efficiency in temperate climates.[286] IEA's Net Zero scenario would require 50 percent of heating demand to be met with heat pumps by 2045.[287]	**Influential actors (i.e., initiatives, coalitions, and organizations)** • Sustainable Energy for All (SEforAll) • International Energy Agency (IEA) • United Nations Environment Programme (UNEP) • UN-Habitat • Global Environment Facility • Global Alliance for Buildings and Construction • World Green Building Council • C40 (including its Net-Zero Buildings Declaration and Clean Construction Declaration) • Excellence in Design for Greater Efficiencies • WBCSD's Building System Carbon Framework • Building Efficiency Accelerator (GEF, UNEP, WRI) • Zero Carbon Buildings for All, supported by national governments (such as Kenya, Turkey, UAE, the UK) and financial institutions[313] • The Three Percent Club for Energy Efficiency

Other key technologies are electric ranges, induction cooktops, and modern biomass stoves and boilers, which could replace traditional biomass.[288] IEA's Net Zero scenario would require no new sales of fossil fuel boilers after 2025.[289]

Developing efficient, electrified buildings also brings benefits beyond climate emissions, and complementary market drivers. If deployed in concert with smarter meters and controls, efficient and electrified buildings create a larger base of flexible electricity demand, allowing power system managers to modulate power needs to reduce peak demand and reliance on heavily polluting peaker plants, ensure greater system reliability and resilience, and ultimately produce a more efficient power system. Similarly, building electrification can support the transition to transportation electrification through vehicle-grid integration.

IEA's Net Zero scenario would require all new buildings to be zero-carbon-ready by 2030 and 50 percent of existing buildings to be retrofitted by 2040. In addition, "around 2.5 percent of existing residential buildings in advanced economies are retrofitted each year to 2050 in the NZE to comply with zero-carbon-ready building standards (compared with a current retrofit rate of less than 1 percent)."[5] The High-Level Climate Champions' 2030 Breakthroughs envision 100 percent of projects due to be completed in 2030 or after are net zero carbon in operation, with all projects (new and existing) net zero across the whole lifecycle by 2050.[290]

Key geographies

- Regions experiencing extreme weather conditions often have increased energy demand, highlighting the criticality of ensuring the efficiency of the devices deployed. This is especially true in extreme weather geographies with large populations that are rapidly scaling up the use of energy-intensive appliances and

- Energy Efficiency Global Alliance
- Clean Cooking Fund, launch by the World Bank and ESMAP[314]
- High-Level Coalition of Leaders for Clean Cooking, Energy, and Health, convened by WHO, UNDP, UNDESA, and the World Bank

In general, key actors include policy makers, urban planners, architects, developers, investors, construction companies, and utility companies.

Policy and other barriers

- High upfront cost of low emission heating and cooling options, including heat pumps
- Myths and misconceptions (held by contractors and consumers)
- Regulatory barriers (policy has not kept pace with available technology)
- Technological barriers (until recently, heat pumps performed poorly in cold climates)
- Climate impacts (heat pumps sold in the United States use (and leak) HFC 410a, a powerful greenhouse gas)[315]

[5] According to IEA's Net Zero by 2050 report, "a zero-carbon-ready building is highly energy efficient and either uses renewable energy directly or uses an energy supply that will be fully decarbonized by 2050, such as electricity or district heat."

devices. The Rocky Mountain Institute estimates that the potential increase in demand for cooling over the next few decades may cause up to 0.5 degree rise in global temperatures by the end of the century.[291] • Globally, space heating is the largest energy use in buildings, accounting for one-third of energy demand—three-quarters of which is consumed in the US, the EU, China, and Russia. Fossil fuel-based and low efficiency heating equipment still make up the majority of heating production in most buildings, in regions with existing natural gas infrastructure.[292] • Heat pumps are mature, low-carbon heating technology and have high market penetration rates in moderate climates such as the United States, Canada, and Western Europe. However, they tend to require a greater up-front investment than fossil fuel alternatives, at least in the U.S. market. **Key actions and policies** Decarbonizing buildings "requires clear and ambitious policy signals to drive a range of measures including passive building design, material efficiency, low-carbon materials, efficient building envelope measures, and highly efficient lighting and appliances." However, "at present, mandatory policies on building and equipment performance cover less than 40 percent of energy use and less than half the carbon dioxide emissions from buildings."[293] Governments can implement new building energy codes to incentivize high efficiency technologies for widespread adoption and pair mandatory minimum energy performance standards (MEPS) with regulatory and financial incentives.[294] Key actions include: • Heat pumps are mature, low-carbon heating technology and have high market penetration rates in moderate climates such as the United States, Canada, and Western Europe.	• Lack of educational and institutional capacity among key professions

• Use of energy performance tools, systems, and standards to enable monitoring and evaluation.[295] Benchmarking and transparency to enable tracking of buildings' energy consumption. • Adoption and update of minimum energy performance standards (MEPS) to set ambitious product requirements for major appliances and systems. "MEPS could be especially effective if developed in collaboration across regions to enable cross-border applicability."[296] • Voluntary and mandatory energy ratings and labelling programs to support energy efficient purchasing decisions.[297] • Creation of regulatory frameworks to facilitate integrated action. Frameworks could address land-use efficiency, transit-oriented development, district clean energy planning, emissions from the production of building materials, use of on-site renewable energy.[298] • Adoption of mandatory building energy codes. Progress in this area is critical, as "more than two-thirds of the buildings constructed between now and 2050 are expected to be built in countries lacking building energy codes (IEA, 2017)."[299] IEA's Net Zero scenario envisions energy-related building codes in all regions by 2030. • Prioritization of low-emission and energy efficient systems in government-owned buildings to foster a strong market for sustainable products.[300] • Financial incentives (e.g., green bonds, tax credits, grants, and rebates) to enable market development and increase production of high-efficiency products. • Capacity building and knowledge transfer to share research and best practices for the building industry.[301] • Strong enforcement to ensure compliance with building codes and regulations.[302] • Roadmaps and strategies that set priorities and facilitate collaboration among key stakeholders	

(governments, communities, industry coalitions, etc.) Examples: • For example, China, Japan and the US have provided subsidies for efficient heat pumps to reduce upfront costs.[303] • Singapore has mandated MEPS and "developed the Super Low Energy Buildings Programme, which supports the research and adoption of cost-effective, energy-efficient and renewable energy solutions."[304] • In 2020, South Korea has committed 61 billion USD to support a net-zero society goal, including construction of zero-energy public facilities such as schools and shifting to renewable energy.[305] • In European countries like the UK, Italy and Switzerland, investment growth in energy efficiency in buildings tends to outpace construction investment growth. The European Commission announced the "Renovation Wave" initiative for public and private buildings to support the green recovery.[306] "Its objective is to at least double the annual energy renovation rate of buildings by 2030 and to foster deep renovation."[307] • The EU has also established the Environmental Performance of Buildings Directive, which aims to decarbonize national building stocks by 2050, with milestones for 2030, 2040 and 2050.[308] • "The Ecodesign Directive provides consistent EU-wide rules for improving the environmental performance of products, such as household appliances, information and communication technologies or engineering. The directive sets out minimum mandatory requirements for the energy efficiency of these products."[309] • In the United States, the ENERGY STAR® program, a joint government program by the U.S. Environmental Protection Agency and Department of Energy, awards the ENERGY STAR® label to highly efficient devices to provide greater transparency for consumers, businesses	

and industry to identify and adopt energy-efficient products and practices. In 2019 alone, ENERGY STAR and its partners helped Americans save nearly 500 billion kWh of electricity, avoiding 39 billion USD in energy costs. According to the ENERGY STAR® website, “every dollar EPA has spent on ENERGY STAR resulted in $250 invested by American businesses and households in energy efficient infrastructure and services.” • New York City’s Climate Mobilization Act established a goal to reduce greenhouse gases from buildings 40 percent by 2030 and 80 percent by 2050.[310] The Act also establishes emissions caps for large buildings (over 25,000 sq. ft.).[311] • In 2020, Berkeley, CA enacted a ban on natural gas lines in new buildings.[312]	

Nature-based solutions

<table>
<tr><td colspan="2">
Estimates of emissions from the land sector vary among sources and by year. According to the IPCC, Agriculture, Forestry and Other Land Use (AFOLU) activities accounted for 23 percent of total net anthropogenic emissions of greenhouse gases from 2007-2016.[316] In 2016, however, agriculture contributed 11.8 percent of global greenhouse gas emissions, while land use change and forestry were responsible for 6.5 percent.[317] Further, EDF analysis suggests that carbon dioxide emissions from gross tropical forest loss alone might be as high as 15 to 21 percent of global carbon dioxide emissions.

While land-based activities can contribute to climate change, landscapes can also act as carbon sinks. Earth's soil stores three times more carbon than the atmosphere,[318] and "plants and soils in terrestrial ecosystems currently absorb the equivalent of ~20 percent of anthropogenic greenhouse gas emissions measured in carbon dioxide equivalents."[319]

By some estimates, natural climate solutions "can provide over one-third of the cost-effective climate mitigation needed between now and 2030 to stabilize warming to below 2 degrees C."[320] Many natural climate solutions also provide non-climate benefits, from improved soil heath and water quality to flood control.

It is important to note that natural land and ocean carbon sinks will become less effective as emissions increase, according to the latest IPCC Working Group I report. In other words, "the proportion of emissions taken up by land and ocean decrease with increasing cumulative carbon dioxide emissions."[321]
</td></tr>
<tr><td colspan="2">Forest Protection</td></tr>
<tr><td>
Description of solution, quantification of opportunity
While forest loss and degradation can be a source of emissions, forest regeneration, reforestation, and afforestation draw down and sequester carbon dioxide from the atmosphere. Specific forest pathways identified by Griscom et al. "offer over two-thirds of cost-effective NCS mitigation needed to hold warming to below 2 degrees C and about half of low-cost mitigation opportunities."[322]

The High-Level Climate Champions' 2030 Breakthroughs envision 50 Gt CO_2e mitigated by 2030 through land use, food and agriculture practices, and reduced inputs and waste.[323]
</td><td>
Influential actors (i.e., initiatives, coalitions, and organizations)

• Lowering Emissions by Accelerating Forest finance (LEAF) Coalition
• Green Gigaton Challenge
• One Planet Business for Biodiversity (OP2B), led by the World Business Council for Sustainable Development (WBCSD) and composed of 27 companies
• Global Campaign for Nature, led by Costa Rica[330]
</td></tr>
</table>

Tropical forest protection, in particular, offers significant emission reduction potential. Estimates show that reducing tropical deforestation could offer cost-effective mitigation potential of around 2.8 $GtCO_2e$ per year.[324] If avoided peatland impacts are also considered, this value increases to around 3.4 $GtCO_2e$ per year. Despite this potential, 63.7 million hectares of tropical forests were lost from 2002-2020.[325] "Each year, more than seven million hectares of forest are lost—an area larger than Sierra Leone.[326] **Key geographies** According to the Food and Agriculture Organization's (FAO) 2020 report, globally the top five countries in terms of forest area in 2020 included: Russia (815 Mha), Brazil (496 Mha), Canada (346 Mha), the United States (309 Mha), and China (219 Mha).[327] FAO also estimated that the top five countries for average annual net loss of forest area in 2020 were Brazil (-1.4 Mha), Democratic Republic of the Congo (-1.1 Mha), Indonesia (-0.753 Mha), Angola (-0.555 Mha), and the United Republic of Tanzania (-0.421 Mha).[328] Other nations (e.g., Costa Rica and Colombia) could provide models for forest protection and restoration. **Key actions and policies** *Increase positive incentives associated with forest protection* • Policies and large-scale incentive programs that create positive economic value for healthy, living forests and support and enhance the livelihoods of forest dependent communities, including Indigenous Peoples and Local Communities. • Jurisdictional-scale approaches to reducing emissions from deforestation and forest degradation (REDD+).	• High Ambition Coalition for Nature and People, led by Costa Rica and France to protect and conserve 30 percent of land and sea. • Leaders' Pledge for Nature, launched in September 2020 to reverse biodiversity loss with 88 countries and the EU. • Natural Climate Solutions Alliance (NCSA) (convened by WBCSD and the WEF) • Convention on Biological Diversity (CBD) • United Nations Environment Programme (UNEP) • United Nations Development Programme (UNDP) • United Nations REDD+ Programme (UNREDD+) • Central African Forest Initiative (CAFI), composed of Cameroon, the Central African Republic, the Democratic Republic of the Congo, Equatorial Guinea, Gabon, and the Republic of Congo, and funded by the European Union, Germany, Norway, France, the United Kingdom, the Netherlands, and Korea[331] • Central America Integration System (SICA) Initiative, led by El Salvador and composed of Belize, the Dominican Republic, Costa Rica, Guatemala, Honduras, Nicaragua, and Panama[332]

<table>
<tr>
<td rowspan="2">• Market-based approaches (e.g., carbon markets) for high-integrity and high-quality credits from jurisdictional-scale REDD+.
• Recognition of the role of Indigenous Peoples as forest stewards.

Increase risk associated with deforestation
• Command-and-control policies
• Forest law enforcement
• Public disclosure of legal offenders
• Conversion-free and deforestation-free supply chains
• Improved transparency

Reduce supply of land available for deforestation
• Protected areas and Indigenous territories*
• No public land available for conversions
• Moratoria on forest conversion
• Secure tenure and protection of Indigenous territories
• Construction of climate-smart roads
• Encouragement of sustainable land-use practices (e.g., intensification of agriculture production)

Reduce demand for alternative use of (once) forested land
• Decrease agricultural commodity demand
• Increase relative financial attractiveness of trees vs. no trees
• Strengthen decentralized resource management
• Reduce competition for land

*Growing evidence indicates that Indigenous territories are some of the most robust buffers against large-scale carbon emissions from deforestation and forest conversion, degradation/disturbance, and deforestation.[329]</td>
<td>• Tropical Forest Alliance (TFA)
• CONSERV

NBS coalition for 2019 UNSG’s Climate Action summit was led by China and New Zealand and supported by UNEP.</td>
</tr>
<tr>
<td>Policy and other barriers

• Land-based sequestration efforts receive about 2.5 percent of climate mitigation dollars.[333]
• Lack of at-scale financing for forest conservation and restoration
• Lack of value on standing trees
• Pressures from cropland, mining, and other extractive activities (e.g., timber harvesting)
• Concerns about permanence of natural carbon storage
• Concerns about competition with food production
• Political barriers
• Policy incoherence
• Lack of enforcement
• Difficulty scaling REDD+ efforts to maximize impact
• Disenfranchisement of Indigenous Peoples and Local Communities, and lack of recognition of their land tenure and rights
• Natural threats like fire, insects, and pathogens</td>
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Improved agricultural practices

Description of solution, quantification of opportunity

In 2015, "food systems" were responsible for 34 percent of anthropogenic greenhouse gas emissions, with carbon dioxide accounting for more than half of that total. CH_4, N_2O, and F-gases accounted for 35 percent, 10 percent, and 2 percent of food system emissions, respectively.[334] Nearly three-quarters (71 percent) of food system emissions originated from agriculture and associated land use and land-use change activities.[335]

Despite greenhouse gas emissions from the agricultural sector, "grassland and agriculture pathways offer one-fifth of the total national climate solutions (NCS) mitigation needed to hold warming below 2 degrees C, while maintaining or increasing food production and soil fertility."[336] Agricultural soils alone could remove 4 to 6 percent of annual U.S. greenhouse gas emissions through carbon sequestration.[337] The High-Level Climate Champions' 2030 Breakthroughs envision 50 Gt of CO_2e mitigated by 2030 through land use, food and agriculture practices, and reduced inputs and wase.

Within the agricultural sector, livestock and manure, soils, and rice cultivation account for 5.8 percent, 4.1 percent, and 1.3 percent of global greenhouse gas emissions (CH_4 and N_2O).[338] Manufacture and use of synthetic fertilizer contribute roughly 60 percent of global N_2O emissions.

Farmers and ranchers can implement a range of agricultural practices to reduce emissions of CO_2, CH_4 and N_2O, and practices that reduce potent methane emissions have the potential to be particularly impactful. Given methane's short-term warming potential, rapid reductions in emissions are a crucial climate mitigation opportunity in the near term (Ocko et. al 2021). Some key practices are described below.

- Reduce emissions from enteric fermentation through feed additives and other practices.

Influential actors (i.e., initiatives, coalitions, and organizations)

- Food and Agriculture Organization (FAO)
- Global Alliance for Climate-Smart Agriculture
- Food and Agriculture Climate Alliance
- Consultative Group on International Agricultural Research (CGIAR)
- California Climate Smart Agriculture Programs
- One Planet Business for Biodiversity (OP2B), led by the World Business Council for Sustainable Development and composed of 27 companies[351]
- Central America Integration System (SICA) Initiative, led by El Salvador and composed of Belize, the Dominican Republic, Costa Rica, Guatemala, Honduras, Nicaragua, and Panama[352]

Policy and other barriers

- Emission reductions require action by many stakeholders, as the agriculture sector is less consolidated than other sectors
- Actions must balance multiple objectives such as food security, biodiversity, rural livelihoods, in addition

Enteric fermentation is responsible for roughly half of all methane emissions from food systems[339] and the majority of methane emissions from livestock.[340] Scalable solutions aren't readily available, though several feed additives for reducing enteric emissions have been proposed. The most commonly researched additive (3-NOP) reduces enteric emissions by 32 percent in dairy and 22 percent in beef.[341] • <u>Manage manure</u> to avoid or capture methane emissions (e.g., change management practices to avoid generating methane, capture methane from liquid manure treatment systems). Captured methane can be flared or processed into fuel grade renewable natural gas using technologies that are ready for implementation and appear to be economical for larger operations. It's important to note, however, that issues with CAFO livestock production are not resolved by methane capture alone, and digestate requires further treatment to avoid detrimental public health and environmental impacts (digestate treatment is also ready for implementation but costs may be a hurdle). In contrast to those of cattle and other ruminants, methane emissions from pigs are primarily driven by manure management practices.[342] • <u>Avoid land conversion</u> to protect natural landscapes, including grasslands and forests (see "forests" section above). "Agriculture activities are responsible for more land-clearing than any other sector, contributing a significant amount of emissions in developing countries."[343] • <u>Optimize nutrient management</u>. Precision agriculture can help farmers tackle fertilizer loss, a major contributor to water pollution and climate change via soil N_2O emissions. Cover crops and natural buffers can also play a role.[344] • <u>Improve rice cultivation</u>. Improved irrigation systems, cropping techniques, and fertilization levels can reduce methane emissions. However,	to climate change mitigation and adaptation • Farm policy that doesn't fully account for climate risk or mitigation opportunities (and supported by entrenched interests) • Incomplete understanding of trade-offs and feasibility of some agricultural practices at scale • Farmers' access to capital, technical expertise, capacity-building • Land tenure …to reducing methane emissions • Limited technical potential and lack of scalable solutions (with respect to enteric fermentation) …to increasing soil carbon[353] • Current protocols used to generate soil carbon credits take a variety of approaches to measuring, reporting, and verifying climate impacts[354] • Limited scientific understanding of what keeps carbon sequestered and whether regenerative practices actually sequester additional carbon • Faulty carbon accounting that does not account for off-farm effects of on-farm practices • Quantities of nitrogen needed to sequester carbon in soils

EDF research found that intermittent flooding could be contributing to elevated emissions of N_2O, a powerful greenhouse gas, and that N_2O emissions from rice farms might be greatly underestimated.[345] • Restore degraded pastures to improve carbon sequestration. • Implement regenerative agriculture practices like no-till and cover crop cultivation, which have the potential to increase soil carbon. These practices do yield environmental benefits, but their potential to mitigate climate change remains unclear (see barriers). • Biochar. "The addition of biochar to soil offers the largest maximum mitigation potential among agricultural pathways, but unlike most other NCS options, it has not been well demonstrated beyond research settings. Hence trade-offs, cost, and feasibility of large-scale implementation of biochar are poorly understood."[346] **Key geographies** Countries with the largest food system emissions: China (2.4 $GtCO_2e$, 13.5 percent of global total), Indonesia (1.6 $GtCO_2e$, 8.8 percent of global total), United States (1.5 $GtCO_2e$, 8.2 percent of global total), Brazil (1.3 $GtCO_2e$, 7.4 percent of global total), European Union (1.2 $GtCO_2e$, 6.7 percent of global total), India (1.1 $GtCO_2e$, 6.3 percent of global total).[347] "Brazil, Indonesia and China represented more than 50 percent of global emissions from agriculture," according to a recent FAO report.[348] "Emissions from deforestation and from peat fires dominated the national emissions from agriculture in Brazil and Indonesia, respectively, whereas farm-gate emissions were the larger contributor in China."[349] India and Latin America represent the largest sources of livestock methane on a global basis (EDF internal analysis – Ilissa Ocko; FAO 2021). Rapid reduction of livestock methane emissions represents a key	• Need for large-scale action to produce significant benefits

opportunity to reduce the rate of temperature increase over the next two decades. **Key actions and policies** • Tailored advice and technical assistance to increase farmers' adoption of conservation practices. • Agricultural carbon markets with appropriate scientific benchmarks. In addition, agricultural lending institutions could conduct climate risk assessments and support the adoption of resilient production practices. Similarly, crop insurance programs could better address climate risks and reward climate-friendly practices. Finally, "given the limited technical potential to address agricultural sector methane emissions, behavioural change and policy innovation are particularly important for this sector. A relatively robust evidence base indicates that three behavioural changes, reduced food waste and loss, improved livestock management, and adoption of healthier diets, have the potential to reduce methane emissions by 65–80 Mt/yr over the next few decades."[350]	
Blue Carbon	
Description of solution, quantification of opportunity The ocean absorbs enormous amounts of anthropogenic heat and heat-inducing carbon dioxide. From 1994 to 2007, the ocean removed about 2.6 petagrams C per year (I Pg = 1 billion metric tons) of newly emitted carbon from the atmosphere, about a third more than all terrestrial ecosystems combined.[355] Moreover, ocean sediments store more than 2300 Pg C, 75 percent more carbon than all terrestrial soils.[356] Overall, about half of all historical carbon emissions have been moved into the deep sea and ocean sediments through the so-called "ocean biological	**Influential actors (i.e., initiatives, coalitions, and organizations)** Coastal blue carbon is a crowded field, including, to name a few: • High-level Panel for a Sustainable Ocean Economy, led by Norway and Palau and composed of 14 countries[361] • Global Campaign for Nature, led by Costa Rica[362]

pump" and nearshore biological activity (so-called "blue carbon").[357] This massive carbon "sink" in the ocean significantly moderates the effects of climate change, but also induces cascading effects on the functioning of ocean ecosystems and their ability to support human uses. This raises key questions about the degree to which human alteration of ocean ecosystems has already affected this essential function, but also what might be done to restore or enhance the ocean's ability to help decarbonize the atmosphere. However, ocean absorption of carbon dioxide does not translate automatically to long-term sequestration, as most dissolved or fixed carbon is subjected to intense biogeochemical and ecological processes—up and downwelling, photosynthesis, respiration, calcification and others. Sequestration times at 100 m depth average only about 14 years, whereas that carbon moved down to 1000 m is held for more than 25 times as long.[358] Under current ocean conditions, only about 2 percent of absorbed carbon dioxide moves deep enough to achieve long-term sequestration. Thus, the central challenge in enhancing carbon sequestration in the global ocean is not only to enhance surface carbon dioxide uptake through expanding photosynthesis (typically limited by the availability of growth limiting nutrients like iron and fixed nitrogen), but also through identifying and characterizing significant opportunities to move fixed carbon deeper, faster. Select solutions are described below: <u>Coastal blue carbon:</u> Coastal wetlands have long been the focus for blue carbon sequestration and interest by NGOs, funders and multilateral institutions is rapidly expanding. They are already beginning to attract attention similar to their terrestrial analogues where EDF is already focused (forests and farmlands). However, serious scientific questions remain about the potential for long-term carbon storage in the coastal	• <u>High Ambition Coalition for Nature and People</u>, with the UK as its ocean co-chair • Global Ocean Alliance, led by the UK and composed of 49 countries. • Blue Carbon Initiative • International Partnership for Blue Carbon • UNEP/GEF Blue Forests Project • Global Mangrove Alliance • Blue Solutions • TNC, WWF, WCS and most international NGOs Macroalgae-based blue carbon programs are mostly at a theoretical/academic stage. EDF will be reviewing that landscape soon. Open ocean blue carbon is also mostly academic to date, though whale advocacy groups (and the IMF) are advocating for that pathway. Otherwise, this landscape remains sparse.
	Policy and other barriers • Far and away the biggest obstacle to all three nature-based blue carbon wedges is the still-sparse science behind net long-term blue carbon sequestration programs, the very large uncertainties that result, and continuing questions about whether and how

zones, especially in the face of sea level rise, storm intensification, warming and alterations of rainfall patterns and other factors that could impair the carbon storage functions of coastal wetlands. Open ocean blue carbon: Generations of human uses have significantly altered the distribution and abundance of organisms there, with significant effects on ocean carbon processing and sequestration (especially via the severe reductions of large marine animals, the great whales and large bodied fishes). For these types of species, poor management of resources leading to overexploitation will be especially important in the high latitudes, where global ocean production will be concentrated under future atmospheric and ocean conditions. Moreover, recent interest in developing new fisheries targeting the swarming small fishes of the middle depths (the so-called mesopelagic realm) could threaten their essential role in moving fixed carbon deeper, through their diurnal vertical migrations. Restraining fishing on these resources and geographies until their carbon sequestration role is better understood could be an immediate opportunity for intervention. Macroalgal culture. Many people all over the ocean world are looking to kelp and other macroalgal culture as a powerful opportunity not only to enhance local marine resource production portfolios, but to leverage rapid macroalgal growth as a new and potentially large-scale pathway to carbon storage. This could take the form of restoring depleted macroalgal habitats, expansion of algal farms, or both. There are few practical limits – other than economics—to how much kelp could be grown.[359, 360] Macroalgae grow unquestionably fast, but they are highly sought after as food, both for humans and farmed herbivores, and also as a chemical feedstock. New carbon sequestration must be based upon initial absorption and then processing and storage that achieve high-quality carbon sequestration outcomes. **Key geographies** Open ocean blue carbon: Global high latitude regions	robust long-term sequestration would prove to be. • Projects and pilots are widely underway in the coastal area, and attention is focused on using sovereign blue bonds and other tools to move national scale blue carbon conservation instruments. All need work on most elements of the high-quality carbon credit front. • Macroalgae is easy to grow in vast quantities, but ideas about net long-term storage at large volumes remain less clear. Deep ocean disposal has been suggested, but the consequences of using that approach at large scales remain uncertain. • In the open ocean, there has been considerable interest for many years in fertilization using natural or engineered approaches, yet the consequences for net sequestration (getting carbon to depth) remain uncertain. • There is interest but not a clear governance pathway for accelerating whale conservation and protecting mesopelagic fishes, which are key actors in moving carbon deeper and faster. Likewise, there is interest in reframing fisheries goals at high latitudes to maximize

<u>Coastal blue carbon:</u> Belize, Mexico <u>Macroalgal culture:</u> China **Key actions and policies** • Better understanding of key uncertainties in each pathway to determine what is required to achieve net carbon sequestration in forms and at scales that could qualify as high-quality carbon credits. • Foster climate resilient fishery management and conservation to improve standing stock biomass of key large-bodied marine animals. • Map and quantify the suite of co-benefits attainable from ocean-based natural solutions that provide both carbon and other ecosystem benefits. • Blue carbon markets are developed with appropriate scientific benchmarks.	potential for deep carbon storage, taking into account the complex effects of shifting these compartments. Systems-level science is needed, which must then be linked to effective governance at those scales. • Climate equity outcomes (improvements and further losses) must be better understood before high quality systems-level design can be developed.

Cross-cutting solutions

<table>
<tr><td colspan="2">Other potential cross cutting solutions could include the use of bioenergy (addressed in part in the “Transport” section) and direct air capture of carbon dioxide emissions.</td></tr>
<tr><td colspan="2">Energy efficiency</td></tr>
<tr><td>

Description of solution, quantification of opportunity
In IEA’s net zero scenario, “the world economy in 2030 is some 40 percent larger than today but uses 7 percent less energy.” This is a significant departure from IEA’s Stated Policies scenario, which estimates that global energy demand will be approximately 10 percent higher than in 2019.[363] As a result, “a major worldwide push to increase energy efficiency is an essential part of these efforts, resulting in the annual rate of energy intensity improvements averaging 4 percent to 2030—about three times the average rate achieved over the last two decades.”[364] More specifically, the net zero scenario is based on an annual reduction in energy intensity (MJ/GDP) of 4.2 percent between 2020 and 2030 (and 2.7 percent between 2030 and 2050).[365]

A wide range of energy efficient solutions (including for buildings, vehicles, home appliances, and industry) are available today and can be scaled up quickly. In many cases, these energy efficiency solutions are already cost-competitive, readily available, and deliver immediate benefits for consumers in enhanced comfort, quality of life and reduced energy costs. To give a sense of scale: according to ACEEE, the United States could use cost-competitive energy efficiency based on currently available technologies to halve greenhouse gas emissions by 2050.[366]

One of the greatest assets—and greatest challenges—of energy efficiency is its tremendous diversity. Every sector has access to a variety of energy efficiency opportunities that can be tailored to optimize energy usage; and every country has cost-effective energy efficiency opportunities that could be pursued. However, investments in energy efficiency do not happen spontaneously, due to a number of barriers, including the need for coordination among a series of stakeholders (e.g., building managers,
</td><td>

Influential actors (i.e., initiatives, coalitions, and organizations)

• International Energy Agency (IEA)
• Sustainable Energy for All (SEforALL)
• UN-Habitat
• UN Environment Programme (UNEP)
• Global Environment Facility (GEF)
• Building Efficiency Accelerator (GEF, UNEP, WRI)
• Zero Carbon Buildings for All
• World Green Building Council
• Cool Coalition
• The Three Percent Club for Energy Efficiency, led by SEforALL and composed of 15 countries (Argentina, Colombia, Denmark, Estonia, Ethiopia, Ghana, Honduras, Hungary, India, Ireland, Italy, Kenya, Portugal, Senegal and the United Kingdom[372]
• Energy Efficiency Global Alliance
• Climate Group’s EP100
• Alliance to Save Energy
</td></tr>
</table>

operators, investors, inhabitants); access to financial strategies and tools to invest in up-front investments with short- to mid-term payback periods (e.g., energy performance contracts); a lack of strong leadership supporting energy efficiency from institutional leaders (e.g., corporate C-suite stakeholders in commercial and industry applications); and a lack of access to information about available options and access to resources to deploy them (e.g., residential customers). <u>Buildings</u>: In this sector, many efficiency measures yield financial savings. Addressing the efficiency of buildings can be divided into new building constructions, and existing building stock. Establishing strong mandatory building energy efficiency codes is an effective strategy to significantly increase the efficiency of new building stock, and while some countries do have such standards in place, a majority of countries globally do not have any standard, meaning the new buildings stock constructed each year is not bound by energy efficiency provisions. However, it is also important to address the energy efficiency of existing building stock; this is primarily accomplished through retrofits and is a critical tool to drive toward more equitable access to healthy and low-carbon buildings. IEA's net zero analysis includes rapid improvements in building efficiency, mostly from retrofits. It envisions that "around 2.5 percent of existing residential buildings in advanced economies are retrofitted each year to 2050" compared with a current retrofit rate of less than 1 percent.[367] See the "Buildings" section for further information. <u>Transport</u>: In this sector, efficiency gains will be driven by stringent fuel-economy standards and a rapid shift toward EVs, according to IEA's net zero analysis. The scenario also envisions continued efficiency improvements to heavy duty vehicles, ships, and planes.[368] Approximately 76 percent of transportation energy consumption globally is from motor gasoline (including ethanol blends up to E85) and distillate fuel (including	**Policy and other barriers** • Need for coordination among a series of stakeholders • Access to financial strategies and tools to invest in up-front investments with short- to mid-term payback periods • Lack of strong institutional leadership supporting energy efficiency • Lack of access to information about available options and access to resources to deploy them *...from IEA's Energy Efficiency 2019* • Potential negative effects of supply-side changes (e.g., increasing percentage of fossil fuels in energy mix).[373] • Countervailing trends (e.g., increased building floor area per person, increased electronic device ownership, consumer preference for larger cars).[374] • Lack of appropriate regulatory incentives and market participation models. • Lack of energy efficiency policies and investment.

diesel).[369] Internationally, a number of countries and regions (EU, Japan, South Korea) are also pursuing significantly more stringent fuel economy standards. Additionally, significantly higher levels of efficiency—and reduction in fossil fuel consumption—are made possible by vehicle electrification. Finally, strengthening more efficient transportation modes, such as public transportation and rail options, is a critical tool to enhance the efficiency of urban transportation while mitigating traffic congestion resulting from global urbanization. <u>Industry</u>: The industrial sector is extraordinarily diverse, including functions as disparate as refrigerating food products to aluminum smelting and cement production. Energy efficiency and process gains can be made across industries. It will be particularly important to make gains in energy-intensive processes, such as cement, iron and steel, nonferrous metals (primarily aluminum), refining, mining, chemicals, pulp and paper, and food. In this sector, incremental gains to 2030 will be driven by energy management systems, best-in-class industrial equipment, and process integration options (e.g., waste heat recovery), according to IEA's net zero analysis. After 2030, the rate of efficiency improvements could slow due to energy needs of emissions reduction technologies (e.g., CCUS).[370] **Key geographies** • Building decarbonization efforts can be significantly strengthened globally; especially significant gains are likely possible in countries that lack energy efficiency building codes and other measures. • Transportation efficiency and electrification efforts are especially relevant where significant highway transportation takes place. • Industrial decarbonization opportunities are especially relevant in countries with a significant manufacturing presence, and/or with significant heavy industry presence, including iron and steel, mining, cement, oil refining, and pulp paper (e.g.,	

<table>
<tr><td>China, United States, India, Japan).

Key actions and policies
• Standards and performance requirements and incentives for appliances, buildings, and efficient and electric vehicles.
• Energy efficiency financing, such as green banks, multilateral/development banks, national or subnational government-led programs, financial institution-led programs, and electric utility-led programs.
• Electric utility energy efficiency programs and enabling legislation/regulations.
• Fuel economy standards.
• Incentives to accelerate the deployment of electric transportation.
• Emissions pricing schemes.

“Estonia’s successful Renovation Loan Programme, for instance, could be used as a template for a European-wide building retrofit initiative.”[371]

The US federal government funds a range of energy efficiency programs, including the Weatherization Assistance Program (WAP) for residential retrofits.

Fuel economy standards can have a significant impact in reducing this consumption. For example, in the United States, since the inception of light-duty fuel economy standards in 1975, real-world fuel economy of new light duty vehicles improved by more than 90 percent while vehicle horsepower and weight both increased.</td><td></td></tr>
<tr><td colspan="2">Reduced methane emissions</td></tr>
<tr><td>Description of solution, quantification of opportunity
While methane emissions tend to receive less attention than carbon dioxide, reducing these emissions will be critical for avoiding the worst effects of climate change. Methane pollution is responsible for 25 percent of today’s global warming and is 84 times more potent than carbon dioxide in the near term. Cutting methane</td><td>Influential actors (i.e., initiatives, coalitions, and organizations, key geographies)

• International Energy Agency
• Oil and Gas Climate Initiative</td></tr>
</table>

pollution from the oil and gas industry is the fastest way to slow climate change.[375] Ocko *et al.* found that "the scale up and deployment of greatly underutilized but available mitigation measures will have significant near-term temperature benefits." In addition, strategies exist to cut global methane emissions from human activities in half within the next ten years and half of these strategies currently incur no net cost. Pursuing all mitigation measures now could […] avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century."[376] ~60 percent of methane emissions are from anthropogenic sources. Of these, more than 90 percent originate from three sectors: fossil fuels (~35 percent), agriculture (~40 percent), and waste (~20 percent).[377] Within the fossil fuels sector, the oil and gas subsector is responsible for about two-thirds of emissions. See the "Agriculture" section for further information about methane emissions from the agricultural sector. It is important to note that there is significant potential for methane emissions to be underreported. Extensive research by EDF revealed that methane emissions in the US are on average 60 percent higher than the government's estimates suggest.[378] In the absence of further action, methane emissions are projected to rise. However, in scenarios consistent with 1.5 degrees C, methane emissions are reduced by ~100–150 Mt/yr (from the fossil fuel and waste sectors combined) and by ~30–80 Mt/yr (from the agricultural sector) in 2030 relative to reference case emissions.[379] In IEA's Net Zero scenario, "methane emissions from fossil fuel supply fall by 75 percent over the next 10 years as a result of a global, concerted effort to deploy all available abatement measures and technologies."[380] Technologies to prevent vented and fugitive emissions are well-known. And, if all the technologies and measures identified in IEA's Methane Tracker 2020 were deployed,	• Oil and Gas Methane Partnership • Climate and Clean Air Coalition • Methane Guiding Principles **Policy and other barriers** • High cost of detection systems • Inaccurate emissions data • Measurement data analytics (technical challenges in converting raw data, such as methane concentration, to actionable data, like site emission rate) • UNFCCC reporting guidelines (countries are required to use consistent methods and report source-level emissions for inventories, which inhibits use of measurements) • Widespread, diverse oil and gas infrastructure (there is no single solution for all regions)

"around 75 percent of total oil and gas methane emissions could be avoided."[381] Notably, the oil and gas industry could achieve two-thirds of methane reductions at no net cost.[382] Abatement options include (see IEA report for detailed list): • Replacement of existing devices • Installation of new devices (e.g., vapor recovery units, blowdown capture) • Leak detection and repair (upstream and downstream) A new wave of technologies linked with big data also holds promise for remote monitoring of methane.[383] "The remote monitoring of well pads, processing plants, and distribution systems could help energy companies recover much of the $30 billion of methane they waste or flare every year. They would also spot super emitters faster, and quickly drive down millions of tons of potent climate pollution."[384] EDF found that "a small number of sites were responsible for a disproportionate amount of total emissions. These 'super-emitters' are sporadic and can pop up anywhere, at anytime, meaning the problem can't be addressed by focusing on a small number of known 'troubled' sites."[385] **Key geographies** Share of global methane emissions by region: Asia Pacific (10.7 percent), Europe (2 percent), North America (20.2 percent), Russia & the Caspian (27.7 percent), Africa (12.9 percent), Middle East (19.7 percent), Latin America (6.7 percent).[386] UNEP's 2021 Global Methane Assessment also provides estimates of methane emissions by region.[387] "Considering the potential for mitigation in different sectors and regions, the largest potential in Europe and India is in the waste sector, in China from coal production followed by livestock, in Africa from livestock followed by oil and gas, in the Asia-Pacific region, excluding China and India, from the coal subsector and the waste sector, in	

the Middle East, North America and Former Soviet Union it is from the oil and gas subsector, and in Latin America from the livestock subsector."[388] The oil and gas industry is one of the largest sources of methane emissions, accounting for an estimated 75 million metric tons every year.[389] Methane emissions from oil and gas production are particularly significant in Russia, the Middle East, North America.[390] Further detail can be found in IEA's Methane Tracker Database. **Key actions and policies** • Measurement-based emission inventories • Methane targets (including in NDCs) • Command-and-control policies that require phase-out or installation of certain devices • Performance-based emissions limits for facilities • Tracking and reporting of emissions by facilities (i.e., information-based regulation) • Tax on greenhouse gas emissions (or a greenhouse gas price elsewhere that enables facilities to generate credits) • Inspection and monitoring of facilities to address fugitive emissions (satellites can reveal major methane leaks) • Regulations that allow for improvements in technology • Complementary policies like government investment in research and development Further detail can be found in IEA's Methane Policy and Regulation Database.	

Appendix I: IEA Data

Energy-related and industrial process carbon dioxide emissions by sector in IEA's stated policies scenario:

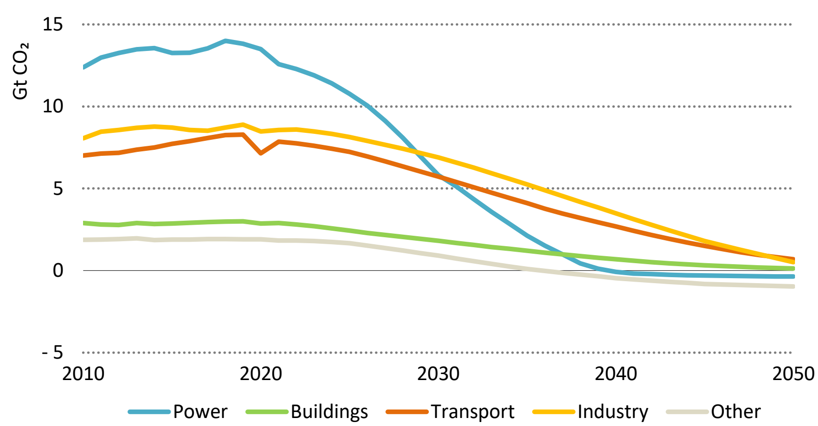
CO_2 emissions by sector (Gt CO_2)

	2020	**2030**	**2050**
Electricity	13.50	12.78	11.63
Industry	8.48	9.26	9.85
Transport	7.15	8.92	9.23
Buildings	2.86	2.84	2.71
Other	1.91	2.22	2.44

Energy-related and industrial process carbon dioxide emissions by sector in IEA's net zero scenario:

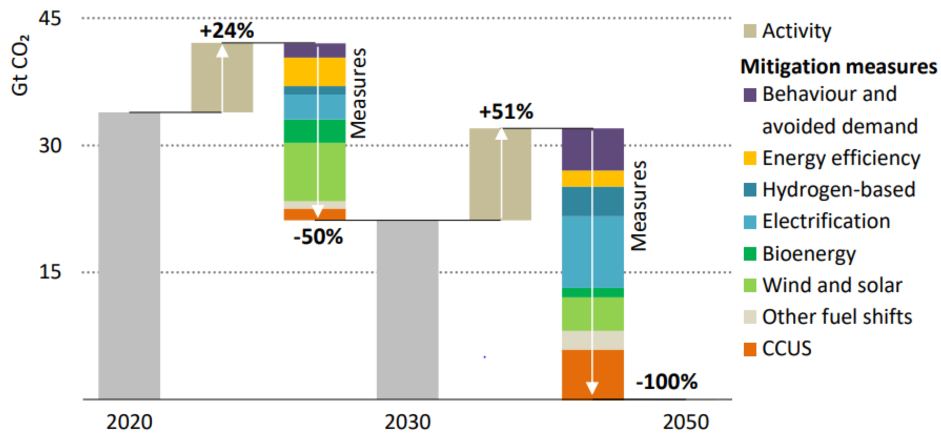
CO_2 emissions by sector (Gt CO_2)

	2020	**2030**	**2050**
Electricity	13.50	5.82	-0.369
Buildings	2.86	1.81	0.12
Transport	7.15	5.72	0.69
Industry	8.48	6.89	0.519
Other	1.91	0.91	-0.962



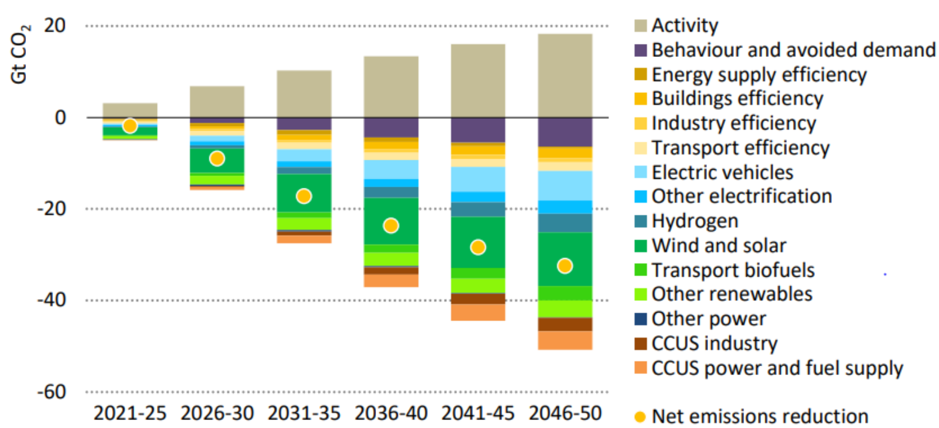
"Emissions fall fastest in the power sector, with transport, buildings and industry seeing steady declines to 2050. Reductions are aided by the increased availability of low-emissions fuels"

Figure 2.12 ▷ **Emissions reductions by mitigation measure in the NZE, 2020-2050**



Solar, wind and energy efficiency deliver around half of emissions reductions to 2030 in the NZE, while electrification, CCUS and hydrogen ramp up thereafter

Figure 2.4 ▷ **Average annual CO_2 reductions from 2020 in the NZE**



Renewables and electrification make the largest contribution to emissions reductions, but a wide range of measures and technologies are needed to achieve net-zero emissions

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